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REVIEW PAPER

Colour Measurement and Analysis in Fresh and Processed Foods: A Review

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Abstract Colour is an important quality attribute in the food and bioprocess industries, and it influences consumer's choice and preferences. Food colour is governed by the chemical, biochemical, microbial and physical changes which occur during growth, maturation, postharvest handling and processing. Colour measurement of food products has been used as an indirect measure of other quality attributes such as flavour and contents of pigments because it is simpler, faster and correlates well with other physicochemical properties. This review discusses the techniques and procedures for the measurement and analysis of colour in food and other biomaterial materials. It focuses on the instrumental (objective) and visual (subjective) measurements for quantifying colour attributes and highlights the range of primary and derived objective colour indices used to characterise the maturity and quality of a wide range of food products and beverages. Different approaches applied to model food colour are described, including reaction mechanisms, response surface methodology and others based on probabilistic and non-isothermal kinetics. Colour is one of the most widely measured product quality attributes in postharvest handling and in the food processing research and industry. Apart from differences in instrumentation, colour measurements are often reported based on different colour indices even for the same product, making it difficult to compare results in the literature. There is a need for standardisation to improve the traceability and transferability of measurements. The correlation between colour and other sensory quality attributes is well established, but future prospects exist in the application of objective non-destructive colour measurement in predictive modelling of the nutritional quality of fresh and processed food products.

Keywords Colour · Non-destructive measurement · Colorimeter · CIELAB · Colour index · Browning index · Colour kinetics · Food quality

Nomenclature

A_w	Water activity
a^*	CIE red(+)/green(−) colour attribute
b^*	CIE yellow(+)/blue(−) colour attribute
BI	Browning index
C^*	Chroma
CI	Colour index
CIRG	Colour index for red grape
CN	Citrus number
cv	Computer vision
CCI	Citrus colour index
COL	Tomato colour index
CY	Citrus yellow
CR	Citrus red
CIE	Commission Internationale de l'Eclairage
E_a	Activation energy (watts per gram or kilojoules per mole)
h^*	Hue angle
H	Hue angle
HSV	Hue, saturation and value
K/S	Kubelka–Munk parameter
L^*	CIE lightness coordinate

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PPO	Polyphenol oxidase
R	Universal gas constant
RGB	Red, green and blue
YI	Yellowness index
WI	Whiteness index
ΔE	Total colour difference
Δ	Change in measured attribute

Introduction

Appearance is one of the most important sensory quality attributes of fresh and processed food, products and their marketing (Costa et al. 2011; Grossman and Wisenblit 1999). It is an all-inclusive term involving size, shape, texture, mass, gloss, colour and others. The colour of food surface is the first quality parameter evaluated by consumers, and it is critical to product acceptance. Food appearance determined mostly by surface colour is the first sensation that the consumer perceives and uses as a tool to either accept or reject food (Leon et al. 2006). Visual appearance of the food manifested as its colour has a strong influence on a consumer's opinion about the food quality (Nisha et al. 2011; Pereira et al. 2009). Colour can be correlated with other quality attributes such as sensory, nutritional and visual or non-visual defects and helps to control them immediately (Francis 1995; Kramer 1976). Industrial food product quality was monitored and controlled by an online imaging system (Pereira et al. 2009; Yu et al. 2003). Skin defects and damage detection is an important application of image analysis to the inspection of fruit and vegetable quality (Cubero et al. 2011).

Colour is a perceptual phenomenon that depends on the observer and the conditions in which the colour is observed. It is a characteristic of light, which is measurable in terms of intensity and wavelength. The colour of a material becomes visible only when light from a luminous object or source illuminates or strikes the surface (Sahin and Sumnu 2006). Colour of agrifood products such as fruit and vegetables is derived from natural pigments, many of which change as the plant proceeds through maturation and ripening. The primary pigments imparting colour quality are the fat-soluble chlorophylls (green), carotenoids (yellow, orange, and red), water-soluble anthocyanins (red, blue), flavonoids (yellow) and betalains (red) (Barrett et al. 2010). Colour features can be used to detect defects in food products, such as those on the surface of apples, or to classify products having different qualities (Leemans et al. 1998). The product should look fresh, have normal size and colour associated with the particular fruit or vegetable, and be without blemishes or signs of decay. The absence of blemishes or signs of decay is also of utmost importance (Lurie 2009). The objective of this article was to provide a review of recent technological development in colour measurement and analysis of fresh and processed food. An overview of colour as a quality attribute in food is presented, including approaches to modelling changes in colour during postharvest handling and processing of food.

Colour as Food Quality Attribute—An Overview

Quality is not a single well-defined attribute but comprises many properties or characteristics. Appearance is one of the major factors the consumer uses to evaluate the quality of food products. The appearance of a product as judged by its colour can often be used to determine the pigment content of a product, which in turn is often an index of quality (Francis 1995). Colour is one of the most important quality components of fresh fruit and vegetables. Fruit ripening is a complex, genetically programmed process that culminates in dramatic changes in texture, colour, flavour and aroma. For instance, the characteristic pigmentation of red, ripe tomato fruit is the result of the de novo synthesis of carotenoids, mainly lycopene and β-carotene, which are associated with the change in fruit colour from green to red as chloroplasts are transformed to chromoplasts (Pék et al. 2010).

Visual quality encompasses the appearance of the product. With the long marketing chain of many fruits and vegetables that is currently in place, bruises are a common problem that can develop. This can take the appearance of a discoloured, soft area as in apples (Van Zeebroeck et al. 2007) or in pitting as in cherries (Toivonen et al. 2004). In the CIELAB colour system, parameter a^* measures the red coloration of fruits, which is caused due to the predominant amount of carotenoid lycopene, and parameter b^* measures the orange colorant of fruits due to β-carotene (Sacks and Francis 2001). The ripening process of tomatoes is well characterised by the colour evolution of the fruit surface (Hertog et al. 2007). Chlorophyll breaks down and carotenoids, mostly lycopene, accumulate during ripening (Brandt et al. 2006). Lang and Hübert (2011) reported the development of a colour ripeness indicator for apples based on the reduction effect of ethylene, causing colour changes in metallic ion (molybdenum blue), and showed that the colour change correlated with the amount of ethylene emitted from a single fruit or with exposition time in an ethylene-containing atmosphere. Colour is also an indicator of heat treatment severity and can be used to predict the corresponding quality deterioration resulting from heat exposure (Lozano and Ibarz 1997; Shin and Bhowmik 1995).

Desirable and Undesirable Colour Attributes

Colour and appearance attract a consumer to a product and can help in impulse purchases. At the point of purchase, the

consumer uses appearance factors to provide an indication of freshness and flavour quality. Colour is usually considered the most important attribute of any food's appearance (Francis and Clydesdale 1975), especially if it is associated with other aspects of food quality, for example, the ripening of fruit or the visible deterioration which occurs when a food spoils. Nearly every food product has an acceptable colour range which depends on a wide range of factors, including variability among consumers, their age and ethnic origin, and the physical nature of the surroundings at the time of judgement (Francis 1995). External appearance of a whole fruit is used as an indicator of ripeness, although it can be a misleading one (Shewfelt 2000). Consumers have a preferred colour for a specific item (Crisosto et al. 2003). Colours that are not appropriate for the item, indicative of loss of freshness or suggestive of a lack of ripeness, can turn away willing consumers. In general, specific food products are associated with specific colour attributes. For instance, good quality and ripe bananas are associated with yellow colour with no brown spots, tomatoes with red and not orange, cherries with red and not yellow and kiwifruit with green flesh and not yellow. However, recent advances in plant breeding have resulted in new cultivars of fruit and vegetables with a wide range of skin and/or flesh colours such as Golden Kiwifruit, yellow tomatoes, etc.

Gloss is a visual aspect of quality that depends on the ability of a surface to reflect light (Mitcham et al. 1996). Gloss on the outside of the whole fruit tends to be a desirable attribute for whole fruits. Products that are freshly harvested often have a bright, glossy surface, and this appearance factor can be greatly reduced with weight loss and other postharvest handling conditions. Freshly cut fruits and vegetables must appear to be fresh, generally indicated by the brightness of colour and the absence of visual defects or drip. Sheen on the outside of most cut fruits is preferred to a dried appearance. Colour and appearance of the package can also influence the purchase decision. Some consumers tend to reject sweet (yellow with brown spots) bananas, nutritious, high β-carotene (yellow and orange) tomatoes and flavourful Ranier (yellow with red blush) cherries due to unexpected coloration. Wilting, browning, dull colours and drip are all indicators of loss of freshness in freshly cut vegetables (Shewfelt 1993). White blush in cut carrots is a quality defect (Emmambux and Minnaar 2003). Visible wilting in lettuce and celery and shrivelling in fruits reduce consumers' acceptability. Yellowing in green vegetables due to loss of chlorophyll is unacceptable (Shewfelt 2003). Less intensity of colour indicates lack of ripeness in freshly cut fruits. Browning is a serious quality defect in freshly cut fruits.

In practice, because the consumer generally associates pleasant flavour with an attractive colour, the attractive pink or red colour of grapefruit has been used in marketing through transparent packages and the use of sliced fruit in advertising. Pink grapefruit juice beverages are notably one of the most popular drink items in the market (Labell 1993). Appropriate coloration increased the acceptability of fruit punch flavoured beverages (Clydesdale 1993). Colour is an indication of ripeness or spoilage. The end point of cooking processes is judged by colour. Changes in expected colours can also indicate problems with processing or packaging. Judgement of food flavour is often influenced by colour; fruits such as cherry, raspberry and strawberry are associated with the colour red; beef flavour is brown (Parker 2001). In order to maintain quality, the colour of food products must be measured and standardised.

Colour Systems (Colour Spaces)

The colour of an object can be described by several colour coordinate systems (Clydesdale 1978; Francis 1980; Hunter and Harold 1987; Minolta 1994). Some of the most popular systems are RGB (red, green and blue), which is used in colour video monitors; Hunter *L a b*, Commission Internationale de l'Eclairage's (CIE) *L*a*b**, CIE XYZ, CIE *L*u*v**, CIE *Yxy*, and CIE LCH. These differ in the symmetry of the colour space and in the coordinate system used to define points within that space. According to CIE concepts, the human eye has three colour receptors—red, green and blue—and all colours are combinations of those. The amounts of red, green and blue needed to form any particular colour are called the tristimulus values and are denoted *X*, *Y* and *Z*, respectively. The most commonly used notations are the CIE *XYZ* colour space devised in 1931 by the International Commission on Illumination. The system is based on the trichromatic principle, but instead of using real red, green and blue primaries with their necessity for negative matching, it uses imaginary positive primaries, *X*, *Y* and *Z*. It uses the chromaticity diagram to designate various colours (Fig. 1). Primary *Y*, known as luminous reflectance or transmittance, contains the entire lightness stimulus. The application of the weighting to a reflectance curve gives the tristimulus values, which are denoted by the capital letters *X*, *Y* and *Z*. These values are then used to calculate the chromaticity coordinates, designated by lowercase letters *x* (red), *y* (green) and *z* (blue). The value for *x* can be calculated as $x=X/(X+Y+Z)$. The values for *y* and *z* can be calculated by replacing *X* with *Y* and *Z*, respectively, in the numerator (Sahin and Sumnu 2006). The Hunter *L a b* developed in 1948 for photoelectric measurement and the CIE *L*a*b** colour space (Fig. 2) devised in 1976 provide more uniform colour differences in relation to human perception of differences.

An object, a light source or an illuminant, and an observer are required for the presence of colour. A light source can

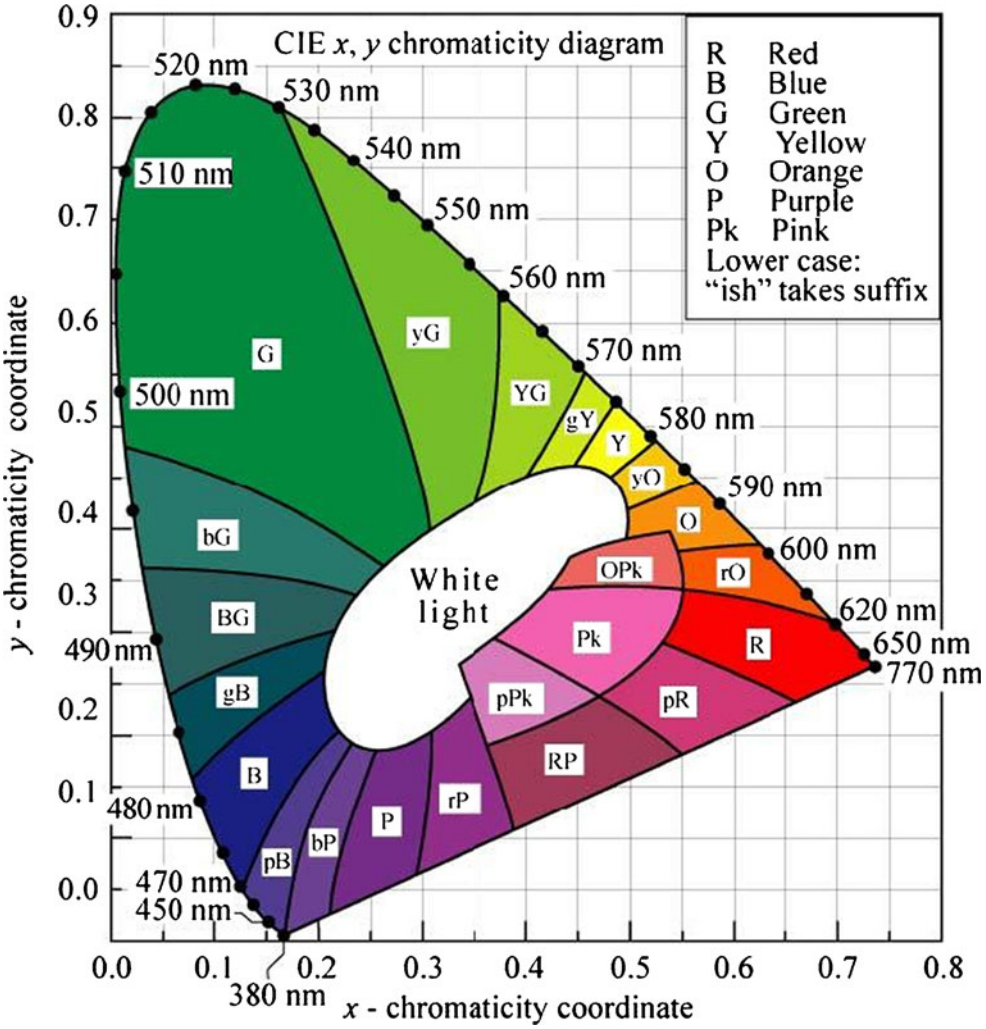

Fig. 1 CIE chromaticity diagram

be turned on and off and can be used to view an object. However, an illuminant is a mathematical description of a light source. In 1931, the CIE recommended three standard illuminants. Illuminant *A* defines light typical of that from an incandescent lamp, illuminant *B* represents direct sunlight, and illuminant *C* represents average daylight from the total sky. In 1966, the CIE proposed a fourth series, the *D* illuminants. These illuminants represent daylight more completely and accurately than illuminants *B* and *C*. The *D* illuminants are usually identified by the first two digits of their colour temperature (Sahin and Sumnu 2006). In 1986, the CIE recommended the use of an *E* series of illuminants for fluorescent lamps (MacDougall 2002).

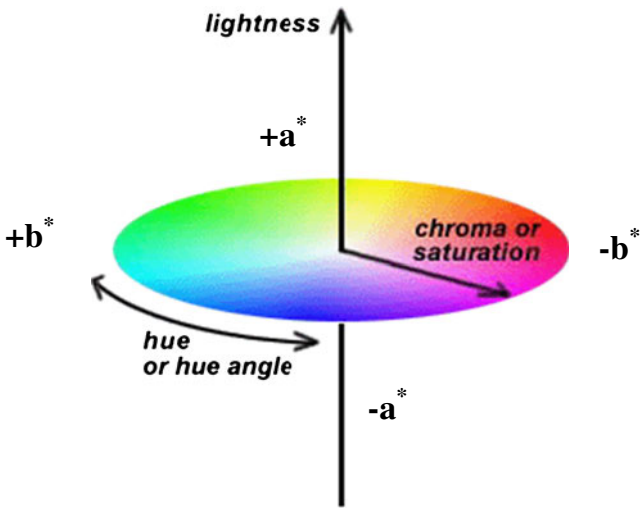

Fig.2 CIELAB colour space

Quantification of Colour

The HunterLab L^*,a^*,b^* and the modified CIE system called CIELAB colour scales were opponent-type systems commonly used in the food industry. The CIELAB coordinates (L^*, a^*, b^*) were directly read. It was considered the CIELAB uniform space in which two colour coordinates, a^* and b^*, as well as a psychometric index of lightness, L^*,

were measured. The parameter a^* takes positive values for reddish colours and negative values for the greenish ones, whereas b^* takes positive values for yellowish colours and negative values for the bluish ones. L^* is an approximate measurement of luminosity, which is the property according to which each colour can be considered as equivalent to a member of the greyscale, between black and white (Granato and Masson 2010).

Chroma (C^*), considered the quantitative attribute of colourfulness, is used to determine the degree of difference of a hue in comparison to a grey colour with the same lightness. The higher the chroma values, the higher is the colour intensity of samples perceived by humans. Chroma was calculated using Eq. 1

$$C* = \sqrt{a*^2 + b*^2} \tag{1}$$

Hue angle (h^*), considered the qualitative attribute of colour, is the attribute according to which colours have been traditionally defined as reddish, greenish, etc., and it is used to define the difference of a certain colour with reference to grey colour with the same lightness. This attribute is related to the differences in absorbance at different wavelengths. A higher hue angle represents a lesser yellow character in the assays (Eq. 2)

$$h* = \tan^{-1}\left(\frac{b*}{a*}\right) \tag{2}$$

An angle of 0° or 360° represents red hue, whilst angles of 90°, 180° and 270° represent yellow, green and blue hues, respectively. It has been extensively used in the evaluation of colour parameters in green vegetables, fruits and meats (Barreiro et al. 1997; Lopez et al. 1997).

Derived General Objective Colour Indices

Total Colour Difference

Colour changes can be measured as the modulus of the distance vector between the initial colour values and the actual colour coordinates. This concept is named total colour difference (Martins and Silva 2002). Total colour difference indicates the magnitude of colour difference between stored and control samples (Patras et al. 2011). Total colour difference (ΔE) indicates the colour difference from the standard plate calculated as (Rhim et al. 1999)

$$\Delta E* = \sqrt{\Delta a*^2 + \Delta b*^2 + \Delta L*^2} \tag{3}$$

Differences in perceivable colour can be analytically classified as very distinct ($\Delta E>3$), distinct ($1.5<\Delta E<3$) and small difference ($1.5<\Delta E$; Adekunte et al. 2010). Total colour difference and chroma was considered as the most sensitive parameter for the measurement of colour degradation in strawberry jam in response to temperature treatment during storage (Patras et al. 2011). Sonication in tomato juice resulted in an increase in total colour difference (Adekunte et al. 2010; Tiwari et al. 2008a).

Dede et al. (2007) observed that high-pressure treatment of 250 MPa/35 °C/15 min produced a lower colour difference compared to fresh sample than thermally processed carrot and tomato juices. Colour changes were minor (ΔE) for high-pressure-treated strawberry and blackberry purees, but the differences were slightly higher for conventional thermally treated samples (Patras et al. 2009).

Whiteness Index

Whiteness indices (WI) are widely measured to yield numbers correlating closely with consumers' preferences for white colours. It mathematically combines lightness and yellow–blue into a single term. The WI represents the overall whiteness of food products that may indicate the extent of discoloration during the drying process (Hsu et al. 2003). WI indicates the degree of whiteness (Rhim et al. 1999).

$$\mathrm{WI} = \sqrt{(100 - L*^2) + a*^2 + b*^2} \tag{4}$$

White surface colour is one of the most critical factors affecting the quality of a Camembert-type cheese. Whiteness index showed a significant fall for the control sample, whilst the modified atmosphere packaging samples held the WI very well on day 14 (Rodriguez-Aguilera et al. 2011).

Qin et al. (2010) analysed the nutritional composition and flavonoid contents of the flour from 39 buckwheat cultivars collected in China and compared the compositions of the flour from common buckwheat with those from tartary buckwheat. The flour of common buckwheat showed a higher whiteness index than that of tartary buckwheat and contained very low levels of flavonoids. Buckwheat-enhanced wheat bread showed lower whiteness index values (Lin et al. 2009).

Yellowness Index

Yellowness is associated with scorching, soiling, and general product degradation by light, chemical exposure and processing. Yellowness indices are used chiefly to quantify these types of degradation with a single value. They can be used when measuring clear, near-colourless liquids or solids in transmission and near-white, opaque solids in reflectance. Yellowness index (YI) indicates the degree of yellowness (Rhim et al. 1999).

$$\mathrm{YI} = \frac{142.86b*}{L*} \tag{5}$$

The Yellowness index of parboiled rice increased with an increase in infrared radiation intensity or

increased heating (Das et al. 2004). The whiteness index of mushroom decreased whilst the yellowness index increased during the drying process. However, the whiteness index increased whilst the yellowness index decreased as the rehydration progressed (Kotwaliwale et al. 2007).

Product-Specific Objective Colour Indices

Several researchers have proposed colour indices which permit a direct correlation with the visual appearance of specific food products and biomaterials, including fruit and vegetables, flour, bread, pasta, mashed potato, meat, wine and juices (Table 1). These indices are characterised by showing a high correlation with the external visual colour of the fruits and can be used in studies of maturation, preservation or storage (Carreno et al. 1995). The ratio a/b has been used as a colour index in apple, tomato, citrus and carambola fruit (Campbell et al. 1989; Little 1975; Stewart and Wheaton 1971). Medlicott et al. (1992) reported a significant correlation between peel colour score (visual assessment) and Hunter's a/b ratio for mango, which is related to maturity.

Colour Measurement

Colour measurement can be carried out in two main ways: visual evaluation and instrumental analysis.

Subjective/Visual Colour Measurement

Visual analysis of food colour is the evaluation of their characteristics by means of the senses (Meléndez-Martínez et al. 2005). Visual colour measurement involves observing a sample without instruments, but under controlled conditions of illumination, along with reference to a set of colour standards with which to compare the sample colours observed. It involves observing the colour of a sample and comparing it against defined colour standards under identical conditions of illumination. This is called finding a colour match and falls into the category of organoleptic (sensory) methods of food quality analysis (Figura and Teixeira 2007). Comprehensive information concerning the sensory evaluation of food colour, including guidelines for panel selection, physical requirements for visual assessments and types of sensory tests, can be found in the literature (Hutchings 1994). As a result of visual analysis, a particular description of colour is obtained, for which there is a certain vocabulary.

Table 1 Recommended colour indices/parameter of selected fresh and processed foods

Produce	Index	Reference
Red table grape	$CIRG=(180-H)/(L^*+C)$	Carreno et al. (1995)
Tomato fruit	$COL=(2{,}000\times a^*)\ (L^*\times C)$	Hobson (1987)
Citrus fruit degreening	$CCI=(1{,}000\times a)/(L\times b)$	Jiménez-Cuesta et al. (1981)
Citrus fruit	$CR=200[(1.277X-.213Z)/Y-1]$ $CY=100(1-0.847Z/Y)$ $CN=22.51+0.165CR+0.111CY$	Buslig et al. (1987)
Orange juice	K/S	Meléndez-Martínez et al. (2011)
Apple, tomato, citrus and carambola fruit	$CI=a/b$	Little (1975); Stewart and Wheaton (1971)
Carambola fruit	$CI=a/b$	Campbell et al. (1989)
Banana peel	Chiquita colour index	Boudhrioua et al. (2003)
Chicken Breast	$E^*=a^*/b^*+a^*/L^*$	Liu et al. (2003)
Meat Redness index	$RI=a^*/b^*$	Chen and Chiu (1997)
Flour colour index (FCI),	$FCI=L^*-b^*$	Oliver et al. (1992)
Pasta colour parameter	$100-L^*$	Resmini et al. (1993)
Baby cereals colour parameter	$100-L^*$; (ΔE)	Fernández-Artigas et al. (1999)
Bread surface colour parameter	(ΔE)	Zanoni et al. (1995)
Sherry wine colour index (CI)	By determination of absorbance at 470 nm using a spectrophotometer	Palacios et al. (2002)
Red wine colour intensity	$C.I.=A_{420}+A_{520}+A_{620}$	Almela et al. (1995)
Sugar syrup (clarification)	Yellow colour value$=a^*/b^*$	Larrauri García and Saura Calixto (2000)
Mash potato	White/yellow ratio$=L/b$	O'Leary et al. (2000)
Fresh broccoli	$H=\tan^{-1}b/a$	Shewfelt et al. (1984)
Paprika colour index (PACI)	$PACI=1{,}000a^*/(L^*+h)$	Nieto-Sandoval et al. (1999)

An overview of subjective colour scores used to characterise visual colour of food products is given in Table 2, which shows the difference in score range for colour description.

Visual assessment of colour can also be carried out by means of colour scales or atlases containing comparative standards, which are very cheap in comparison to the instrumentation used for objective measurement of colour. It is important to note that, despite the human eye being good at discriminating between different colours, the capacity of the brain for remembering them is poor. This is not such an important problem in some industries (paint, textiles) because stable standards can be stored for comparison. In the food industry, samples have to be matched to a colour chip from a colour order system (Hutchings 1994). These scales must include all the possible hues and intensities of different colours, and each point in the scale must be assigned a number. Obenland et al. (2009) visually rated the external naval orange colour (3, dark green, to 13, orange) by using a pictorial colour chart. The colour chart was developed by researchers at the University of California, Riverside, and a rating was carried out by the same person each time, except for the very few times when that person was not present. Table 3 shows the range of semi-objective scores in different colour charts used for fresh and processed food products.

Pedreschi et al. (2012) classified potato chips in quality categories according to their colour after frying at different oil temperatures and undergoing some pretreatments. To define quality categories according to the surface colour, the authors worked with 79 frequent consumers of potato chips who classified the colour scores of the potato chip photographs located in a standard colour chart (Fig. 3) into the following categories: (000) non-desirable colour/grade 3, (00) non-desirable colour/grade 3, (0) still acceptable colour/grade 2, (1) desirable colour/grade 1, (2) still acceptable colour/grade 2, and (3) non-desirable colour/grade 3. Time–temperature modelling was achieved in order to get the potato chip with the best colour surface for the pretreatments tested.

Instrumental Methods for Colour Measurement

Colour is subject to perception. Different people interpret the expressions of colour in many different ways. Thus, subjective expression of colour may not be accurate enough to communicate the colour. Objective approaches in colour measurement and expression would help minimize colour-related problems, and colour communication between processors and buyers would be much simpler and exact (Lee 2000). In the case of instrumental measurement, colour is expressed by means of the colour coordinates. Colour may be determined instrumentally using either colorimeters or spectrophotometers. Table 4 shows a summary of the different instruments used in objective food colour measurement found in the literature analysed.

Colorimeters

Colorimeters measure the colour of primary radiation sources, which emit light, and secondary radiation sources, which are those that reflect or transmit external light.

Table 2 Range of subjective colour scores used to characterise visual colour of food products

Colour score range	Colour description	Food product	References
1–9	1=Colour light yellow 9=intense orange	Mango gel snack	Ekpong et al. (2006)
Nine-point hedonic scale	Intensity of the brown colour of coffee samples (light brown–black brown)	Instant coffee	Geel et al. (2005)
1–5	1='very bad', 2='bad', 3='maybe good or maybe bad', 4='good', 5='very good'	Apple	Kühn and Thybo (2001)
0–9 score range	Shell colour intensity 0=low, 9=high	Walnut	Sinesio and Moneta (1997)
Nine-point hedonic scale	The lowest and highest scores for colour is 1 and 9	Smoothie-type beverages	Walkling-Ribeiro et al. (2010)
0–9 score range	'low intensity' and 'high intensity'	Sweet cherry (*Prunus avium* L.)	Esti et al. (2002)
1–5	1=colourless, 2=light red, 3=red, 4=dark red, 5=dark red–violet	Sweet cherry Juice	Usenik et al. (2008)
1–5	1=white, 2=light red, 3=bright red, 4=dark red, 5=black	Sweet cherry (*Prunus avium* L.)	Usenik et al. (2008)
0–9	0–4=very bad–bad; 5–9= acceptable–excellent	Pomegranate juice	Vardin and Fenercioğlu (2003)

Table 3 Range of semi-objective scores in colour charts used for fresh and processed food products

Product	Colour scoring	Description	Reference
Banana Peel	Chiquita colour scale 2–7	2=Entirely green, 3=More green than yellow, 4=More yellow than green, 5=Yellow with green necks, 6=Entirely yellow, 7=Entirely yellow with brown spot	Boudhrioua et al. (2003)
Tomato	Big Red Color Chart, FL, USA: 1–6	1=Mature green, 2=breaker, 3=turning, 4=pink, 5=light red, 6=red	Maharaj et al. (1999)
Citrus	0–12	0=Dark green, 7=orange, 12=deep reddish orange	Iwahori et al. (1986)
Navel oranges	3–13	3=Dark green, 13=orange	Obenland et al. (2009)
Granny Smith apple	Deciduous Fruit Board chart A38;1–12	1=Dark green	Wand et al. (2006)
Braeburn apple blush	Deciduous Fruit Board chart A44: 1–8	1=Red	Wand et al. (2006)
Fuji apple blush	Deciduous Fruit Board chart A45: 1–12	1=Red	Wand et al. (2006)
Granny Smith apple	Colour chart: 0.5–5.0	0.5=Dark green and 5=yellow	Wand et al. (2006)
Royal Gala apple blush colour	Deciduous Fruit Board chart A42: 1–12	1=Red	Wand et al. (2006)
Cripps Pink apple	Pink Lady colour chart 1–12	12=Red	Wand et al. (2006)
Golden Delicious apples	Deciduous Fruit Board (DFB) colour chart no. A28: 1–9	1=Dark green, 9=full yellow	Eksteen and Truter (1987)
Packham's Triumph pears	Colour rating 1–5 dark red;	1=Dark green, 2=light green, 3=more green, than yellow, 4=more yellow than green, 5=yellow	Eksteen and Truter (1987)
Santa Rosa plums	Colour rating: 1–5	1=25 % red, 2=50 % red, 3=75 % red, 4=100 % (full) red, 5=Dark red	Eksteen and Truter (1987)
Forelle pears (blush development)	Deciduous Fruit Board's colour chart: 1–12	1=Green, 12=red	North and Cook (2006)
Apples (background colour)	Unifruco colour chart: 1–5	1=Green, 5=yellow	North and Cook (2006)
Pears (Background colour)	Unifruco colour chart: 1–5	1=Green, 5=yellow	North and Cook (2006)
Potato chips	Commercial potato chip colour (Belgapom, Brussels, Belgium) 000-4	000=Defective colour (non-desirable colour or grade 3) 00=Defective colour (non-desirable colour or grade 3) 0=Intermediate colour (still acceptable colour or grade 2) 1=Very good colour (desired colour or grade 1) 2=Intermediate colour (still acceptable colour or grade 2) and 3=Defective colour (non-desirable colour or grade 3)	Pedreschi et al. (2011)
Salmon fillet	SalmonFan card (Hoffmann-La Roche Basel, Switzerland): 20–34	20=Very pale red to 34=very intense red	Quevedo et al. (2010)
Beef carcasses (fat colour)	6-point photographic colour chart (Paul Frapple pers. comm.): 1–6	1=White, 6=very yellow	Walker et al. (1990)

Tristimulus values X, Y and Z are optically, not mathematically, obtained. Colorimeters simulate the response of only a standard observer and a standard illuminant, so the values obtained differ as a function of the apparatus used. Based on the three types of cones in the retina of the human eye, colour-measuring instruments have been developed with three filters that function like each of the three types of cones. A tristimulus colorimeter has three main components: (1) source of illumination, (2) combination of filters used to modify the energy distribution of the incident/reflected light and (3) photoelectric detector that converts the reflected light into an electrical output. Measurements made on a tristimulus colorimeter are normally comparative. Therefore, it is necessary to use calibrated standards of

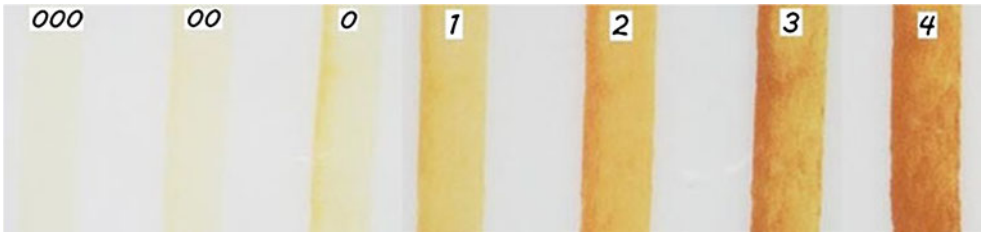

Fig. 3 Chart for sensory analysis of commercial potato chip colour. Source: Pedreschi et al. (2011)

similar colours to the materials to be measured to achieve the most accurate measurements. Colorimeters are the most commonly used instruments in the colour measurement of food and other products, presumably due to their ease of use and interpretation of colour data.

Spectrophotometers

Spectrophotometers measure the spectral distribution of transmittance or reflectance of the sample. From these measurements, colour is calculated under different conditions.

Table 4 Types of instruments used in objective colour measurement in selected publications

Instrument	Model	Reference
Digital camera	PowerShot A70 (Canon, USA)	Mendoza et al. (2006)
	FUJIFILM FinePix S5800/S800 (10× optical zoom)	Lv et al. (2009)
	Canon Powershot, Model A520, (Japan)	Fathi et al. (2011)
Konica Minolta Chroma Meter (Osaka, Japan)	CR200	Abe et al. (2011)
	CR-300	Arabhosseini et al. (2010)
	CR-331	Mohapatra et al. (2010)
	CR-400	Rhim and Hong (2011)
Hunter colorimeter (Hunter Associates Laboratory, Reston, Va., U.S.A.)	D25 optical sensor	Ahmed et al. (2002a)
	D25-PC2	Chutintrasri and Noomhorm (2007)
	DP-9000 D25A	Nisha et al. (2011)
	ColorFlex, A60-1010-615 model	Maskan (2001)
	Mini Scan XE plus colorimeter	Jha et al. (2007)
A tristimulus colorimeter Data Lab India Pvt. Ltd., Silvasa, (Gujarat, India)	Model 2810	Saxena et al. (2010)
Dr. Lange colorimeters (Dr. Lange, Germany)	Dr. Lange Micro Colour	Mendoza et al. (2006)
Sheen Micromatch Plus tristimulus colorimeter (Sheen Instruments Ltd., Kingston-Upon-Thames, UK)		Pék et al. (2010)
Macbeth spectrophotometer (Kollmorgen Instruments Corp., Newburgh, NY)	Color-Eye 3100	Lee (2000)
	Color-Eye 3000	Buslig et al. (1987)
Minolta Spectrophotometer (Konica Minolta Sensing, Inc., Japan)	CM-2500D	Vandekinderen et al. (2008)
	CM-3600D	Benlloch-Tinoco et al. (2011)
Spectrophotometer (Shimadzu 300 UV, Tokyo, Japan)		Suh et al. (2003)
Reflectance spectrophotometer (Datacolor S.A., Spain)	Elrepho 2000	Ramirez-Jimenez et al. (2000)
Spectrocolorimeter (Hunter Associates Laboratory, Virginia)	LabScanXE Spectrocolorimeter (model no. LX16244)	Singh and Reddy (2006)
	Spectrocolorimeter (Hunter,model ColorQuest XE, Reston, VA)	Zepka et al. (2009)
	Spectrophotometer (Model D25L-2, Hunter Assoc. Laboratory, Reston, VA, USA)	Granato and Masson (2010)

The *X*, *Y* and *Z* values obtained depend on the illuminant, the measurement geometry and the observer. Both transmittance and reflectance are inherent and relative properties of the objects which do not depend on either the illumination or the observer, whereas, as has been mentioned before, colour does depend on both of them. Transmittance measurements, by means of a spectrophotometer, are the ratio between the response when the sample is in the optical pathway of the instrument and the response when the sample is not present.

Colorimeters give measurements that can be correlated with human eye–brain perception and give tristimulus (*L*, *a* and *b*) values directly (HunterLab 1995). Colorimeters are typically quite rugged and desirable for routine quality control measurements. Spectrophotometers provide wavelength-by-wavelength spectral analysis of the reflecting and/or transmitting properties of objects and are more commonly used in research and development laboratories (HunterLab 1995). The advantage of spectrophotometers over colorimeters is that adequate information can be obtained to calculate colour values for any illuminant and metamerism (the difference in colour under different lighting). Spectrophotometers can also automatically detect colour measurement at different angles (Sahin and Sumnu 2006).

Colour Measurement by Computer Vision System

Chemical or physical components of food products are usually reconstructed during processing; colour, which is strongly affected by these components, can reflect the reconstruction of these components. The changes of chemical and physical components are difficult to measure or quantify; computer vision is an alternative technique for colour evaluation and quantification (Yam and Papadakis 2004). Computer vision has been used to objectively measure the colour of different foods since they provide some obvious advantages over a conventional colorimeter, namely, the possibility of analysing each pixel of the entire surface of the food and quantifying surface characteristics and defects (Brosnan and Sun 2004; Du and Sun 2004). The system generally consists of five basic components: the illuminant, a digital camera, an image capture board (frame grabber or digitizer), and computer hardware and software to process the images (Quevedo et al. 2010). Image acquisition is the first step in computer vision, and data quality is the main concern during acquisition (Jackman et al. 2011). Correct acquisition equipment precision is essential as precision must be fine enough to see the required details and coarse enough for rapid image processing. Correct camera exposure and focus are required for good contrast and exclusion of blurring. Common image acquisition equipment used in food applications are the charge-coupled device (CCD) camera, magnetic resonance imaging (MRI), ultrasound, computed tomography (CT) and electrical tomography (Du and Sun 2004).

Once the image of an object is acquired, it is processed for feature extraction and analysis. Pre-processing improves the quality of the image by removing noise and distortion and also data transformation into more convenient formats, intermediate processing which primarily involves the issue of segmenting the region of interest from the image and high-level processing which involves describing the region of interest and building a predictive model from those features (Brosnan and Sun 2004; Du and Sun 2004). Images captured by CCD camera, ultrasound, MRI and CT are subject to various types of noises. These noises may degrade the quality of an image and subsequently cannot provide correct information for subsequent image processing. In order to improve the quality of an image, operations need to be performed to remove or decrease degradations suffered by the image during its acquisition. The purpose of pre-processing is an improvement of the image data which suppresses unwilling distortions or enhances some image features that are important for further processing and creates a more suitable image than the original for a specific application. Two different types of image pre-processing approaches can be identified for food quality evaluation—pixel pre-processing and local pre-processing—according to the size of the pixel neighbourhood that is used for the calculation of a new pixel. Pixel pre-processing is a simple but important image processing technique which converts an input image into an output image in such a way that each output pixel corresponds directly to the input pixel having the same coordinates. However, local pre-processing methods use a small neighbourhood of a pixel in an input image to produce a new brightness value in the output image, which is also called filtration.

Colour space transformation is the most common pixel pre-processing method for food quality evaluation. RGB, HSV and CIELAB are the most popular space colour models used in food computer vision (Dana and Ivo 2008; Du and Sun 2004; Leon et al. 2006; Sun 2004). Usually, colour images are taken by a digital device and saved in the three-dimensional RGB colour space. However, RGB space is not quite perceptually uniform and does not represent the colours perceived naturally by humans very well. Perceptual uniformity is the property by which the perceptual similarity of two colours is measured based on the distance between the two colour points in the colour space (Jain 1989). CIELAB and the HSV colour space are preferred in foods because these colour spaces effectively represent the colours naturally perceived by humans, and they are perceptually uniform (Quevedo et al. 2010). A thorough analysis of reliable RGB to $L^*a^*b^*$ conversion is discussed by Leon et al. (2006). Tao et al. (1995) transformed the RGB colour space to HSI for efficient colour image processing of

potatoes and apples. The method of using the HSI colour system proved highly effective for colour evaluation and image processing.

Image segmentation partitions an image into its constituent objects, which is a challenging task because of the richness of visual information in the image. Removal of the background should be fairly straightforward, but removing non-useful sub-regions of an object can be far more difficult. Ideally, a segmentation process should be fully automatic so that it can provide fully objective and consistent data. Thresholding, gradient-based, region-based and classification-based are the main types of segmentation algorithm found in food quality applications (Du and Sun 2004). Many researchers (Leon et al. 2006; Mendoza and Aguilera 2004; Papadakis et al. 2000; Pedreschi et al. 2004; Quevedo et al. 2010; Scanlon et al. 1994; Segnini et al. 1999) used computer vision techniques for food colour measurement. Machine vision system is used to detect rotten citrus fruit that is rotten due to *Penicillium digitatum* (Gómez-Sanchis et al. 2008).

Browning

Browning colouration is an important phenomenon in food handling and processing, including baking, drying and frying, because it affects appearance quality. Therefore, the measurement and quantification of browning is important in food research and industrial practice during sorting and grading to meet market requirements. It results from both enzymatic and non-enzymatic oxidation of phenolic compounds. Once cell walls and cellular membranes lose their integrity, enzymatic oxidation proceeds much more rapidly. Enzymatic browning is an indirect result of polyphenol oxidase (PPO) action (Walker 1975). Browning of raw fruits and vegetables due to mechanical injury during postharvest handling and processing is an important cause of quality and value loss in affected commodities (Sapers and Douglas 1987). Enzymatic browning is beneficial when it contributes to the desirable colour and flavour of such products such as raisin, prunes, coffee, tea and cocoa (Mayer and Harel 1979; Vamos-Vigyazo 1981). This reaction results from the PPO-catalyzed oxidation of phenolic compounds to *o*-quinones which subsequently polymerize to form dark-coloured pigments (Mayer and Harel 1979; Vamos-Vigyazo 1981).

Colour formation in bakery products during baking is widely known as browning (Purlis 2010). Non-enzymatic browning is the general denomination of darkening of a food product due to any reaction not owing to enzymatic activity (Quintas et al. 2007). Non-enzymatic browning is mainly associated with carbohydrate degradation reactions, such as the Maillard and caramelisation reactions (BeMiller and Whistler 1996). The Maillard reaction takes place where reducing sugars and amino acids, proteins and/or other nitrogen-containing compounds are heated together, whilst caramelization is a term for describing a complex group of reactions that occur due to direct heating of carbohydrates, in particular sucrose and reducing sugars (Fennema 1996).

The formation of a brown colour has been measured by different experimental techniques, which can be divided into two main categories: direct and indirect techniques. The first group involves chemical methods that aim to measure the concentration of browning reaction products (or alternatively the consumption of reactants). Conversely, the indirect approach is focused on registering the variation of colour produced by the Maillard reaction and caramelization, i.e. it is related to technological applications (Purlis 2010). Direct or chemical techniques are mostly intended to measure the concentration of HMF and furfurals in products during baking. The general procedure consists of an extraction method and subsequent quantification by HPLC-UV; UV detection is carried out at 280 or 284 nm (Ameur et al. 2006, 2007; Ramirez-Jimenez et al. 2000). A similar protocol is used for furosine determination, which is a compound formed at the early stages of Maillard reaction (Ramirez-Jimenez et al. 2000). The development of browning can also be followed by measuring the reactant consumption. Ameur et al. (2007) quantified the degradation of sugars in biscuit baking with a HPLC-RI (refractive index) detection method after a water–ethanol extraction. Indirect techniques are based on a technological or sensorial approach. The main advantages of chemical techniques are objectivity, since a compound concentration is being measured, and sensibility (Ramirez-Jimenez et al. 2000). On the other hand, such methods are destructive, laborious and time-consuming. Inversely, indirect techniques are automated, rapid and non-destructive, although they have a sensorial basis. The traditional way of measuring the variation of colour has been the use of a colorimeter, colour sensor or computer vision systems.

The colour of the dried fruit changes due to the formation of browning, which has often been associated with the Maillard reaction (Baini and Langrish 2009). The Maillard reaction is often responsible for colour change and colour development, particularly in untreated fruits. Krokida et al. (1998) evaluated the colour development in dried apples and bananas. Assessing the formation of browning in dried food helps in the selection of an appropriate drying technique, which minimizes the degradation of quality in terms of colour.

The degree of browning colouration is visually considered one of the most important parameters in the definition of quality of fried foods (Scanlon et al. 1994). Fried potato colour is the result of Maillard, non-enzymatic browning reactions that depends on the reducing sugar content on the slice surface and the temperature and frying period

(Marquez and Anon 1986). Low reducing sugar contents are required to minimize colour development during frying (Mottur 1989).

Browning Index

The browning index (BI) is used to characterise the overall changes in browning colour (Quitão-Teixeira et al. 2008). It is defined as brown colour purity and is one of the most common indicators of browning in food products containing sugar (Buera et al. 1986). In order to carry out a detailed characterization of the colour of a food item, and thus to more precisely evaluate its quality, it is necessary to know the colour value of each point of its surface (Leon et al. 2006). Enzymatic browning has been quantified using browning indicators through a biochemical index (Lunadei et al. 2011). For example, using polyphenol oxidase activity (Hosoda et al. 2005; Osanai et al. 2003) or physical indicators such as surface colour have been used (Kang et al. 2004; Lambrecht 1995).

*Browning Index Based on CIE L*a*b* Coordinates*

In the case of physical indicators of browning, the CIE *L*a*b** colour space has been the most extensively used colour model due to the uniformity in the distribution of colours in the space (Yam and Papadakis 2004). Based on CIE *L*a*b** coordinates, especially on the *L** value, or on the CIE *XYZ* colour space, browning indicators in fruit have been developed (Lu et al. 2007; Pristijono et al. 2006). To capture this variation in a single index that would be related to a brown colour, the BI is calculated using the following expression (Maskan 2001; Mohapatra et al. 2010):

$$\mathrm{BI} = 100 \times \left(\frac{X - 0.31}{0.17} \right) \tag{6}$$

where

$$X = \frac{(a* + 1.75L)a}{(5.645L + a* - 3.012b*)} \tag{7}$$

Browning Index Based on Spectroscopy

Suh et al. (2003) studied the thermal kinetics of mulberry fruit extract treated with high temperature at various pH values. The absorbance ratio at 510 and 420 nm was used as the browning index. The change of the browning index (A_{510}/A_{420}) was increased with an increase in pH and was lower at pH 2.0 than that at pH 5.0. A zero-order kinetic model was proposed because of the better fit. Chutintrasri and Noomhorm (2007) reported the change in the relative absorbancy at 420 nm which was related to a brown pigment formation in pineapple puree and was adequately described by a zero-order kinetic model.

The browning index of basil increased with an increase in microwave drying time, at a lower applied power, and hence this value was proportional to the applied microwave output power. The modelling studies showed that the data of browning index calculated were accurately fitted to a first-order model with high values for the coefficients of determination (Demirhan and Ozbek 2009).

Dadali et al. (2007a, b) used a quadratic model to represent the dependence of browning index on the ratio of microwave output power to the sample amount. The browning index increased up to power/sample amount of 9.0 W/g, and after this value, no significant change was found; this indicates that the colour of the samples was very different from their initial colour for 9.0 W/g. This is not in agreement with the work of Chutintrasri and Noomhorm (2007), who stated that the browning index increases as the temperature increases and that no constant period was observed on the drying of pineapple puree with thermal treatment.

Food Colour Modelling Approaches

Different modelling approaches have been used to study food colour properties (Table 5). Recently, quality models incorporated the biological age at harvest to describe the variation in postharvest behaviour (Hertog et al. 2004; Schouten et al. 2004; Tijskens et al. 2005). Biological (or physiological) age refers to the developmental stage of an individual organism relative to an averaged development pattern typical of that particular species (Hertog et al. 2004). If all fruit would be harvested at the same biological age, variation at harvest would be negligible and would remain negligible throughout the postharvest period. As fruits are not harvested at such a homogenous stage, variation will exist both at harvest and during postharvest

Table 5 Approaches adopted by researchers for modelling colour of food products

Colour modelling approach	Produce	Reference
Response surface methodology	Orange juice	Tiwari et al. (2008a, b)
	Hazelnut	Ozdemir and Devres (2000a)
	Cooked meatball	Saricoban and Yilmaz (2010)
Logistic model	Tomato	Tijskens and Evelo (1994)
	Avocados	Hertog (2002)
Modified Gompertz equations	Sucrose solution	Quintas et al. (2007)

storage. Depending on the underlying mechanism, the variation of colour observed at harvest can remain the same during postharvest storage or can be transformed.

Schouten et al. (2007) presented a tomato colour model as a function of the biological age. The colour model focuses on the red component synthesis and describes postharvest colour behaviour as a function of the amount of colour precursor present at the time of harvest, the colour at harvest and the storage time. It includes the effect of the colour precursor on the final (red) colour as a function of the (colour) biological age at harvest.

Biological variation of tomatoes becomes discernible through their initial colour at harvest. Assuming all tomatoes go through the same developmental ripening process from fruit set to fruit senescence, the initial colour at harvest can be interpreted as a measure of the biological age of an individual tomato (Tijskens et al. 2003; Tijskens and Evelo 1994).

Tijskens and Evelo (1994) developed a mathematical model to describe the behaviour of tomato colour at different temperatures during storage and at harvest maturity stages. The mathematical description used in the model is a logistic (sigmoid) function with a correction for the actual biological age of the tomato. The growing period and the circumstances during growth are important for developing fruit colour (Tijskens et al. 2011).

Hertog et al. (2004) developed a probabilistic kinetic approach to interpret postharvest batch behaviour combining kinetic models describing colour change as a function of time and temperature, with the concept of biological age modelled by a random variable of tomato fruit (*Lycopersicon esculentum Mill.)*.

Tijskens and Evelo (1994) modelled the colour change of tomatoes using a logistic curve. Hertog (2002) studied the ripening of avocados that turn from green to black which resulted in hue values (H) decreasing over time and successfully applied the model to the colour change of avocado describing hue (H, in degree) during time (t, in days).

$$H_t = H_{+\infty} + \frac{H_{-\infty} - H_{+\infty}}{1 + e^{kH_t \cdot (H_{-\infty} - H_0)/H_0 - H_{+\infty}}}, H_{-\infty} = (1 + C) \cdot H_0 \tag{8}$$

with the two asymptotic hue values ($H_{+\infty}$ and $H_{-\infty}$, both in degree) at plus and minus infinite time, the rate constant k_H (per day) and the initial hue value H_0 (degree).

Tijskens et al. (2001) modelled the colour of green beans and broccoli by a simplified kinetic mechanism of two consecutive reactions: one that increases colour and one that degrades colour. Response surface methodology, a statistical technique for the investigation of processes, is also a useful tool to describe quality indicators during food processing. It has been successfully applied to colour measurement during food processing (Ozdemir and Devres 2000a; Tiwari et al. 2008b). Purlis and Salvadori (2009) applied a non-isothermal kinetics approach to model the browning development at bread surface during baking, which considered the variation of local temperature and water activity.

Colour Degradation Modelling Kinetics

The colour kinetics of food products is a complex phenomenon, and dependable models to predict experimental colour change, which can be used in engineering calculations, are limited (Ahmed et al. 2002a). Therefore, experimental studies and application of various simplified models to represent the behaviour are required (Suh et al. 2003). For the design process, kinetic modelling is necessary to derive basic kinetic information for a system in order to describe the reaction rate as a function of experimental variables and, hence, to predict changes in a particular food during processing and storage (Van Boekel 1996). There are numerous references on the kinetics of colour of food materials in the literature. The majority of these works report zero-order (Eq. 10) or first-order (Eq. 11) degradation reaction kinetics (Table 6).

Empirical mathematical modelling techniques may be used to determine the end point and kinetic effect (Ahmed et al. 2002a). Numerous researchers (Ahmed et al. 2000, 2002a, b; Chutintrasri and Noomhorm 2007; Shin and Bhowmik 1995) have studied the kinetics of pigment and colour degradation of fruits and vegetables during thermal processing. Generally, the rate of change of a quality factor C can be represented as

$$\frac{dC}{dT} = -kC^n \tag{9}$$

where k is the kinetic rate constant, C is the concentration of a quality factor C at time t, and n is the order of reaction. For the majority of foods, the time dependence relationships appear to be described by zero-order or first-order kinetic models. By integrating Eq. 9, the zero-order Eq. 10 and first-order kinetic model Eq. 11 can be derived as

These kinetic types are expressed by

$$\text{Zero order}: C = C_0 + k_0 t(1) \tag{10}$$

$$\text{First order}: C = C_0 \exp k_1 t \tag{11}$$

where C is the measured colour scale value or a combination of the colour scale values, C_0 is the initial C, t is the heating time, k_0 is the zero-order kinetic constant, and k_1 is the first-order kinetic constant. The Arrhenius equation to relate the dependence of the rate constant with temperature is represented by

$$k = k_0 \exp(-E_a/RT) \tag{12}$$

Table 6 Selected publications on thermal kinetics of colour changes of fresh and processed food products

Produce	Processing method	Operating conditions	Colour parameter	Kinetic model/s	Reference
Basil	Microwave drying	Microwave output power: 180–900 W	L, ΔE, hue angle a, b, chroma, browning index	Zero-order, first-order	Demirhan and Ozbek (2009)
Okra	Microwave drying	Microwave output power: 180–900 W	a, ΔE, hue angle L, b, chroma, browning index	Zero-order, first-order	Dadali et al. (2007a)
Spinach	Microwave drying	Microwave output power: 180–900 W	a, ΔE, hue angle L, b, chroma, browning index	Zero-order, first-order	Dadali et al. (2007b)
Onion	Hot air drying	Drying temp.: 50–75 °C Air velocity: 1.0–1.5 ms^{-1}	Optical index	Zero-order	Kaymak-Ertekin and Gedik (2005)
Grape juice and leather	Hot air drying Sun drying	Drying temp.: 40–90 °C Wet bulb temp.: 27–33 °C –	L, a, b	Zero-order	Maskan et al. (2002)
Apple, banana, potato, carrot	Hot air drying, vacuum drying, microwave drying, freeze drying, osmotic drying	–	a, b	First-order	Krokida et al. (2001)
Apple, banana	Osmotic dehydration	Solute type: sucrose, glucose	L, a, b	First-order	Krokida et al. (2000)
Avocado, prune, strawberry	Hot air drying	Drying temp.: 50–70 °C Air velocity: 3–5 ms^{-1} Sample thickness: 5–15 mm	ΔL, Δa, Δb	First-order	Tsami and Katsioti (2000)
Apple, banana, carrot, potato	Hot air drying, vacuum drying	Drying temp.: 50–90 °C	Δa, Δb	First-order	Krokida et al. (1998)
Potato	Tunnel hot air drying	Drying temp.: 30–60 °C	Concentration of browning pigment	Zero-order	McMinn and Magee (1997)
Apple	Hot air drying, vacuum drying	Drying temp.: 40–90 °C	Browning index	Zero-order	Voegel-Turenne et al. (1997)
Pineapple puree	Thermal processing	70–110 °C	L, a, b, ΔE, Browning index	Zero-order, first-order	Chutintrasri and Noomhorm (2007)
Watermelon Juice	Thermal processing	50–90 °C	L, a, b,	First-order	Sharma et al. (2008)
tomato puree	Thermal processing	50–120 °C	L, a, b,	First-order	Nisha et al. (2011)
Kiwifruit	hot air, microwave (MW) and hot air ± MW drying	Maximum output of 700 W at 2,450 MHz	L, a, b, chroma, Hue, ΔE, and (BI)	Zero-order, first-order	Maskan (2001)
Pineapple concentrate	Microwave vacuum, evaporation (MVE), microwave heating evaporation (MHE), and rotary vacuum evaporation (RVE)		L, a, b, ΔE, and browning index (BI)	Zero-order, first-order	Assawarachan and Noomhorm (2010)
Papaya puree	Thermal processing	70–105 °C	L, a, b	First-order	Ahmed et al. (2002c)

where k_0 is the pre-exponential factor (per minute), E_a is activation energy (in kilojoules per mole), R is the gas constant (8.314 J/mol K), and T is the absolute temperature (in Kelvin). Table 7 presented the published data on activation energy.

Optimizing thermal processing to improve the product colour requires data on colour degradation kinetics (k values) and temperature dependence that can be described by the activation energy, E_a (Chutintrasri and Noomhorm 2007). First-order and zero-order kinetic models have been used to evaluate the appearance of browning (Stamp and Labuza 1983).

Zero-order and first-order kinetic models were used for the mathematical modelling of the colour change of basil (*Ocimum basilicum* L.). It was observed that a and b values, chroma and browning index were sufficiently fitted to a first-order model; the values of L and total colour change, hue angle, followed a zero-order kinetic model Demirhan and Ozbek (2009).

Ibanoglu (2002) studied colour change during infrared heating of wheat germ at 100–150 °C for 5–40 min. An increase in L values and a decrease in a values were observed at increased time and temperature of heating. The

Table 7 Selected recent publications on activation energy of colour in fresh and processed food products

Produce	Processing condition	Activation energy, E_a	Reference
Okara	Microwave drying	7.45–11.59 W/g	Dadali et al. (2007a, b)
Basil	Microwave drying	39.81–43.40 w/g	Demirhan and Ozbek (2009)
Spinach	Microwave drying	31.16–39.43 W/g	Dadali et al. (2007a, b)
Puree of mustard leaves	Thermal processing 75 and 115 °C	E=41.64 kJ/mol	Ahmed et al. (2002a)
Spinach puree	Thermal processing 75 and 115 °C	E=28.75 kJ/mol	Ahmed et al. (2002a)
Mixed puree (mustard:spinach: fenugreek = 1:0.75:0.25) puree	Thermal processing 75 and 115 °C	E=34.01 kJ/mol	Ahmed et al. (2002a)
Pea puree	Thermal processing, 110–125 °C	67.9 kJ/mol	Shin and Bhowmik (1995)
Green chilli puree	Thermal processing, 60 to 90 °C	11.4–16.0 kJ/mol	Ahmed et al. (2000)
Pineapple puree	70–90 °C	36.7–83.7	Chutintrasri and Noomhorm (2007)
Pineapple puree	95–110 °C	94.4–129.4	Chutintrasri and Noomhorm (2007)
Pineapple juice	55–95 °C	39.2–47.4	Rattanathanalerk et al. (2005)
Mango puree	50–90 °C	36.3–36.8	Ahmed et al. (2002b)
Peach puree	80–98 °C	110–148	Garza et al. (1999)
Pear puree	80–98 °C	62.5–102.91	Ibarz et al. (1999)
Double tomato paste	70–100 °C	42.6–85.7	Barreiro et al. (1997)
Apple pulp	56–94 °C	66.4	Lozano and Ibarz (1997)
Plum pulp	56–94 °C	67.8	Lozano and Ibarz (1997)
Peach pulp	56–94 °C	45.1	Lozano and Ibarz (1997)
Peach puree	115–135 °C	107–109	Avila and Silva (1999)
Grape juice	60–95 °C	92.8	Rhim et al. (1989)
Mulberry fruit extract	80–100 °C	30.68–43.49	Suh et al. (2003)
Watermelon Juice	50–90 °C	24.19–55.47 kJ/mol	Sharma et al. (2008)
Papaya puree	70–105 °C	32.59 kJ/mol	Ahmed et al. (2002)
Tomato puree	50–120 °C	27.44 kJ/mol	Nisha et al. (2011)
Cupuaçu puree	80–115 °C	31–36 kJ/mol	Silva and Silva (1999)
Wheat germ	Infrared heating, 100–150 °C	36.6 kJ/mol	Ibanoglu (2002)
Hazelnut	100–160 °C	62.3 kJ/mol	Ozdemir and Devres (2000a, b)

colour kinetics of wheat germ can be successfully modelled using a third-degree polynomial equation to predict colour changes during infrared heating.

Ozdemir and Devres (2000a, b) described the kinetics of colour changes during hazelnut roasting for a temperature range of 100–160 °C for 60 min. Roasted hazelnut samples produced significantly lower L and b values in ground-state colour measurements compared with whole-kernel measurements. The kinetics of colour changes during hazelnut roasting was satisfactorily described by a third-degree polynomial with Arrhenius-type temperature dependence of the model coefficients.

Pedreschi et al. (2007) described that the colour changes of control and NaCl-soaked potato slices during frying followed first-order kinetics. The measurement of colour was done using computer vision technique.

Ochoa et al. (2001) studied the kinetics of colour change in preserves of raspberries and sweet and sour cherries exposed to different lighting conditions (light and darkness), at constant temperature, as well as stored at several temperatures. The kinetics of colour change was evaluated using the concept of fractional conversion, and a first-order kinetics was found in relation to both the effect of lighting conditions and temperature.

Corzo et al. (2006) determined the kinetics of colour change of sardine sheets during vacuum pulse osmotic dehydration. The rates of colour changes followed first-order kinetics and an Arrhenius relationship for temperature dependence. Temperature sensitivity of rate constant for a and L values increases with an increase in brine concentration, whilst that for b value decreases.

Changes in Colour of Food Products During Postharvest Handling and Processing

Understanding colour changes during postharvest handling and processing is important for the quality optimization of food products and bioprocess conditions. Colour change

measured by tristimulus reflectance of a colorimeter may be used to predict quality change in food (Lozano and Ibarz 1997). Colour can also be used to define adequate thermal processing conditions for maximizing the final product quality if its degradation kinetics is determined (Silva and Silva 1999).

The effect of thermal processing on the colour of food material has been studied by various researchers, and different colour systems have been used for describing the colour changes of food materials (Ahmed et al. 2002b; Lee 2000; Lozano and Ibarz 1997; Maskan 2001; Shin and Bhowmik 1995; Silva and Silva 1999; Suh et al. 2003). Rhim and Hong (2011) investigated the influence of temperature and water activity on its colour change of red pepper. As temperature and A_w increased, the red colour of pepper powder increasingly faded out to become brown and tarnish black, which is mainly attributed to the degradation of carotenoid pigments and the development of browning compounds. Colour parameters such as Hunter L, a, b values and other colour functions, as well as the browning index and ASTA colour values represent the colour changes of red pepper powder as influenced by temperature and A_w. They can also be used for practical purposes in controlling the colour characteristics of the product.

Zepka et al. (2009) studied the thermal degradation kinetics of the main carotenoids of cashew apple juice model system by HPLC and related it to the changes of its CIE-LAB colour parameters. The curves for the decay of the main carotenoids and colour changes showed a biphasic behaviour that was best fitted by a bi-exponential equation. For the same heating conditions (60 or 90 °C), similar rate constants for the fast (γ_1) and slow (γ_2) decays were obtained for both the chemical (carotenoids) and physical (colour) parameters. It indicates that colour parameters, such as ΔE^*, are good predictors of both all-*trans*-β-cryptoxanthin and all-*trans*-β-carotene thermal degradation.

Shi et al. (1999) reported that the colour degradation of tomato was less severe when the drying temperature was lowered from 90 to 55 °C. Pott et al. (2005) reported that high temperatures and excessive drying resulted in a noticeable increase in redness in mango slices. The change of colour could be attributed to the browning reactions (Maillard) that occur during drying (Adam et al. 2000).

Arslan and Özcan (2010) studied the effect of sun, oven (50 and 70 °C) and microwave oven dying (210 and 700 W) on the colour changes of red bell pepper slices. Sun-dried followed by microwave oven-dried (700 W) samples revealed the highest L^*, a^* and b^* colour values than the other dried samples. High temperatures involved in oven drying (50 and 70 °C) led to reductions in the lightness, redness and yellowness of the samples. The decrease in L^* values can be attributed to brown pigment formation during drying due to the high levels of reducing sugars and amino acids in red pepper (Park and Lee 1975). Oven-dried (50 and 70 °C) and microwave oven-dried (210 W) samples had lower a^* values than sun- and microwave oven-dried (700 W) samples. The longer drying time required during microwave drying at low output and convective heat transfer style and the high temperatures involved in oven drying might lead to reductions in the redness of the samples (Arslan and Özcan 2010).

Soysal (2004) reported that a^* and b^* values of microwave-dried parsley leaves were not significantly different from the values of fresh leaves and indicated that the change in colour values was not dependent on the microwave output power. It was also reported in another study that air-dried carrot slices were found darker with less yellow and red hues as compared with microwave-dried ones (Sumnu et al. 2005). Microwave drying prevented colour damages during drying (Krokida and Maroulis 1999).

Maskan (2001) reported for kiwi fruit that an L^* value of about 40 was reached after 5 min of microwave drying and about 325 min of hot air drying; therefore, microwave would give a destruction rate 65 times faster than hot air (60 °C). Cárcel et al. (2010) concluded for persimmon that pretreatment with potassium meta-bisulphite generated significantly brighter dried samples than both the untreated samples and those pretreated using citric acid. Maskan et al. (2002) found that the parameters a and b increased and L value decreased during grape juice concentration processing. The decrease in L and the increase in a and b values may be attributed to the destruction of anthocyanins and occurrence of Maillard reactions during juice concentration and cooking, resulting in a colour change from a natural red or purple to a more dull brownish colour (Skrede 1985).

Standardisation of Colour Measurement and Analysis

Colour is one of the most widely measured product quality attributes in postharvest handling and in the food processing research and industry. Apart from differences in instrumentation, colour measurements are often reported based on different colour indices even for the same product, making it difficult to compare results in the literature. A survey of recent research papers published in Food and Bioprocess Technology: An International Journal (2008–2011) showed that out of the 29 articles, the majority (58.62 %) used a Minolta colorimeter, 24.14 % used a HunterLab instrument, and 17.24 % used other types of instruments (Table 8). The majority of articles did not include information on the type of illuminant; when this information is included, D65 was the preferred illuminant.

Furthermore, there is a general lack of consistency or standards to choose and report a set of colour attributes even

Table 8 Summary of colour parameters, instrumentation and type of food product reported in recent papers published in Food and Bioprocess Technology: An international journal (2008–2011)

Reference	Produce	Country	Instrument	Colour parameters reported	Illuminant/aperture size/ observation angle
Turabi et al. (2008)	Rice cakes	Turkey	Minolta Color Reader (CR-10, Japan)	Total colour change (ΔE), CIE L^*, a^*, and b^* colour scale	Not reported
Rosales-Juárez et al. (2008)	Bread quality	Mexico	Colormate-HDS spectrophotometer (Milton Roy, USA)	L^*, a^*, b^*	D65/10°
Hur et al. (2008)	Hanwoo (Korean native cattle) and Holstein Steer	South Korea	Minolta colorimeter (CR-400, Tokyo, Japan)	CIE L^*, a^*, b^*	Not reported
Giannou and Tzia (2008)	crust and crumb colour of baked samples	Greece	A Minolta CR/200 chromatometer (Minolta Company, Chuo-ku, Osaka, Japan)	CIELAB	Not reported
Quitão-Teixeira et al. (2008)	Carrot juice	Brazil/ Spain	Macbeth Color-Eye 3,000 colorimeter (Macbeth-Kollmorgen, Newburgh, NY, USA).	Hue angle, Chroma, BI as absorbance at 420 nm	D75/10°
Sabanis et al. (2008)	Crust and crumb colour loaf	Greece	Minolta Chromameter (Minolta CR-200, Osaka, Japan)		Not reported
Sabanis and Tzia (2009)	Crust and crumb colour of baked samples	Greece	Minolta CR200 tristimulus chromatometer (Minolta Company, Osaka, Japan)	CIELAB	Not reported
Opara et al. (2009)	Pomegranate	Oman	colorimeter (Model CR-400, Minolta, Japan)	CIELAB	Not reported
Walkling-Ribeiro et al. (2009)	Orange juice	Ireland	tristimulus colorimeter (CR 300, Minolta Co. Ltd., Osaka, Japan)	Hunter L^* a^* b^* colour space	Not reported
Nevares et al. (2009)	Red wines	Spain	spectrophotometer (Shimazu, Japan)	CIELAB Red (%A_{520}), yellow (%A_{420}), and blue (%A_{620}) percentages were the variables calculated	Not reported
Narender Raju and Pal (2009)	Misti dahi	India	'Colorflex' colorimeter supplied by Hunterlab (Hunter Associates Laboratory, Reston, VA, USA)	CIELAB	Not reported
Tiwari et al. (2009)	Orange juice	Ireland	HunterLab colorimeter (ColorFlex, model A60-1010-615, Hunter Associates Laboratory Inc., Reston, VA, USA)	L^*, a^*, b^*	Not reported
Ribotta et al. (2010)	Soy–wheat bread	Argentina	Minolta 508d spectrophotometer,	CIE	D65/8 mm/10°
Alvarez et al. (2010)	Mashed potatoes	Spain	HunterLab model D25 (Reston, VA, USA)	CIELAB Colour was expressed as L^*/b^*, i.e., the white/yellow ratio	5-cm diameter aperture
Sciarini et al. (2010)	Bread	Argentina	Minolta Spectrophotometer CM-500d series (Osaka, Japan)	L^*, a^* and b^*	Not reported
Quevedo et al. (2010)	Salmon fillets	Chile	A HunterLab colorimeter (model 45/0–version 1.51)	$L^*a^*b^*$	Not reported
Brites et al. (2010)	Gluten-free bread	Portugal/ Spain	Minolta Chromameter Model CR-2b colorimeter	L^*, a^*, b^*	Not reported
Manickavasagan et al. (2010)	Wheat	Canada	Minolta Spectrophotometer (Konica Minolta Sensing Americas, NJ, USA)	Minolta method for $L^*a^*b^*$ values	Not reported
Rekha et al. (2010)	Dry soup mix extracts	India	Shimadzu Color measuring system (UV-2100, Japan)	Hunter colour values	Not reported
Kaya et al. (2011)	Pekmez	Turkey/ USA	spectrocolorimeter (HunterLab ColorFlex, A60-1010-615 Model Colorimeter, HunterLab, Reston, VA, USA).		10°
Lebesi and Tzia (2011)	Cupcakes	Greece	Minolta CR200 tristimulus chromatometer (Minolta Company, Osaka, Japan)	CIELAB	Not reported

Table 8 (continued)

Reference	Produce	Country	Instrument	Colour parameters reported	Illuminant/aperture size/ observation angle
Wambura et al. (2011)	Peanut	USA	(Model No 45/0, Colorfex, Hunter Associates Lab Inc., Reston, VA, USA)	L^*, a^*, and b^*colour spaces	Not reported
Erkan et al. (2011)	Horse Mackerel	Turkey	Konica Minolta chroma meter (model CR 400/410; Minolta, Osaka, Japan)	Total colour change (ΔE)	Not reported
Mangaraj and Goswami (2011)	Litchi	India	Minolta Colorimeter (CR-400/410)	CIE	Not reported
Arzate-Vázquez et al. (2011)	Avocado	Mexico/ Chile	Colorimeter (Minolta Chroma Meter CR400, Japan);	Total colour change (ΔE)	D65
Fathi et al. (2011)	Kiwi fruit	Iran	(Canon Powershot, Model A520, Japan)	RBG	Not reported
Jin et al. (2011)	Surimi	Korea/USA	Minolta colorimeter (CR-400, Tokyo, Japan)	Whiteness Index	Not reported
Ganjloo et al. (2011)	Seedless guava	Malaysia	Minolta CR-300 portable colorimeter	Total colour change (ΔE), L, a, and b	D 65
Jing et al. (2011)	Egg white proteins and fructose and inulin Maillard Reaction Products	China/ Canada	HunterLab Labscan 600 spectrocolorimeter (version 3.0; Hunter Associates Laboratory Inc., Reston, VA, USA)	Total colour change (ΔE)	5-cm diameter aperture

among researchers on the same type of food product (Tables 1 and 8). The plethora of primary (such as $L^*a^*b^*$) and derived (such as C^*, H^*, YI, WI and BI) colour parameters and numerous other product-specific colour indices (Table 1) for objective colour makes it difficult to compare results. There is, therefore, a need for standardisation to improve the traceability and transferability of measurements, including specifications on a minimum set of parameters for food colour evaluation for specific products and/or process requirements.

Future Prospects for Colour Measurement and Analysis in Foods and Bioprocessing

At first instance, food quality is judged by appearance comprising colour, gloss, size and, secondly, by texture, total soluble solids (TSS) content and/or titrable acidity. These parameters may supply important information to the consumers in making food choices, including purchase. Different techniques or expressions have been reported to determine various quality parameters, but there is currently no single or combination of techniques and computational methods to quantify the overall quality incorporating both external and internal qualities. The conceptualisation and development of such a universal quality index for foods represents an ongoing challenge, especially due to the differences in market requirements and consumer preferences.

The role of colour in the perception of other food quality attributes is important, but the use of objective colour parameters to predict quality attributes such as the flavour and nutritional value of foods is less explored and represents an opportunity among researchers. It is generally accepted that colour is important in identifying the characteristic flavour of foods and that altering typical colour may render the identification of flavour less precise (Bayarri et al. 2001). Given increasing consumer interest on the role of food intake and human health (Opara and Al-Ani 2010a, b; Drogoudi et al. 2008), in-depth studies are required to investigate the prediction of nutritional quality based on objective non-destructive measurement of colour appearance. As an example, researchers have shown that mango colour can be used to estimate the content of all-*trans*-β-carotene (Vásquez-Caicedo et al. 2005) and the most important provitamin A carotenoid (Wolf 1984).

Machine vision systems are powerful tools for the automatic inspection of quality estimation of fresh foods from external parameters or internal features, monitoring of fruit processes during storage or evaluation of experimental treatments (Cubero et al. 2011). With ongoing rapid advances in information and communication technologies and predictive modelling, the time is ripe to focus attention on harnessing objective colour measurement for online measurement and

sorting of fresh foods such as fruit and vegetables based on nutritional quality.

Conclusion

Colour is one of the most important quality attributes influencing consumer food choices, perceptions and purchase behaviour. Colour measurement and analysis is therefore important in postharvest handling and bioprocessing to optimize the quality and value of food. This review examined the latest developments in the measurement and analysis of colour of freshly processed food. Several subjective and objective indices have been used to characterise the colour of food products during handling, processing and marketing. The colorimeter and CIELAB colour space have emerged as the predominant choice among researchers for objective colour measurement and analysis. Whilst non-destructive measurement of external colour of products is now a routine practice in research and industry, non-destructive measurement and prediction of internal colour is less practised and remains both a technological and practical challenge. The plethora of indices used to characterise the colour of fresh and processed foods, even for the same type of food product, makes it difficult to compare results. There is a need for standardisation to improve the traceability and transferability of measurements. Given the importance of colour in consumer food choices and preference, and the increasing consumer demand for internal quality attributes of food products including nutrients, there is opportunity to develop rapid, non-destructive methods and indices of colour that are related to nutritional value. Recent advances in image acquisition and high-power computing make this a future reality.

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