Trends in Food Science & Technology 42 (2015) 116–133

Review

Image acquisition techniques for assessment of legume quality

Shveta Mahajan[a,b], Amitava Das[a,b,*] and Harish Kumar Sardana[a,b]

[a]Academy of Scientific and Innovative Research (AcSIR), Central Scientific Instruments Organisation, Sector 30-C, Chandigarh 160030, India

[b]CSIR-Central Scientific Instruments Organisation, Sector 30-C, Chandigarh 160030, India) (Tel.: +91 172 2637994 (office); fax: +91 172 2637994; e-mails: shvetamahajan@ymail.com, amtds06@gmail.com, hk_sardana@csio.res.in)

This paper reviews different image acquisition techniques that have been employed for quality evaluation of leguminous seeds and has relevance for engineers, food scientists and other agricultural researchers. The inspection and quality evaluation of food grains using machine vision can be achieved with greater speed, consistency and accuracy. Image acquisition is central to the success of any quality inspection system based on machine vision. Soybeans, peas, beans, lentils and chickpeas are the legumes, which form the staple food and hence have great ecological and economic importance. The image acquisition techniques that are reviewed in this paper are non-destructive in nature and are based on visible, infrared and other bands of the electromagnetic spectrum. These include techniques for external surface examination, measurement of moisture content, oil content, insect infestation detection and internal structure visualization. The advantages of machine-vision techniques over the conventional techniques based on manual methods for seed quality estimation are also discussed.

Introduction

Legumes are the second most economically important crops after the Graminiae family and the third largest family of the flowering plants after sunflowers and orchids. Legume family consists of the important crops like soybean (*Glycine max*), common pea (*Pisum sativum*), chickpeas (*Cicer arietinum*), mung bean (*Vigna radiata*) and lentil (*Lens culinaris*) (Bewley, Black, & Halmer, 2006). These have numerous uses as a food grain, seed and as a soil enhancing green manure. Some of the important edible legumes are common bean, chickpea, mung bean, adzuki bean, cowpea, pigeon pea, lima bean, andean lupin, broad or fava bean, runner bean and lentil. Legumes offer numerous opportunities for improving agriculture and to support industries. Flavors, medicines, poisons, gums, dyes, tannins and other end products are obtained by processing various species of legumes. Soybean oil is put to a number of industrial uses. Peanut (groundnut), carob and guar are also well known industrial legumes. Most of the species of this family are well adapted to grow in soil with poor nutritional content. Legumes are among the best sources of plant protein and are able to survive in a land where nitrogen is not adequately available (Faria, Lewis, Sprent, & Sutherland, 1989; Vance, 2001). The importance of legumes is increasing as the growing world population is exerting considerable pressure on the available land resources (Du & Sun, 2006). Increased productivity of legumes is required to meet the dual challenges of rising demand and better utilization of marginal arable land. One of the possible solutions can be the usage of high quality seeds for cultivation.

High quality seeds can tolerate poor planting conditions which leads to direct advantage to growers and producers (Singh & Chauhan, 2010). The quality assessment of seeds is traditionally performed manually by skilled or semi-skilled workers. However this is not an efficient method as the rising labor costs and the shortage of skilled labor hampers the efficiency of the assessment process (Kannur, Kannur, & Rajpurohit, 2011). Visual assessments of seed quality using color, size, shape and texture are easy to perform, but can be highly subjective, tedious,

* Corresponding author.

http://dx.doi.org/10.1016/j.tifs.2015.01.001

costly and inconsistent, if done manually (Brosnan & Sun, 2004; Du & Sun, 2004, 2006; Gunasekaran, 1996). On the other hand, seed quality evaluation based on machine vision can be achieved in less testing time and with increased efficiency due to its speed and consistency. Additional benefits include better accuracy and round the clock availability which leads to lesser evaluation costs (Brosnan & Sun, 2002; Jayas, Paliwal, & Visen, 2000).

Quality assessment parameters of seeds depend upon the nature of its usage. The germination rate, vigor and physical purity are three seed quality characteristics that are monitored for the cultivation purpose. On the other hand, the seeds that are consumed as grains, oil, oil cake, meal and biodiesel are evaluated by its oil content, protein content, moisture content and acid content (Agrawal, 1995; Basra, 1995). The percentage by weight of the damaged seeds (insect damaged, discolored, immature and shriveled, broken and cracked) also plays a key role in evaluating the quality of the seeds for both cultivation and consumption (Bewley, 1994; Tiwari, 2012). Several publications have indirectly expressed the viability of seeds using external physical attributes. Altuntas and Yildiz (2007); Isik and Unal (2007) have correlated the size of the bean to the moisture content of the bean. It has also been reported that a larger bean germinates faster than medium and small sized beans (Firatligil-Durmus, Sarka, & Bubník, 2008).

In agriculture, the role of imaging is increasing day by day due to the availability of cost effective imaging products, better computation power and increased interest in non-destructive examination of food items. The physical and chemical properties of the internal and external parts of the legume seeds are primarily used for designing a quality evaluation system based on machine vision. Images need to be acquired with high level of accuracy in terms of shape, size and color of the objects being studied. For accurate image acquisition, utmost consideration should be given to selection of type of the image acquisition technique, excitation source, type of detector and placement of seeds with respect to imaging sensors.

Within the legume family, each member is having distinct shape, size, color and biochemical characteristics. In certain cases, these characteristics pose challenges in image acquisition. For example, soybean seeds are elliptical in shape. This factor poses a problem in seed separation using a mechanical sieve. Additionally, non-spherical seeds have problem in maintaining orientation when placed randomly on a flat imaging surface. The orientation is an important issue for ellipsoid seeds as the surface of the seed to be examined in a single view, depends on it. Seed shape and size may be evaluated from images by using a seed sample holder in which all the seeds are placed in the same orientation. Methods for seed positioning used by the researchers are discussed in the later sections of the paper. Similarly, in visible imaging techniques, the color of the legume seeds is a vital design consideration for selecting appropriate background for image acquisition.

In order to design a machine vision system, careful consideration of several aspects of the underlying imaging technique like characterization of the image acquisition technique (visible imaging, X-Ray imaging, etc.), physical principles of interaction between illumination and sample, and calibration of illumination and detector systems is required. Machine vision systems also include techniques for image analysis, feature extraction, feature selection and classification for understanding and recognition. The purpose of this survey is to categorize and review the literature on image acquisition techniques used for quality estimation of seeds belonging to the legume family, and to illustrate their role and discuss the challenges associated with these techniques.

Components of image acquisition techniques

The selection of appropriate image acquisition technique is the initial step in developing any machine vision system. Images are used for acquiring information, as this technology aims to duplicate the role of human vision by electronically perceiving and understanding an image. Machine vision system implements the theoretical and algorithmic computations by which useful information about an object or scene can be automatically extracted and analyzed from an acquired image. A review of non-destructive techniques for the quality evaluation of the agricultural products has been reported by Chen and Sun (1991). The authors have reported about the various radiographic methods and the machine vision systems employed for quality testing. Chen, Chao, and Kim (2002) investigated the requirements and the recent developments in hardware and software for machine vision systems based on multispectral and hyperspectral imaging for the inspection of poultry carcasses and apples. Sun (2004) discussed the use of computer vision systems in quality grading of various agricultural products. A valuable review of the developments in computer-aided image analysis systems for improving insight of seed morphology and biology, in relation to seed quality and germination has been reported (Dell'Aquila, 2006a, 2007, 2009). The recent developments and application of image analysis and computer vision systems in sorting and grading of agricultural and food products were reported by Narendra and Hareesh (2010) in a critical review. A review on the techniques and features used for the external grading of the agricultural products using non-destructive methods was conducted by Alfatni, Shariff, Abdullah, Saeed, and Ceesay (2011). Another review was reported by the same authors on the signal processing techniques and the systems used for the non-destructive internal grading of the agricultural products (Alfatni, Shariff, Abdullah, Marhaban, & Saaed, 2013). Both of these survey papers have included only a few leguminous seeds in their study, focusing more on fruits and other agricultural products. This paper will focus on the application of various image acquisition techniques that have been applied to the leguminous seeds. Other aspects of the imaging techniques will not be discussed here; interested readers may refer to the relevant scientific publications and books on such topics for details.

Illumination

All vision systems are affected by the nature and quality of illumination. By adjustment of the light source, the appearance of an object can be radically changed with the features of interest being clarified or blurred. Therefore, the performance of the illumination system can greatly influence the quality of images and hence, play an important role in the overall efficiency and accuracy of the vision system. Gunasekaran (1996) reported that most lighting arrangements can be grouped as either front or back lighting. Front lighting (reflective illumination) is used in situations where surface feature extraction is required. Back lighting (transmitted illumination) is employed for the production of a silhouette image for critical edge dimensioning or for sub-surface feature analysis.

Imaging sensors

Images can be captured using different sensors, depending upon the requirement. During the last decade, there have been considerable attempts to develop non-destructive, non-invasive sensors for assessing quality of various agricultural seeds. Sensors such as charge-coupled device (CCD), complementary metal–oxide–semiconductor (CMOS), amorphous silicon have been used for legume seed imaging for various purposes (Alfatni *et al*., 2013; Brosnan & Sun, 2002; Du & Sun, 2004).

Sample holders

Proper positioning of the seeds is required for accurately capturing external and internal features, especially when the seeds are having non-flat base and are elliptical or spherical in shape. A sample holder needs to be selected according to the morphological characteristics of the seeds under examination. Geometrical shapes of legume seeds can be ellipsoidal or spherical. Ellipsoid is a three dimensional shape that can be oblate spheroid, prolate spheroid or a tri-axial ellipsoid depending on the length of major and minor axis. Firatligil-Durmus, Sarka, Bubnik, Schejbal, and Kadlec (2010) have estimated the size properties of lentil and bean varieties using three-dimensional geometrical models. In this work, the authors have concluded that locust bean, faba bean, kidney bean, tigar bean, white bean and white speckled red bean (Czech Republic) are having tri-axial ellipsoid geometry and white speckled red bean (Turkey), red and green lentils have two sphere segment geometry. In fact, the unique shape of the lentils that are convex on both sides are especially termed as being lenticular in shape. In the following section, the methods for seed positioning in different imaging techniques used by the researchers are discussed.

Sample holder used for visible imaging

For cracked soybean seed detection, Gunasekaran, Cooper, and Berlage (1988a) kept such seeds in such an orientation so that the cracked area of the seeds was always directly captured by the camera. Paulsen, Wigger, Litchfield, and Sinclair (1989) recommended that the orientation of major diameter of the seed has to be kept parallel or perpendicular to the horizontal rows of pixels from the camera in order to measure the morphological features of the soybean or maize seeds. The authors also suggested placing the fungal damaged area of the seeds towards the camera to enable the vision system to detect and classify the damaged seeds. In an another publication, a sample holder made up of clear plastic has been used to acquire images of green lentil seeds having flat base which enables them to be imaged without any necessary consideration to its orientation (Shahin & Symons, 2001a). Yet another work has been reported by the same authors, in which they have used the similar plastic sample holder to classify legume seed varieties (Shahin & Symons, 2003b, 2005). This method was used for spherical seeds, but was found to be inappropriate for elliptical seeds. Kilic, Boyaci, Koksel, and Kusmenoglu (2007) used a sample holder of dimensions 12 cm × 15 cm, properly covered with a black material (fabric) to eliminate the shadows and placed it at the bottom of the image acquisition box. This system was designed for the quality inspection of beans using size and color information. Bacchetta, Grillo, Mattana, and Venora (2008); Smykalova, Grillo, Bjelkova, Hybl, and Venora (2011) arranged the seeds on the scanner tray in such a way so that the seeds do not touch each other. This type of arrangement was done to study the size, shape and color variations of the seeds. Smykalova *et al*. (2011) used two different backgrounds, namely black and white, to clearly highlight the color variations on the seed boundary of peas using two covering boxes dressed with opaque black and white paper, to avoid interference of environmental light. Size and shape properties of eleven registered common bean cultivars were studied using the digital images of the seeds, which were positioned to obtain the multiple orthogonal views of the same (Kara, Sayinci, Elkoca, Ozturk, & Ozmen, 2013). Seeds were placed on the transparent and opposite colored fiberglass plate in 2 × 5 matrix formations in two orientations using putty.

Sample holder used for X-ray imaging

Flor, Cicero, Neto, Barros, and Krzyzanowski (2004) used a transparent adhesive tape to fix the soybean seeds in individual wells on acrylic plate, with their embryos at an angle of 45° to the plate. This type of arrangement was made to assess the health of embryo. A similar arrangement was used by Pinto, Cicero, Franca-Neto, and Forti (2009); Pinto, Mondo, Gomes-Junior, and Cicero (2012) for evaluating mechanical damage of soybean seeds using X-ray imaging system. In this work, soybean seeds were fixed on an acrylic plate so that the embryonic axis of the seed was always parallel to plate. This type of orientation was used to detect its internal damage.

State of the art of image acquisition techniques

Imaging techniques have been the "eyes of science" since the time of Galileo. The different image acquisition techniques that have been reported for usage on various leguminous seeds are presented in the following section in chronological order of their application. In Table 1, the types of electromagnetic radiation, the nature and the range of excitation, the sensors used in these techniques and the seed quality parameters that were measured using these techniques are listed.

CCD camera

CCD sensors convert photons into electrical charges. They are linear in their response to light. The advantages of using CCD sensors are that they produce high quality images, less noise and high sensitivity. CCD camera is employed to extract external attributes of objects such as color, shape, size, texture and external defects. CCD camera has numerous applications in fields like surveillance, astronomy, traffic monitoring and inspection of industrial and agricultural products. Imaging techniques based on CCD camera have great potential for numerous applications in inspection of agricultural products. CCD camera with the front lighting arrangement is used to extract external surface information whereas with back lighting, it is used to obtain the internal details of the seed structure. However, back light imaging is suitable for seeds where the cotyledons or the endosperm is visible (Jones, Foster, & Rimathe, 2011).

Seed shape and size measurements

The morphological properties of legume seeds are the key parameters required for the design of sizing and grading machinery, storage structures and process control. For studying the shape of soybean seed, Sakai and Yonekawa (1992) measured the three-dimensional (3-D) shape properties of soybean seed. Axial length (LA, mm), surface area (S_a, mm^2), volume (V, mm^3), particle density (D, g/cm^3), compactness (C, dimensionless) and sphericity (E, dimensionless) were calculated and 3-D properties like surface area and volume were expressed in terms of seed mass. The authors demonstrated this work using a laser based "structured light system". The camera was placed over the sample at a known distance and a He–Ne gas laser of 632.8 nm wavelength and 5 mW maximum output was used as an incident light source. Firatligil-Durmus *et al.* (2008) performed digital image analysis on lentil seeds to extract seven geometrical features, namely the projected area (A, mm^2), equivalent diameter (d_e, mm^2), perimeter (o, mm), minferet, maxferet, circularity and elongation, from images acquired using a CCD camera having two object lenses of 2.5 and 0.5 magnification in series. Feret diameter refers to the dimensions of the rectangular bounding box, which completely encloses the object. Minferet or maxferet is the smallest or largest Feret diameter. A lighting table was used for the illumination purpose. Firatligil-Durmus *et al.* (2010) also evaluated the seed sizes of lentil and bean varieties using an image analysis system consisting of Cohu 2252 camera having low-noise CCD sensors and lens magnification of 2.5 and 0.5 in series. The acquired images were processed to obtain 3-D models of the seeds by incorporating the height of the seeds, which were measured using a digital caliper. The surface area, volume and shape of seeds were estimated using the approximation models, i.e. tri-axial ellipsoid and the oblate spheroid for different varieties of beans and two sphere segments for different varieties of lentils. The geometric parameters measured in these studies are important for designing of engineering processes such as heat treatment, air transport, germination, milling, drying, harvesting, cleaning, separation, handling, aeration, storing and cooking. In both the papers, a simple, rapid, and non-invasive methodology was demonstrated, to estimate the geometric features using the same image acquisition technique. Najafabadi and Farahani (2012) used a digital camera to measure the morphological features of common bean (*Phaseolus vulgaris* L.) seeds. Morphological features extracted from the obtained binary images were area, perimeter, major and minor axis length, eccentricity, convex area, extent, compactness, aspect ratio, feret

Table 1. Electromagnetic spectrum based data acquisition techniques and seed quality assessment parameters.

Acquisition techniques	Nature & range of excitation	Sensors/device	Quality Parameters that were measured
Visual Imaging	400–700 nm	CCD/CMOS Camera	Color, size, shape, texture, embryo pixels
		Flatbed scanners	Size, color, shape, texture
X-Ray Imaging	0.1–10 nm	Amorphous silicon	Internal cracks, insect infestation, embryo size, condition and structural features
Thermal Imaging	8–15 μm	Thermal camera	Insect infestation, water and oil content, seed germination ability
Multi-spectral Imaging	400–2500 nm	CCD & IR Camera	Oil content, moisture content, starch, protein and other chemical composition, internal insect infestations.
NMR Imaging	RF excitation	NMR scanner	Stress cracks, moisture distribution, water migration
NIR spectroscopy	800–2500 nm	Spectrometer	Color, insect infestation, oil content, protein content

CCD: charge-coupled device, NIR: near infrared, MRI: magnetic resonance imaging.

diameter, roundness and elongation. Eccentricity is a measure of how much the conic section deviates from being circular. Aspect ratio is defined as the ratio of the longest side to the shortest side of the object. The results of this study indicated that the extracted features could be used in automated detection or classification of different seed cultivars.

Shahin, Symons, and Wang (2012) reported an image analysis system to predict the dehulling efficiency of red lentils using the side camera of the dual camera system developed by Shahin, Symons, Schepdael, and Tahir (2006). Side view images of lentil seeds were captured and the shape, plumpness (ratio), thickness (mm), diameter (mm) and edge angle (degree) of lentil seeds were measured using a commercial image analysis software (KS400, Carl Zeiss, Halbergmoos, Germany). The authors claimed that these parameters had a significant effect on estimating the dehulling efficiency of red lentils. Kara *et al.* (2013) developed an image processing method using digital images of twelve different bean cultivars to determine their shape and size properties such as length (L, mm), width (W, mm), thickness (T, mm), perimeter (P, mm) and projected area (PA, mm^2). The geometric mean diameter (D_g, mm), elongation at the width (E_w), thickness (E_t) and vertical (E_v) orientation, surface area (S, mm^2), sphericity (φ, %), and shape factor (SF) were calculated for each seed using the mathematical definitions as listed in Table 2. The seed images were acquired in a dark room by a Nikon D300 digital SLR camera that was fixed at a height of 35 cm on a frame perpendicular to the fiberglass surface. The features measured in this study were crucial in designing the seed metering mechanism of seed drills and sizing systems and thus, this study can be useful to engineers, machine designers and manufacturers.

Seed color measurements

Gunasekaran *et al.* (1988a) used a solid state video camera (Hitachi KP120) to evaluate the seed coat and cotyledon cracks in soybeans. The pixel intensity values were used to distinguish between normal and cracked regions of the seeds. The contrast between the different seed regions was improved by the use of a black plate in the background of the seeds. For non-invasively studying the haricot bean aka red bean, Laurent, Ousman, Dzudie, Carl, and Emmanuel (2010) used a CCD camera (Fujifilm FinePix F480) placed at the top of the lighting box (Silvania 50–60 Hz, 220 V, 36 W), as indicated in Fig. 1, with focal length varying from 4.6 to 18.4 mm at a distance of 100 mm from the samples. The lighting arrangement consisted of front lighting with two halogen lamps connected in parallel at the top of the samples. The authors demonstrated an image analysis system based on the bean color to correlate their color changes during storage with the hard-to-cook phenomenon.

Seed shape, size, color and texture measurements

Lucerne and vetch seed images were acquired using a high resolution 3-CCD camera (KY-FSB, JVC Corp, Japan) and a color frame grabber (VP1300-768-E-AT, Imaging Technology Inc., Bedford, USA) to identify the seed varieties. Shape, size and texture parameters were extracted from RGB and monochrome images. The system was able to achieve high seed classification rate of 99% (Chtioui, Bertrand, Dattee, & Devaux, 1996). Kilic *et al.* (2007) used a CCD camera to evaluate beans for consumption through size and color quantification of samples. Length, width, area and other shape-size attributes were measured and skewness, kurtosis and other statistical parameters were calculated to extract the color features to classify the beans as damaged or sound. The automated system accurately classified 99.3% of white beans, 93.3% of yellow–green damaged beans, 69.1% of black damaged beans, 74.5% of low damaged beans and 93.8% of highly damaged beans. The bean classification system developed in this study had two major advantages over manual inspection, namely reproducibility and accuracy. Alban, Laurent, Ousman, and Emmanuel (2012) used the same acquisition technique consisting of camera and a light box to improve the temporal change detection on a pair of beans images, acquired before and after storage under high temperature and humidity, using color and texture features. The results of this study indicated high correlation between the cooking time of bean seeds and their hard-to-cook characteristics.

Table 2. Parameters to quantify seed size and shape.

Geometric mean diameter (D_g)	$(L. W. T)^{1/3}$
Surface area, S_a	$\pi. D_g^2$
Compactness, C	$4S/R^2$
Sphericity, Φ	$(D_g/L). 100$
Equivalent diameter, d_e	$\sqrt{\frac{4A}{\pi}}$
Circularity	$\frac{4\pi A}{\rho^2}$
Elongation	Maxferet/Minferet
Feret diameter	$\sqrt{(4 \times Area/\pi)}$
Roundness	$4\pi \times$ Area/Perimeter^2
Aspect Ratio	Minor Axis/Major Axis
Shape factor, SF	4π PA/P^2
Plumpness	Seed thickness/Seed diameter

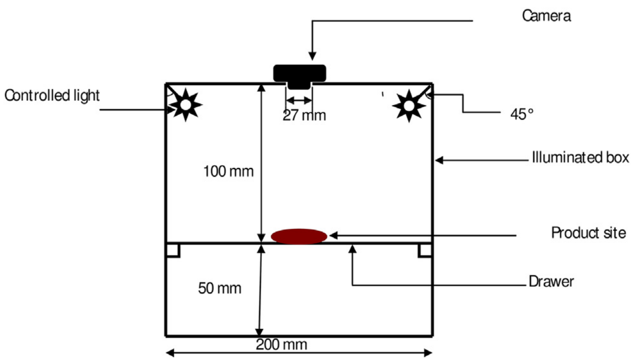

Fig. 1. Diagram of the experimental set-up for capturing images (Laurent *et al.*, 2010).

Using color filters

In certain cases, the features required for detection of defective or damaged seeds are not prominent in images acquired in the entire visible range but in certain specific spectral bands within the visible range. In such cases, researchers have used specific filters fitted to CCD cameras. This enables the analysis of images acquired in specific spectral regions. Gunasekaran, Cooper, and Berlage (1988b) fitted a series of Wratten filters in the visible light range of 370 nm–610 nm to evaluate mold contamination in soybeans. The experiment was conducted for both corn and soybean using red light (610 nm) in front lighting mode with a black background. It was observed that mold contamination could be detected using the described set-up. Paulsen *et al.* (1989) used a CCD camera equipped with an infrared blocking filter to reduce the saturation of the photodiode array by infrared radiation. The objective was to measure length, width, projected area and to detect the fungal damaged soybean seeds and the type of fungal damage. The authors developed two different algorithms for measuring morphological and color features. They also detected the probable species of fungi that caused damage to the soybean seeds like discoloration and different texture. The image acquisition technique used for detecting fungal damage was quite accurate and has considerable potential for detecting fungus in other legumes as well. In the research publication by Ahmad, Reid, Paulsen, and Sinclair (1999), three primary color filters (RGB) were fitted to a CCD camera in a striped filter configuration on a single chip to achieve high fidelity color reproduction to examine the contrast between symptomatic and asymptomatic soybean seeds. The authors employed diffused front lighting by using a cylindrical light chamber that was internally coated with flat white enamel paint to acquire the soybean seed images to extract color features to characterize symptoms associated with fungal damage, viral diseases, and immature seeds. The authors concluded that the performance of the classifier could be improved by using the combination of color, morphological and texture features. In a study to determine the water absorption capacity of beans, Ousman (2013) correlated the color features with the measured water absorption capacity. The acquisition technique used for capturing the color filter array (CFA) images was the same as used by Laurent *et al.* (2010). The color features extracted from color filter array images were mean and standard deviation values of R (red), G (green) and B (blue) components. This study reported an accurate, reliable and non-destructive method for the evaluation of hard-to-cook defect in bean grains. A summary of parameters and techniques used for external quality evaluation of legume seeds using CCD Camera is shown in Table 3.

Flatbed scanners

The basic mechanism of a flatbed scanner involves an image sensor that slides along the glass window, on which the objects to be scanned are placed. The object being imaged is illuminated by a lamp. The scan head consisting of mirrors, lens, filter and CCD array, is moved below the object using a motorized mechanism. Scanners employ two-mirror or three-mirror set-up to reflect the image of the object on a lens, which focuses the same to the CCD array through a filter. Flatbed scanners are widely used as periphery equipment for providing the scanned information of different types of objects for various applications. They

Table 3. Summary of CCD Camera applications for quality evaluation of legume seeds.

Legumes	Parameter	Application	References
Lentils	Size	Size distribution of (red and green) grains	Firatligil-Durmus *et al.*, 2008.
	Size	Study of geometric parameters	Firatligil-Durmus *et al.*, 2010.
	Size and shape	Predicting dehulling efficiency of red lentils	Shahin *et al.*, 2012.
Beans	Size and color	Evaluating the quality of the beans and to classify them as sound or damaged	Kilic *et al.*, 2007.
	Color	Correlating water capacity absorption (WCA), a classical indicator of the degree of hard-to-cook beans	Laurent *et al.*, 2010.
	Shape and size	Discrimination of cultivar seeds from each other	Najafabadi & Farahani, 2012
	Size	Study of geometric parameters	Firatligil-Durmus *et al.*, 2010
	Size and shape	Analysis of shape and size of Turkey cultivars	Kara *et al.*, 2013
	Color and texture	Evaluating hard-to-cook beans	Alban *et al.*, 2012
	Color	Nondestructive determination of water absorption capacity	Ousman, 2013
Soybeans	Cracks	Detection of seed coat and cotyledon cracks	Gunasekaran *et al.*, 1988a
	Color	Characterization of symptoms associated with fungal damage, viral diseases, and immature seeds	Ahmad *et al.*, 1999
	Size, shape and color	Detection of fungal damaged soybean seeds and the type of fungal damage	Paulsen *et al.*, 1989
	Color	Detection of mold contamination	Gunasekaran *et al.*, 1988b
	Size and shape	Study the shape of soybean seed	Sakai & Yonekawa, 1992
Lucerne	Shape, size and texture	Identification of seeds	Chtioui *et al.*, 1996
Vetch	Shape, size and texture	Identification of seeds	Chtioui *et al.*, 1996

CCD: charge-coupled device.

offer several advantages, like no separate arrangement for illumination and magnification lenses is required, over other imaging devices, such as a video camera or digital camera (McDonald, Evans, & Bennett, 2001). In the field of agriculture, flatbed scanners have been used for the evaluation of seeds and other agricultural products by determining size, color or other external features such as surface defects or other abnormalities.

Seed shape and size measurements

Shahin and Symons (2001b) determined the size of lentil seeds from images of bulk samples which were acquired using a flat-bed scanner (UMAX Astra 4000U, USA) at 100 dpi resolution. An image analysis method was developed using a commercial software package (KS400, Carl Zeiss, Germany) to extract features of interest. The size of lentil seeds computed using the developed image analysis software was compared with those obtained from the caliper and sieve methods. The developed method proved to be an effective approach for measuring lentil seed size as it offered a simpler, faster and accurate alternative. Shahin, Symons, and Meng (2004) reported an image analysis system to determine the size of different shaped seeds like peas (circular), soybean (elliptical) and chickpeas (multi-faceted) using a flat-bed scanner (ScanMaker 4, Microtek, Denver, CO). The imaging of the bulk samples were performed at 100 dpi resolution. The developed application automatically computed the individual sizes of the seeds by separating the boundaries and reports the size distribution for user selectable sieve combination in metric or imperial units. The results in terms of the accuracy of measuring seed size using image analysis closely matched the sieving method. In another research work being done by Shahin and Symons (2005), similar acquisition method has been used to measure the seed size from the images of non-singulated seed samples of green peas, yellow peas, soybean and chickpeas. It was used for both spherical and non-spherical seeds and its performance in determining the seed size closely matched with the performance of the manual sieving method. The image of bulk samples of kabuli chickpea seeds used in this study is shown in Fig. 2.

Fig. 2. Scanned image of bulk poured sample of kabuli chickpeas taken with a flatbed scanner (Shahin & Symons, 2005).

In the research publication by Shahin, Symons, and Poysa (2006), the soybean sample images were captured using the above mentioned scanner set-up, to predict the size uniformity of the seeds. The image analysis method reported in this paper was used to quantify size uniformity in soybean samples and was found to emulate the manual grading system. Geneve and Dutt (2008) developed a sequential imaging system to study seed germination and dormancy of honeylocust seeds using a flat-bed scanner (HP Scanjet 5370 C with transparency adapter). The authors measured the increase in seed size until radicle emergence and seedling size for excised redbud embryos using the gray scale images of seeds and seedlings. This publication reported an alternative research tool to study the various aspects of seed germination and related processes. The results indicated that the excised redbud embryos from stratified seeds grew into larger seedlings than those from the untreated embryos.

Seed color measurements

The grain inspection capability of scanners has been further investigated for its machine independency for lentil seeds by studying the scanner-to-scanner variability at 100 dpi resolution (Shahin & Symons, 2003a). In this study, four scanners from three different manufacturers were included, namely Microtek Scanmaker 4, Umax Astra 4000U, Microtek Scanmaker X6 and Canon Canoscan FB1200S, in order of their use. The first scanner was used as the reference scanner, whereas the remaining ones were used as the test scanners requiring calibration. Calibration was done by acquiring images of Q60 (Kodak, Canada) color chart from all four scanners. Color correction or mapping functions using grayscale (GS) transformation, red-green-blue (RGB) transformation and histogram matching transformation were developed and it was concluded that histogram transformation gives good results for color correction. Dell'Aquila (2006b) related germination rate of the lentils with the color changes of its seed coat using colored images acquired by a commercial scanner (Sharp mod. JX-330, Japan) at 600 dpi at full color setting. Image analysis software (Image Pro-Plus v.4.5, Media Cybernetics, USA) has been used to measure area of the seed, the aspect factor (i.e., the ratio between the longer axis and the shorter axis of the ellipse equivalent to the seed area) and the intensity values of red, green and blue components of single seeds. Lentils used in this study were subjected to deterioration and the color attributes indicative of the damaged seeds were measured. This method was operative, easy, non-destructive and inexpensive and hence, was suggested to be used for routine seed testing procedures.

Seed shape, size, color and texture measurements

Shahin and Symons (2001a) developed an online grading system to evaluate the quality of large green lentils based on its color and texture attributes. In this study, the grading system was reported to have an accuracy of 90% and color and texture were considered the good predictors of the color grade as per the guidelines of Canadian Grain Commission. In another work reported by Shahin and Symons (2003b), five major lentil varieties, namely Laird, Eston, Redwing, Crimson and Richlea, were identified using size and color features. It was reported that the developed method has the potential to identify the lentil type automatically. Both of the above works were performed using a 100 dpi resolution flat-bed scanner having a scanner area of 520×520 pixels. Venora, Grillo, Shahin, and Symons (2007) developed an image analysis system to identify Sicilian landraces and Canadian cultivars of lentil by measuring color and size attributes that are responsible for its grading as well. Images were scanned at 100 dpi with 512×512 pixel resolution after the seeds were directly placed on the scanner glass plate in a singular manner. The reported method was quick and reliable and the developed classifier correctly identified 97% of the samples. An image analysis system based on flat-bed scanner was developed by Venora, Grillo, Ravalli, and Cremonini (2007), which utilized the morphological and color features of Tuscany bean for varietal discrimination. In this study, the authors were able to discriminate 99.56% of the test samples. In another work reported by the same authors, Italian landraces of bean were identified using an image analysis system based on its color and morphology (Venora, Grillo, Ravalli, & Cremonini, 2009). In both the studies, a flatbed scanner (ScanMaker 9800 XL, Microtek Denver, CO) was used to acquire the images of the bean seeds at 100 dpi and the scanner was calibrated using a Q60 Kodak color chart. The authors obtained a high classification success rate of 98.49% using the extracted parameters. A flatbed scanner of 200 dpi and 1024 × 1024 pixel resolution was used in Bacchetta *et al.* (2008); Grillo, Mattana, Venora, and Bacchetta (2010); Mattana, Grillo, Venora, and Bacchetta (2008). Bacchetta *et al.* (2008) identified diaspores of different wild plant species including *Fabaceae* family using an algorithm specially developed for the extraction of morphological and color features from the images acquired using a flatbed scanner (Epson GT-15,000). A statistical analysis was performed to classify the different species of a family but it could be inferred from the results that the classifier was not able to discriminate satisfactorily at the family level and there is a need to create individual classifiers for each family separately. Also the designed system analyzed the images from a single view, so it was not able to distinguish between flat and spherical seeds. Mattana *et al.* (2008) also performed a similar image analysis using the same scanner settings. In this study, additional color and morphological features were integrated in the analysis to improve the performance of the classifier. The authors obtained high classification success rate using the increased number of features. Another statistical seed classifier was implemented by same authors to classify ten plant families including *Fabaceae* family by using thirty-four morphological and color features (Grillo *et al.*, 2010). All the seed samples were dried at 15 °C temperature and 15% relative humidity so that the shape, size and color of seeds do not undergo any change during image acquisition. In this work, the authors measured the mean seed weight, as an estimate of the thickness of the seed, to distinguish between flattened and globose seeds. In addition, the statistical classifiers described in Bacchetta *et al.* (2008); Mattana *et al.* (2008) were validated in this work by the implementation of a general database and by using dedicated classifiers for each family representative of the Mediterranean vascular flora (Grillo *et al.*, 2010). To identify and discriminate five Czech varieties of pea, Smykalova *et al.* (2011) implemented an image analysis method based on flatbed scanner (Canon 4400F, Canon Inc., Japan) using morphometric and colorimetric features of the seeds. The images of the seed samples were acquired at 200 dpi resolution and 24-bit color depth. The results of varietal discrimination were poor due to the high visual resemblance among the five varieties of pea seeds, but were useful for identification of seed lots during harvest and storage of seeds. Grillo, Mattana, Fenu, Venora, and Bacchetta (2013) performed discriminant analysis of seed morpho-colorimetric data of *Astragalus* genus of legume family, especially the *Astragalus tragacantha* L. complex group, to classify the samples by region of provenance. In this study, the authors used similar scanner settings and procedure, and the calculation of mean seed weight as in Grillo *et al.* (2010). High intra-specific morpho-colorimetric variability indicated wide geographical distribution among the seed species. Table 4 summarizes the applications of using a flat-bed scanner for quality evaluation of legume seeds.

X-ray imaging

The principle behind the X-ray imaging technique is that the X-rays pass selectively through the object being imaged, which reveals its internal density variations. The acquired image data is analyzed for extraction of internal structural information. The factors that determine the quality of X-ray images are the type of source (wavelength), X-ray converter and imaging medium with its casing (Kotwaliwale *et al.*, 2011).

X-ray imaging technique is predominantly used in medical applications and has been utilized in several other applications including safety and quality inspection of agricultural produce. X-ray imaging systems have been used for extracting information like presence of cracks, insect infestation, and morphological and structural features

Table 4. Summary of flat-bed scanner based applications for quality evaluation of legume seeds.

Legumes	Parameter	Application	References
Lentils	Color	Quality grading	Venora, Grillo, Ravalli, *et al.*, 2007
	Color	Correlating germination rate with color changes of its seed coat	Dell'Aquila, 2006b
	Size and color	Classifying different varieties of seeds	Shahin & Symons, 2003b
	Color and texture	Quality grading	Shahin & Symons, 2001a
	Color	Grain inspection	Shahin & Symons, 2003a
	Size	Distribution of seed sizes	Shahin & Symons, 2001b
Soybeans	Size	Determine seed size	Shahin & Symons, 2005; Shahin Symons, & Poysa, 2006; Shahin, Symons, Annie, & Meng, 2004
Peas	Size	Determine seed size	Shahin & Symons, 2005; Shahin *et al.*, 2004
	Color, size and shape	Measurement of morpho-colorimetric traits	Smykalova *et al.*, 2011
Chickpeas	Size	Determine seed size	Shahin & Symons, 2005; Shahin *et al.*, 2004
Beans	Color and size	Online identification from seeds inspection	Venora, Grillo, Shahin, *et al.*, 2007
	Color, size and shape	Identification of Italian landraces of bean	Venora *et al.*, 2009
Honeylocust	Size and shape	Study seed germination and dormancy	Geneve & Dutt, 2008

of internal parts of the seeds. Soft X-rays generated at low voltage have relatively low penetration power, which makes them suitable for inspection purpose and are used on seeds and grains (Davies, 2009).

X-ray inspection is one of the most promising techniques for seed quality evaluation and is employed by ISTA (International Seed Testing Association) (Burg, 2009). Milner, Lee, and Katz (1952) developed a radiographic method for the detection of internal insect infestation in wheat, rice, corn and bean grains by using low energy radiation from a cobalt-target beryllium-window X-ray tube. This is one of the earliest reported literature on usage of X-rays for detecting insect infestation in seeds/grains. Xingwei, Xianchang, and Jianchun (1999) studied five distinct techniques, including X-ray imaging, to detect hidden insect infestations in three different kinds of grain, in which one of them was mung bean. The authors performed X-ray tests using a Softex-type S–E system from Japan with 5 × 7 X-ray films, on which the X-ray images were taken and insect infested seeds were identified.

X-ray imaging technique is a precise method to locate and examine damaged or defective regions inside the seed. Flor *et al.* (2004) used Faxitron X-Ray Model MX-20 for an exposure time of 45 s at an intensity of 20 kV to detect mechanical damage, weathering and stink-bug damage in soybean seeds. The authors analyzed the visual and radiographic images to extract the external and internal details of the seed to find out the extent of damage caused to the seed. The image analysis system reported in this paper was successful in detecting weathering and stink-bug damage in three cultivars of soybean seeds. A comparative study of the techniques used for insect detection in stored grains like cereals and legumes was conducted by Neethirajan, Karunakaran, Jayas, and White (2007). It was reported that the detection of internal and external insects, live and dead insects inside the grain kernels could be detected non-destructively with higher accuracy by the use of X-ray imaging technique. The inability of this technique to detect the presence of insect eggs inside the seed was one of the drawbacks described by the authors. Pinto *et al.* (2009) used X-ray imaging to detect the damages caused by the mechanical stress and the stink-bugs in soybean seeds. Furthermore, the authors evaluated the damage to the seed viability by conducting germination tests on the same set of seeds. The X-ray system used in this work was Faxitron MX-20 at voltage intensity of 25 kV for 40 s. The X-ray image analysis technique was effective in the assessment of mechanical and stink-bug damage in soybean seed and in sorting healthy seed from those which were broken. In a recent study, MagDa De oLiveira (2010) presented a method to evaluate the quality of castor bean seed using radiographic analysis at optimum exposure time and radiation intensity defined using tube voltage ranging from 20 to 50 kVp and exposure times from 15 to 75 s. The authors performed the X-ray test to identify the various types of internal tissues, morphological and physical damage in castor bean seeds and these deformities were related to the germination, emergence and seed vigor test results. The results obtained were useful in assessing the quality of the castor bean seeds. In Fig. 3, the radiographs of castor bean seeds reported in this work are shown.

Belin, Rousseau, Lechappe, Langlois-Meurinne, and Durr (2011) used X-ray imaging to detect internal cracks and abnormal morphological structures of internal parts of the pea seed, i.e. cotyledons, embryo and seed coat. Cesium Iodide (CsI) micro-sensors were used for absorbing X-ray photons and for generating visible photons that were later digitized by a CCD camera. Faxitron MX-20DC12 at voltage of 25 kV for 15 s and Faxitron 43,805A at voltage of 20 kV for 2 min were used to produce analog X-ray images that were digitized by scanning at 1200 dpi. For assessment of mechanical damage in soybean seeds, Pinto *et al.* (2012) reported an X-ray image analysis method using Faxitron MX-20 at voltage intensity of 25 kV for 40 s. It has been inferred from the study that the mechanical damages on the seeds depend on the location of impact, and is directly proportional to the impact

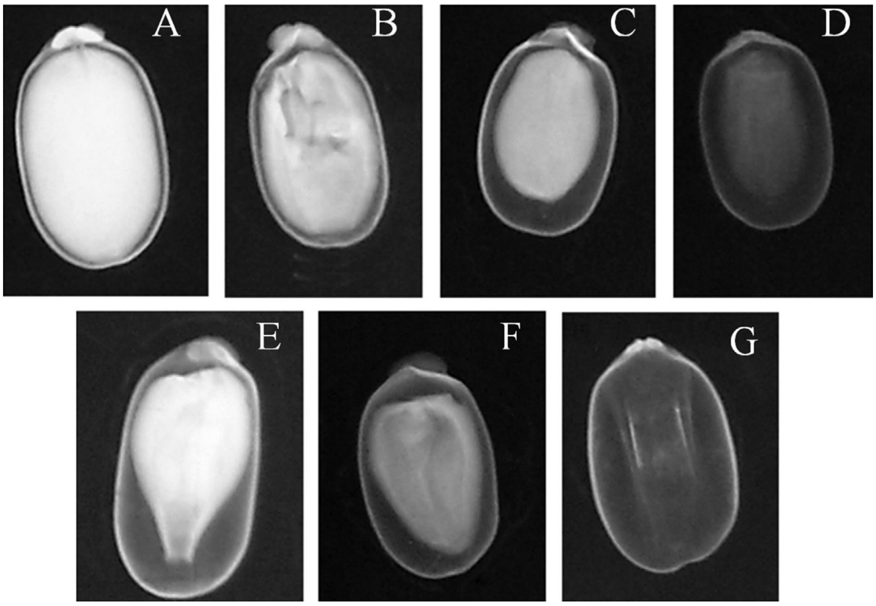

Fig. 3. Radiographs of castor bean seeds classified into seven categories, according to their internal morphology: A – Full and opaque, B – Full and blemished, C– Partially full and opaque, D – Partially full and translucent, E – Partially full, with embryo deformation, F – Partially full and blemished, G – Empty (MagDa De oLiveira, 2010).

pressure being exerted on the seed, and the moisture content of the seed.

Ramakrishnan, Babu, and Babu (2012) reported an X-ray imaging application to detect hidden insect infestations in pulses and to find the best combinations of tube voltage, current and exposure time. Additionally, the effect of soft X-rays on the pulses was also studied by performing germination tests on the same set of seeds. Out of 100 different combinations, 20 kV, 10 mA, 25 s for urdbean and mung bean; 20 kV, 12 mA for 25 s for cowpea; 25 kV, 10 mA, 25 s for soybean; 15 kV, 12 mA, 25 s for lentil; and 25 kV, 8 mA, 25 s for Dolichos or horse bean were selected as a standardized combination for detecting hidden insect infestations in the respective pulses. Table 5 summarizes parameters and techniques used for internal quality evaluation of legume seeds using X-Ray imaging.

Nuclear magnetic resonance (NMR) imaging

NMR imaging, also known as Magnetic Resonance Imaging (MRI), is based on the absorption and emission of

Table 5. Summary of X-Ray imaging applications for quality evaluation of legume seeds.

Legumes	Parameter	Application	References
Soybean	Mechanical damage	Examining damaged regions inside the seed	Flor *et al.*, 2004; Pinto *et al.*, 2009; Pinto *et al.*, 2012
	Internal insect infestation	Detection of hidden insect infestations and effect of soft X-rays	Ramakrishnan *et al.*, 2012
Pea	Internal cracks and internal morphological structures	Detection of internal cracks and abnormal internal morphological structures, i.e. cotyledons, embryo and seed coat	Belin *et al.*, 2011
Mung bean	Internal insect infestation	Detection of hidden insect infestations and effect of soft X-rays	Ramakrishnan *et al.*, 2012; Xingwei *et al.*, 1999
Lentil	Internal insect infestation	Detection of hidden insect infestations and effect of soft X-rays	Ramakrishnan *et al.*, 2012
Castor bean	Internal morphological damage	Quality evaluation	MagDa De oLiveira, 2010
Cowpea	Internal insect infestation	Detection of hidden insect infestations and effect of soft X-rays	Milner *et al.*, 1952; Ramakrishnan *et al.*, 2012
Urdbean	Internal insect infestation	Detection of hidden insect infestations and effect of soft X-rays	Ramakrishnan *et al.*, 2012
Dolichos bean	Internal insect infestation	Detection of hidden insect infestations and effect of soft X-rays	Ramakrishnan *et al.*, 2012
Pinto Bean	Internal insect infestation	Detection of internal insect infestations	Milner *et al.*, 1952
Kidney bean	Internal insect infestation	Detection of internal insect infestations	Milner *et al.*, 1952

energy in the radio frequency range of the electromagnetic spectrum. It is performed by placing an object in a strong magnetic field, which aligns the hydrogen nuclei spins parallel and anti-parallel to the field. A radio frequency pulse sequence is then applied to excite nuclear spins and after its removal, the signal strengths in orthogonal directions are measured. The measured signals are transformed by reconstruction algorithms to generate internal images of the object. Good contrast between a region of interest and its adjacent area can be accomplished by the selection of optimal parameters of the pulse sequence. This is a non-destructive technique primarily used to obtain high quality images of internal parts of the object in two or three dimensions. Several publications have reported the use of this technique for quality estimation of the agricultural produce (Zhang and McCarthy (2013)).

The researchers have demonstrated the potential of NMR imaging to investigate physical or biological properties of seeds and other food products. The use of NMR imaging to study the process of germination, i.e. the water uptake by the embryo and to relate the changing status of water in the embryo to the development of the seed was reported by Fountain *et al.* (1998). The possibility that ethylene induces disturbance in embryo water status was investigated in common bean seed. The work done in this study supports the hypothesis that "*in vivo*, quiescence at this developmental stage is induced and maintained by sequestration of water within the cotyledons". Wojtyla *et al.* (2006) used NMR spectroscopy and imaging technique to study the imbibition process and germination of pea seeds. Imbibition involves absorption of water into the seeds during the process of germination. The authors investigated the relationship between the distribution of water in embryo and cotyledons and the metabolic process of the germinating pea seeds by studying temporal and spatial water uptake and distribution in pea seeds. On observing the findings of the study in terms of the changes in the free radical levels, antioxidant contents, enzymatic activities in embryo axes, it appears that these changes were related to metabolic processes associated with preparations for germination instead of being related to hydration of the cotyledons and embryo axes. In a study done on lupine seeds by Garnczarska, Zalewski, and Kempka (2007a), NMR imaging has been used to determine temporal and spatial water uptake by the germinating lupine seeds in order to understand the structural changes of the seed when soaked in water during germination. It was concluded from the experiments that water distribution in lupine seeds is inhomogeneous, and seed tissues hydrate at different rates and extent. In another work by the same authors, the loss of water in maturing lupin seeds was visualized using NMR imaging. The authors inferred from this study that lupin seeds have similar states of the various water components (bound, intracellular, extracellular) with respect to moisture content of seeds at seed maturation and germination (Garnczarska, Zalewski, & Kempka, 2007b). Garnczarska, Zalewski, and Wojtyla (2008) reported a comparative study of spatial distribution of water and localization of dehydrin protein in maturing pea seeds by using nuclear magnetic resonance imaging. The water loss in maturing pea seeds was visualized using this technique. This study suggested the involvement of dehydrin proteins in promoting water influx into the vascular bundles. In a research work reported by Hong *et al.* (2009), NMR imaging was used to study the water distribution in soaked and cooked soybean seeds. Lipid suppression method was applied to the images to obtain independent water images. The authors had inferred from the study that NMR images acquired with only water signal do not have any chemical shift artifacts. NMR imaging was used to interpret the direction of the imbibed water in seeds and for tracing the seed parts and pathways that are responsible for absorption of water to check the germination capability of the seeds (Borisjuk, Rolletschek, & Neuberger, 2012). Vinogradova and Falaleev (2012) have demonstrated the use of NMR imaging to study the seed growth, development and conductive system of bean seeds. The authors have also used this technique to analyze the pathways for uptake of nutrients. A study of the amount of water absorbed by the navy beans during cooking was reported by Zhang and McCarthy (2013). They monitored the hydration process of the beans at macroscopic levels using the proton density maps, which were obtained by NMR imaging technique. Proton density maps were studied at various cooking stages of the navy bean to understand the spatial distribution of water in the bean. In Fig. 4, the proton density maps of the transverse cross section of a navy bean used in this study are shown at different intervals of time.

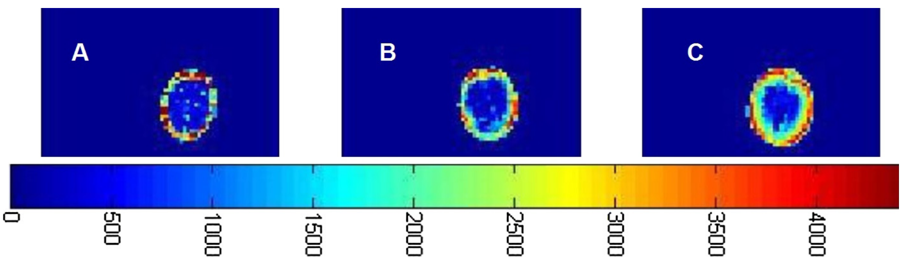

Fig. 4. Proton density map, obtained by MRI technique, of the transverse cross section of a navy bean cooked for different lengths of time. A – 15 min, B – 50 min, C – 200 min (Zhang & McCarthy, 2013).

NMR imaging is also used to generate lipid and metabolic maps of seeds, thus enabling researchers to non-invasively determine the internal quality attributes of seeds like the oil content, moisture content and other biochemical characteristics (Borisjuk *et al.*, 2012). Lakshminarayana, Joshi, Gowda, and Khetrapal (1992) reported an NMR imaging technique to detect oil and water spatial distribution in intact oil seeds. The authors selected appropriate field of views for the transverse and longitudinal slices and the slice thickness, echo time, repetition time and the number of data acquisitions for all the experiments. Water and oil content was seen clearly and the region for storage of oil was estimated. Melkus *et al.* (2009) developed a three dimensional model of pea seed using NMR imaging technique to study the metabolic contents like sucrose present in the endosperm and to discuss the role of the endosperm in the metabolic process of the legume seeds. In Fig. 5, the NMR imaging of a pea seed is shown that has been used to extract the internal morphological structures of the seed. A Bruker MQ60 device (Bruker GmbH) having a magnetic field strength of 1.5 T was used to non-destructively measure the lipid content of ten different seeds. Peas and soybean were also included in the study of Borisjuk, Rolletschek, Fuchs, Melkus, and Neuberger (2011) using low field NMR. In addition, a high field NMR of 17.5 T and 20 T was used for capturing seed structure and to assess the lipid and metabolite distribution within the seed. Table 6 summarizes NMR imaging applications for internal quality evaluation of legume seeds.

Hyperspectral imaging

It is a powerful technique for providing the spectral and spatial information of an object by merging two

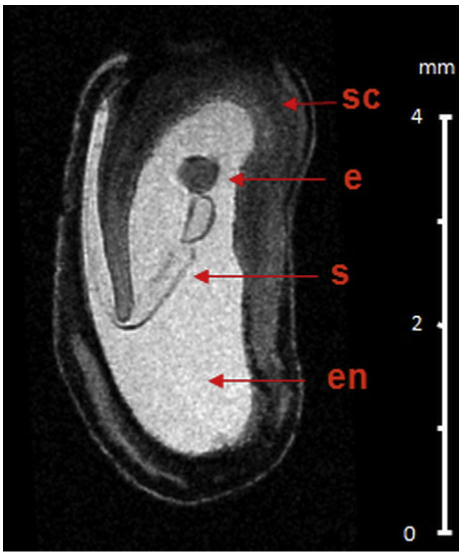

Fig. 5. Fragment of three-dimensional image of the longitudinal section captured using MRI showing internal structures of a pea seed. e, Embryo; en, endosperm; ev, endosperm vacuole; s, suspensor; sc, seed coat (Melkus *et al.*, 2009).

technologies, namely imaging and spectroscopy (Gowen, O'Donnell, Cullen, Downey, & Frias, 2007). Hyperspectral images are acquired using the imaging spectrometers. The basic principle on which a hyperspectral imaging system works is that it detects and measures elusive absorption bands in the reflectance spectra of various objects and collects the image data in dozens or hundreds of narrow, adjacent spectral bands with a very high accuracy (Van der Meer & de Jong, 2001). The visual imaging provides spatial information whereas the spectroscopy system gives limited spectral information of the sample. It provides 2-D spatial coverage of spectral measurements and therefore, the hyperspectral images integrate spectral information from each of its pixels in a spatially resolved manner and thus, these images contain much more information than those of conventional imaging and spectroscopy techniques (Singh, Jayas, Paliwal, & White, 2009; Singh, Jayas, Paliwal, & White, 2010). Hyperspectral imaging has been reported to be used extensively in reflectance mode due to the sensitivity of hyperspectral sensors to subtle variations. Emission, transmission or fluorescence modes have also been investigated for the development of online automated multispectral imaging systems (Gowen *et al.*, 2007).

Hyperspectral imaging technique has numerous applications in resource management (Govender, Chetty, & Bulcock, 2007), agriculture (Monteiro, Minekawa, Kosugi, Akazawa, & Oda, 2007; Smail, Fritz, & Wetzel, 2006; Uno *et al.*, 2005), mineral exploration (Sabins, 1999), astronomy (Hege, O'Connell, Johnson, Basty, & Dereniak, 2004; Wood, Gulian, Fritz, & VanVechten, 2002), remote sensing (Gat, Subramanian, Barhen, & Toomarian, 1997), medicine (Gat *et al.*, 1997), military (Gat *et al.*, 1997) and environmental monitoring (Gat *et al.*, 1997). In the agricultural field, it has been applied for seed quality evaluation. This technique has been used to detect internal insect infestations (Kaliramesh *et al.*, 2013; Singh *et al.*, 2009, 2010), to measure oil and moisture content, starch, protein and other chemical compositions without damaging the seeds (Gowen *et al.*, 2007; Van der Meer & de Jong, 2001). However, most of the work is reported for cereal crops like maize (Cogdill, Hurburgh, & Rippke, 2004) and wheat (Singh *et al.*, 2009, 2010) whereas only limited number of publications have been reported for leguminous seeds. It is an emerging technique and may have good potential in leguminous seed quality evaluation tasks.

In a recent work, Kaliramesh *et al.* (2013) used NIR hyperspectral imaging system to detect infestation by *Callosobruchus maculatus* in mung bean seeds by selecting the specific wavelengths (1100, 1290 and 1450 nm) for image acquisition in the NIR region and then classified the seeds as infested and uninfected. The authors have used a thermo-electrically cooled Indium Gallium Arsenide (InGaAs) camera, with two VariSpec liquid crystal tunable filters (LCTFs), a 25 mm F1.4 C-mount lens, a sample stage, and a light source controlled through a Dell Optiplex GX280 Intel(R) computer as shown in the Fig. 6. This

Table 6. Summary of nuclear magnetic resonance imaging applications for quality evaluation of legume seeds.

Legumes	Parameter	Application	References
Soybean	Seed lipid content	Study seed structure and to assess the lipid and metabolite distribution within the seed.	Borisjuk *et al.*, 2011
	Water distribution	Investigation of true water distribution	Hong *et al.*, 2009
Peas	Distribution of water	Study imbibition process and germination of seeds.	Wojtyla *et al.*, 2006
	Seed lipid content	Study seed structure and to assess the lipid and metabolite distribution within the seed.	Borisjuk *et al.*, 2011
	Internal morphology	Study the metabolic contents like sucrose present in the endosperm and the role of the endosperm in the metabolic process of the legume seeds.	Melkus *et al.*, 2009
	Water loss	Study of spatial distribution of water and localization of dehydrin protein in maturing seeds.	Garnczarska *et al.*, 2008
Lupine	Structural changes during germination	Determine temporal and spatial water uptake by the germinating seeds.	Garnczarska *et al.*, 2007a
	Water distribution	Study of distribution of water in seeds at different seed stages	Garnczarska *et al.*, 2007b
Common bean	Spatial distribution of water	Study of the amount of water taken during cooking.	Zhang & McCarthy, 2013
	Water uptake	Study the process of germination	Fountain *et al.*, 1998
Lima bean	Vascular system	Study vascular systems in developing bean	Vinogradova & Falaleev, 2012
Groundnut	Oil and water content	Detection of oil and water spatial distribution in intact oil seeds.	Lakshminarayana *et al.*, 1992

system had a spatial resolution of 640 × 480 pixels with 27 μm pitch and a spectral resolution of 0.01 nm. The liquid crystal tunable filter used in this experiment is a high quality interference filter that has an aperture of 20 mm and a transmission bandwidth of 10 mm. Promising results were achieved in identifying the infested seeds, particularly at pupae and adult stages of infestation.

Thermal imaging

The principle behind this technique is the measurement of infrared radiation emitted by a body based on the fact that all objects emit infrared radiation. The surface temperature of the body is estimated based on the infrared energy emitted by it (Gowen, Tiwari, Cullen, McDonnell, & O'Donnell, 2010).Thermal imaging system consists of a thermal camera equipped with infrared detectors and a signal processing unit (Vadivambal & Jayas, 2011). Thermo-graphic cameras convert the infrared energy emitted, transmitted and reflected by an object into a 2-dimensional visible image. Such cameras have the ability to detect the infrared radiations that ranges from 9 to 14 μm in the electromagnetic spectrum. For online applications, an external heat source is required to improve the contrast between the object and the background. The images that are the visual displays of the infrared radiation are known as thermal images or thermo-grams. It is an emerging technique that does not involve usage of any harmful radiation (Gowen *et al.*, 2010).

Originally, thermal imaging was designed for military applications like surveillance because of its usability in

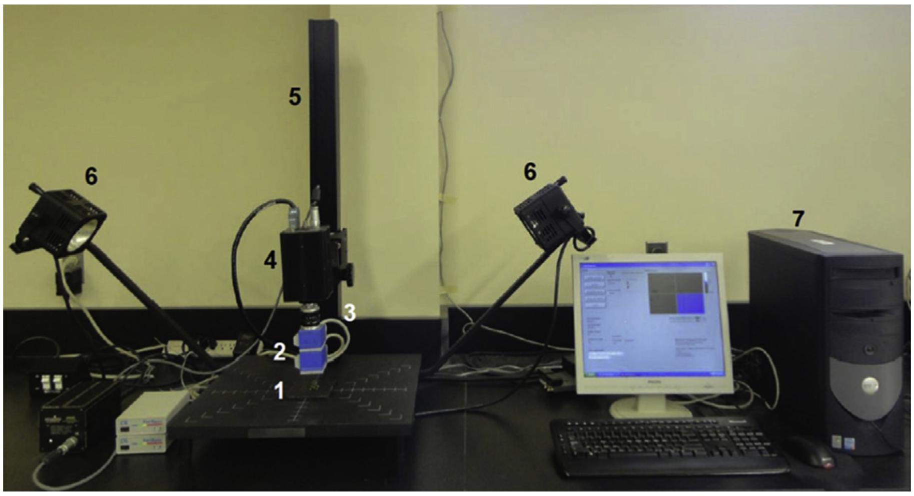

Fig. 6. Hyperspectral imaging system set-up using long-wave near-infrared to detect infestation in mung bean seeds. The components of the system are: 1. Mung bean sample, 2. Liquid crystal tunable filter (LCTF), 3. Lens, 4. NIR camera, 5. Copy stand, 6. Illumination (Halogen-tungsten lamp), 7. Data processing system (Kaliramesh *et al.*, 2013).

night vision (Wong, Tan, Loo, & Lim, 2009). However, with the progress in the imaging research and availability of cameras with better resolution, it has found applications in fire-fighting, medicine, structural health monitoring, material science and many other industries (Gowen *et al.*, 2010). It has become a powerful analytical technique that is also suitable for inspection applications in the food industry.

Thermal imaging is used for quality evaluation of the agricultural products (Gowen *et al*., 2010; Vadivambal & Jayas, 2011). It has been used on seeds to detect insect infestations (Chelladurai, Kaliramesh, & Jayas, 2012; Manickavasagan, Jayas, & White, 2008; Manickavasagan, Jayas, White, & Paliwal, 2008), fungal infections (Chelladurai, Jayas, & White, 2010), determine water and oil contents (Kranner, Kastberger, Hartbauer, & Pritchard, 2010), identify varieties of wheat (Manickavasagan, Jayas, White, & Paliwal, 2010), and to predict whether a seed will germinate or die upon water uptake (Kranner *et al*., 2010). A valuable review of the application of thermal imaging in agriculture and food industry was conducted by Vadivambal & Jayas, 2011. The authors have elaborated the role of thermal imaging in temperature mapping of essential crops and products and have suggested great potential in real time applications in the near future. Chelladurai *et al.* (2012) used an uncooled focal planar array type infrared thermal camera having spectral range of 7.5–13.0 μm and thermal sensitivity of 0.07 °C at 30 °C with 320 × 240 pixels resolution for acquiring images of mung beans to detect the *C. maculatus* infestation. The experimental set-up of the thermal camera in the referred publication is shown in Fig. 7. The results of this study highlighted the capability of the thermal imaging in detection of *C. maculatus* infestation in mung beans. Baranowski, Mazurek, and Walczak (2003) used a thermographic AGEMA 880 LWB camera to enable calculation of average seed temperature to evaluate germination capacity of leguminous seeds like pea. It is inferred from the study that the thermographic method reduces the time to select highly viable leguminous seeds from seed samples.

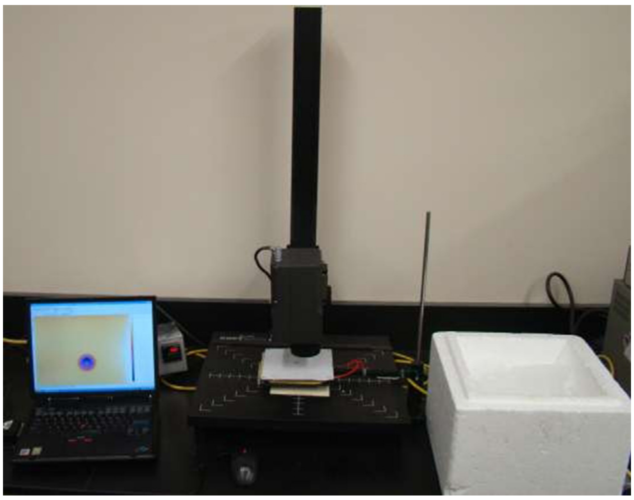

Fig. 7. Thermal imaging system set-up used for acquiring thermographs of mung bean seeds (Chelladurai *et al.*, 2012).

Kranner *et al.* (2010) used thermal imaging to understand the thermal profiles of highly viable, aged and dead pea seeds during water imbibition. These thermal profiles were investigated to correlate with the germination ability of the seeds. In this work, approximately 22,000 images per seed were analyzed every 20 s over five days to determine the relative seed temperature, i.e., the difference between each individual seed and its immediate environment. In Fig. 8, the infrared thermographs of the pea seeds are shown in which changes in the seed temperature can be seen clearly of untreated and aged pea seeds during imbibition of pea seeds. The authors concluded that infrared thermography method can detect imbibition and germination associated biophysical and biochemical changes. Table 7 summarizes broad applications of thermal imaging and hyper-spectral imaging for internal quality evaluation of legume seeds.

Conclusions and future trends

This review gave an overview of research activities on image acquisition techniques employed for quality evaluation of leguminous seeds. In this section, the merits and demerits of these imaging techniques specific to their usability and applicability are discussed.

CCD camera with front lighting set-up has been used for acquisition of external physical characteristics such as shape, size, color and texture information. Camera systems are available in a wide range of resolutions. Other advantages of camera systems include real time 2-D and 3-D surface image acquisition. Several aspects that require careful design consideration are the type of the illumination and camera system, the nature of the imaging chamber, and the distance between the source, sample and camera system. Commonly occurring errors in camera based imaging systems include inter-reflections, color inconstancies, highlights, shadows of nearby objects, etc. Moreover, the CCD camera is not capable of extracting biochemical characteristics like oil content, protein content etc. that are also important quality parameters of seeds.

Flatbed scanners have also been widely reported for acquisition of external features such as shape, size, color and texture information of cereal grains and legume seeds. The main advantage of imaging systems based on scanner lies in its low cost, simplicity in operation and rapid acquisition of digitized images with good depth of field. However, some of the challenges of image acquisition based on CCD camera exist in scanner systems like non-linearities in intensity and spectral power distribution of the illumination, highlights and shadows. Additionally, scanners are not suitable for large sized seeds of spherical or irregular geometry.

Internal characteristics can be retrieved using X-ray, NMR imaging, thermal imaging, and hyperspectral

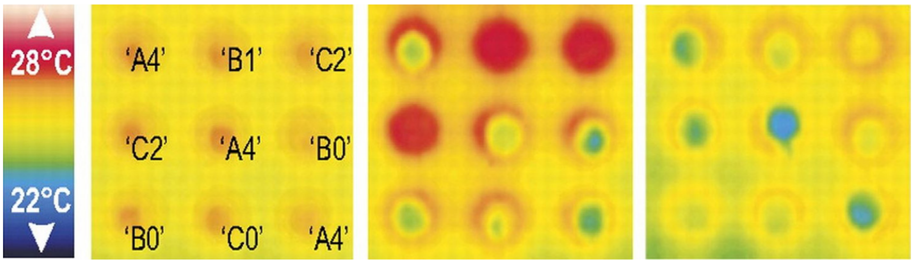

Fig. 8. (Left to Right)Temperature scale and infrared thermographs of pea seeds 0, 4, and 80 h after onset of imbibition; note the radicle protrusion in the middle seed in the last thermograph (Kranner *et al.*, 2010).

Table 7. Summary of thermal and hyper-spectral imaging applications for legume seed quality evaluation.

Legumes	Parameter	Technique	Application	References
Pea	Seed temperature	Thermal imaging	Study the thermal profiles of highly viable, aged and dead seeds during water imbibition.	Kranner *et al.*, 2010
	Seed temperature	Thermal imaging	Calculation of average seed temperature to evaluate the germination capacity of the leguminous seeds.	Baranowski *et al.*, 2003
Mung bean	Internal insect infestation	Hyper-spectral imaging	Detection of hidden insect infestations by *C. maculatus*.	Kaliramesh *et al.*, 2013
	Internal insect infestation	Thermal imaging	Detection of hidden insect infestations by *C. maculatus*.	Chelladurai *et al.*, 2012

imaging. Hyperspectral imaging is a promising technique that has been used to detect internal insect infestations, to measure oil and moisture content, starch, protein and other chemical compositions without damaging the seeds. However, impediments like high costs, complexity in its operation and analysis, and poor availability have significantly contributed to low adoption of this technology by the seed research community.

Thermal imaging is a non-contact imaging technique that is portable and allows real-time imaging. It is used for subsurface imaging and mainly for detection of insect infestation and damaged seeds without the use of any harmful radiations. Poor resolution and sensitivity to environmental conditions are some of the limitations of this technique. Current research data clearly shows the numerous opportunities that exist for its application in seed testing industry.

The combination of thermal imaging and hyperspectral imaging would provide a more complete description of the seeds under investigation. With the development of such integrated imaging systems, fast, robust and efficient leguminous seed quality evaluation may be achieved.

X-ray imaging is a non-contact type subsurface imaging technique. However, X-rays can ionize and thus damage the living cells and tissue, which is one of the major risk factors to be considered while using this technique. Additionally, X-ray imaging systems have limited spatial resolution and are unable to image different parts of objects having similar density.

NMR imaging systems produce high-resolution *in vivo* images of internal structures in two or three dimensions. The researchers have demonstrated the potential of NMR imaging to investigate physical, biological and biochemical properties of seeds that are vital quality parameters. It does not involve any harmful radiation and thus, can be used in routine seed quality analysis. However, the NMR imaging systems are quite costly, complex in operation and maintenance, and require trained personnel as operators.

The imaging techniques as discussed in this paper are non-contact and non-destructive in nature. Hence, these techniques may be employed for quality evaluation of seeds based on machine vision instead of the subjective, tedious, costly and inconsistent manual methods. Most of the quality evaluation applications discussed in this survey are still in the experimental stages; additional research work is required for the industrial adoption of these techniques in large-scale agricultural industries.

Acknowledgments

One of the authors, Shveta Mahajan acknowledges the grant of SRF-GATE fellowship from Council of Scientific and Industrial Research (CSIR), New Delhi. This study was supported in part by CSIR-CSIO under the network project ASHA, Task 1.4.

References

Agrawal, R. L. (1995). *Seed technology* (2nd ed.). New Delhi, India: Oxford & IBH Publishing Co. Pvt. Ltd.

Ahmad, I. S., Reid, J. F., Paulsen, M. R., & Sinclair, J. B. (1999). Color classifier for symptomatic soybean seeds using image processing. *Plant Disease, 83*(4), 320–327.

Alban, N., Laurent, B., Ousman, B., & Emmanuel, T. (2012). Color and texture information processing to improve storage beans. *British Journal of Applied Science & Technology, 2*(2), 96–111.

Alfatni, M. S. M., Shariff, A. R. M., Abdullah, M. Z., Marhaban, M. H. B., & Saaed, O. M. B. (2013). The application of internal grading system technologies for agricultural products–Review. *Journal of Food Engineering, 116*(3), 703–725.

Alfatni, M. S., Shariff, A. R. M., Abdullah, M. Z., Saeed, O. M. B., & Ceesay, O. M. (2011). Recent methods and techniques of external grading systems for agricultural crops quality inspection-review. *International Journal of Food Engineering, 7*(3).

Altuntas, E., & Yildiz, M. (2007). Effect of moisture content on some physical and mechanical properties of faba bean (*Vicia faba* L.) grains. *Journal of Food Engineering, 78*(1), 174–183.

Bacchetta, G., Grillo, O., Mattana, E., & Venora, G. (2008). Morpho-colorimetric characterization by image analysis to identify diaspores of wild plant species. *Flora-Morphology, Distribution, Functional Ecology of Plants, 203*(8), 669–682.

Baranowski, P., Mazurek, W., & Walczak, R. (2003). *The use of thermography for pre-sowing evaluation of seed germination capacity*. Paper presented at the International Conference on Quality in Chains. An Integrated View on Fruit and Vegetable Quality.

Basra, A. S. (1995). *Seed quality: Basic mechanisms and agricultural implications*. Binghamton, Newyork: Food Products Press.

Belin, E., Rousseau, D., Lechappe, J., Langlois-Meurinne, M., & Durr, C. (2011). Rate-distortion tradeoff to optimize high-throughput phenotyping systems. Application to X-ray images of seeds. *Computers and electronics in agriculture, 77*(2), 188–194.

Bewley, J. D. (1994). *Seeds: Physiology of development and germination*. New York: Plenum Press.

Bewley, J. D., Black, M., & Halmer, P. (2006). *The encyclopedia of seeds: Science, technology and uses*. CABI.

Borisjuk, L., Rolletschek, H., Fuchs, J., Melkus, G., & Neuberger, T. (2011). Low and high field magnetic resonance for *in vivo* analysis of seeds. *Materials, 4*(8), 1426–1439.

Borisjuk, L., Rolletschek, H., & Neuberger, T. (2012). Surveying the plant's world by magnetic resonance imaging. *The Plant Journal, 70*(1), 129–146.

Brosnan, T., & Sun, D.-W. (2002). Inspection and grading of agricultural and food products by computer vision systems—a review. *Computers and electronics in agriculture, 36*(2), 193–213.

Brosnan, T., & Sun, D.-W. (2004). Improving quality inspection of food products by computer vision––a review. *Journal of Food Engineering, 61*(1), 3–16.

Burg, J. v. d. (2009). *Raising seed quality: What is in the pipeline?*.

Chelladurai, V., Jayas, D., & White, N. (2010). Thermal imaging for detecting fungal infection in stored wheat. *Journal of Stored Products Research, 46*(3), 174–179.

Chelladurai, V., Kaliramesh, S., & Jayas, D. (2012). *Detection of callosobruchus maculatus (F.) infestation in mung bean (vigna radiata) using thermal imaging technique*. Paper presented at the AGM NABEC-CSBE Orillia, Canada.

Chen, Y.-R., Chao, K., & Kim, M. S. (2002). Machine vision technology for agricultural applications. *Computers and Electronics in Agriculture, 36*(2), 173–191.

Chen, P., & Sun, Z. (1991). A review of non-destructive methods for quality evaluation and sorting of agricultural products. *Journal of Agricultural Engineering Research, 49*(May–August), 85–98.

Chtioui, Y., Bertrand, D., Dattee, Y., & Devaux, M. F. (1996). Identification of seeds by colour imaging: Comparison of discriminant analysis and artificial neural network. *Journal of the Science of Food and Agriculture, 71*(4), 433–441.

Cogdill, R. P., Hurburgh, C., & Rippke, G. (2004). Single-kernel maize analysis by near-infrared hyperspectral imaging. *Transactions of the ASAE, 47*(1), 311–320.

Davies, E. (2009). The application of machine vision to food and agriculture: a review. *Imaging Science Journal, 57*(4), 197–217.

Dell'Aquila, A. (2006a). Computerized seed imaging: a new tool to evaluate germination quality. *Communications in Biometry and Crop Science, 1*(1), 20–31.

Dell'Aquila, A. (2006b). Red-Green-Blue (RGB) colour density as a non-destructive marker in sorting deteriorated lentil (*Lens culinaris Medik.*) seeds. *Seed Science and Technology, 34*(3), 609–619.

Dell'Aquila, A. (2007). Towards new computer imaging techniques applied to seed quality testing and sorting. *Seed Science and Technology, 35*(3), 519–538.

Dell'Aquila, A. (2009). *Digital imaging information technology applied to seed germination testing: A review sustainable agriculture* (pp. 377–388). Springer.

Du, C.-J., & Sun, D.-W. (2004). Recent developments in the applications of image processing techniques for food quality evaluation. *Trends in Food Science & Technology, 15*(5), 230–249.

Du, C.-J., & Sun, D.-W. (2006). Learning techniques used in computer vision for food quality evaluation: a review. *Journal of Food Engineering, 72*(1), 39–55.

Faria, S. D., Lewis, G., Sprent, J., & Sutherland, J. (1989). Occurrence of nodulation in the Leguminosae. *New Phytologist, 111*(4), 607–619.

Firatligil-Durmus, E., Sarka, E., & Bubník, Z. (2008). Image vision technology for the characterisation of shape and geometrical properties of two varieties of lentil grown in Turkey. *Czech Journal of Food Sciences, 26*(2), 109–116.

Firatligil-Durmus, E., Sarka, E., Bubnik, Z., Schejbal, M., & Kadlec, P. (2010). Size properties of legume seeds of different varieties using image analysis. *Journal of Food Engineering, 99*(4), 445–451.

Flor, E. P. O., Cicero, S. M., Neto, F., Barros, J. d., & Krzyzanowski, F. C. (2004). Evaluation of mechanical damages in soybean seeds by image analysis. *Revista Brasileira de Sementes, 26*(1), 68–76.

Fountain, D. W., Forde, L. C., Smith, E. E., Owens, K. R., Bailey, D. G., & Callaghan, P. T. (1998). Seed development in *Phaseolus vulgaris* L. cv. Seminole. 3. NMR imaging of embryos during ethylene-induced precocious germination. *Seed Science Research, 8*(03), 357–365.

Garnczarska, M., Zalewski, T., & Kempka, M. (2007a). Water uptake and distribution in germinating lupine seeds studied by magnetic resonance imaging and NMR spectroscopy. *Physiologia Plantarum, 130*(1), 23–32.

Garnczarska, M., Zalewski, T., & Kempka, M. (2007b). Changes in water status and water distribution in maturing lupin seeds studied by MR imaging and NMR spectroscopy. *Journal of experimental botany, 58*(14), 3961–3969.

Garnczarska, M., Zalewski, T., & Wojtyla, L. (2008). A comparative study of water distribution and dehydrin protein localization in maturing pea seeds. *Journal of plant physiology, 165*(18), 1940–1946.

Gat, N., Subramanian, S., Barhen, J., & Toomarian, N. (February 26, 1997). *Spectral imaging applications: Remote sensing, environmental monitoring, medicine, military operations, factory automation, and manufacturing*. Paper presented at the 25th Annual AIPR Workshop on Emerging Applications of Computer Vision, Washington, DC.

Geneve, R. L., & Dutt, M. (2008). Using sequential digital images to study seed germination. *Propagation of Ornamental Plants, 8*(1), 13–16.

Govender, M., Chetty, K., & Bulcock, H. (2007). A review of hyperspectral remote sensing and its application in vegetation and water resource studies. *Water South Africa, 33*(2), 145–152.

Gowen, A., O'Donnell, C., Cullen, P., Downey, G., & Frias, J. (2007). Hyperspectral imaging–an emerging process analytical tool for food quality and safety control. *Trends in Food Science & Technology, 18*(12), 590–598.

Gowen, A., Tiwari, B., Cullen, P., McDonnell, K., & O'Donnell, C. (2010). Applications of thermal imaging in food quality and safety assessment. *Trends in Food Science & Technology, 21*(4), 190–200.

Grillo, O., Mattana, E., Fenu, G., Venora, G., & Bacchetta, G. (2013). Geographic isolation affects inter-and intra-specific seed variability in the *Astragalus tragacantha* complex, as assessed by morpho-colorimetric analysis. *Comptes rendus biologies, 336*(2), 102–108.

Grillo, O., Mattana, E., Venora, G., & Bacchetta, G. (2010). Statistical seed classifiers of 10 plant families representative of the Mediterranean vascular flora. *Seed Science and Technology, 38*(2), 455–476.

Gunasekaran, S. (1996). Computer vision technology for food quality assurance. *Trends in Food Science & Technology, 7*(8), 245–256.

Gunasekaran, S., Cooper, T., & Berlage, A. (1988a). Soybean seed coat and cotyledon crack detection by image processing. *Journal of Agricultural Engineering Research, 41*(2), 139–148.

Gunasekaran, S., Cooper, T., & Berlage, A. (1988b). Evaluating quality factors of corn and soybeans using a computer vision system. *Transactions of the ASAE, 31*(4), 1264–1271.

Hege, E. K., O'Connell, D., Johnson, W., Basty, S., & Dereniak, E. L. (January 7, 2004). *Hyperspectral imaging for astronomy and space surviellance*. Paper presented at the Optical Science and Technology, SPIE's 48th Annual Meeting-Imaging Spectrometry IX, San Diego, California, USA.

Hong, Y.-S., Cho, J.-H., Kim, N.-R., Lee, C., Cheong, C., Hong, K. S., et al. (2009). Artifacts in the measurement of water distribution in soybeans using MR imaging. *Food chemistry, 112*(1), 267–272.

Isik, E., & Unal, H. (2007). Moisture-dependent physical properties of white speckled red kidney bean grains. *Journal of Food Engineering, 82*(2), 209–216.

Jayas, D., Paliwal, J., & Visen, N. (2000). Review paper (AE—Automation and emerging technologies): multi-layer neural networks for image analysis of agricultural products. *Journal of Agricultural Engineering Research, 77*(2), 119–128.

Jones, M. A., Foster, D. J., & Rimathe, D. M. (2011). *Method and apparatus for analyzing quality traits of grain or seed*. US 8,031,910 B2(10/928,760).

Kaliramesh, S., Chelladurai, V., Jayas, D., Alagusundaram, K., White, N., & Fields, P. (2013). Detection of infestation by *Callosobruchus maculatus* in mung bean using near-infrared hyperspectral imaging. *Journal of Stored Products Research, 52*(January 2013), 107–111.

Kannur, A., Kannur, A., & Rajpurohit, V. S. (2011). Classification and grading of bulk seeds using aritificial neural network. *Int. J. Machine Intelligence, 3*(2), 62–73.

Kara, M., Sayinci, B., Elkoca, E., Ozturk, I., & Ozmen, T. B. (2013). Seed size and shape analysis of registered common bean (*Phaseolus vulgaris* L.) cultivars in Turkey using digital photography. *Journal of Agricultural Sciences, 19*(3), 219–234.

Kilic, K., Boyaci, I. H., Koksel, H., & Kusmenoglu, I. (2007). A classification system for beans using computer vision system and artificial neural networks. *Journal of Food Engineering, 78*(3), 897–904.

Kotwaliwale, N., Singh, K., Kalne, A., Jha, S. N., Seth, N., & Kar, A. (2011). X-ray imaging methods for internal quality evaluation of agricultural produce. *Journal of Food Science and Technology, 51*(1), 1–15.

Kranner, I., Kastberger, G., Hartbauer, M., & Pritchard, H. W. (2010). Noninvasive diagnosis of seed viability using infrared thermography. *Proceedings of the National Academy of Sciences, 107*(8), 3912–3917.

Lakshminarayana, M., Joshi, S., Gowda, G. N., & Khetrapal, C. (1992). Spatial distribution of oil in groundnut and sunflower seeds by nuclear magnetic resonance imaging. *Journal of biosciences, 17*(1), 87–93.

Laurent, B., Ousman, B., Dzudie, T., Carl, M. M., & Emmanuel, T. (2010). Digital camera images processing of hard-to-cook Beans. *Journal of Engineering and Technology Research, 2*(9), 177–188.

MagDa De oLiveira, L. (2010). Radiographic analysis in castor bean seeds (*Ricinus communis* L.). *Revista Brasileira de Sementes, 32*(1), 170–175.

Manickavasagan, A., Jayas, D., & White, N. (2008a). Thermal imaging to detect infestation by *Cryptolestes ferrugineus* inside wheat kernels. *Journal of Stored Products Research, 44*(2), 186–192.

Manickavasagan, A., Jayas, D., White, N., & Paliwal, J. (2008b). Wheat class identification using thermal imaging: a potential innovative technique. *Transactions of the ASABE, 51*(2), 649–651.

Manickavasagan, A., Jayas, D., White, N., & Paliwal, J. (2010). Wheat class identification using thermal imaging. *Food and Bioprocess Technology, 3*(3), 450–460.

Mattana, E., Grillo, O., Venora, G., & Bacchetta, G. (2008). Germplasm image analysis of *Astragalus maritimus* and *A. verrucosus* (subgen. *Trimeniaeus, Fabaceae*). *Anales del Jardín Botánico de Madrid, 65*(1), 149–155.

McDonald, M., Evans, A., & Bennett, M. (2001). Using scanners to improve seed and seedling evaluations. *Seed Science and Technology, 29*(3), 683–689.

Melkus, G., Rolletschek, H., Radchuk, R., Fuchs, J., Rutten, T., Wobus, U., et al. (2009). The metabolic role of the legume endosperm: a noninvasive imaging study. *Plant Physiology, 151*(3), 1139–1154.

Milner, M., Lee, M. R., & Katz, R. (1952). Radiography applied to grain and seeds. *Food Technology, 6*(2), 44–45.

Monteiro, S. T., Minekawa, Y., Kosugi, Y., Akazawa, T., & Oda, K. (2007). Prediction of sweetness and amino acid content in soybean crops from hyperspectral imagery. *ISPRS Journal of Photogrammetry and Remote Sensing, 62*(1), 2–12.

Najafabadi, S. S. M., & Farahani, L. (2012). Shape analysis of common bean (*Phaseolus vulgaris* L.) seeds using image analysis. *International Research Journal of Applied and Basic Sciences, 3*(8), 1619–1623.

Narendra, V., & Hareesh, K. (2010). Prospects of computer vision automated grading and sorting systems in agricultural and food products for quality evaluation. *International Journal of Computer Applications, 1*(4), 1–9.

Neethirajan, S., Karunakaran, C., Jayas, D., & White, N. (2007). Detection techniques for stored-product insects in grain. *Food Control, 18*(2), 157–162.

Ousman, B. (2013). Nondestructive Determination of beans water absorption capacity using CFA images analysis for hard-to-Cook evaluation. *International Journal of Electrical and Computer Engineering (IJECE), 3*(3), 317–328.

Paulsen, M., Wigger, W., Litchfield, J., & Sinclair, J. (1989). Computer image analyses for detection of maize and soybean kernel quality factors. *Journal of Agricultural Engineering Research, 43*(May–August), 93–101.

Pinto, T., Cicero, S., Franca-Neto, J., & Forti, V. (2009). An assessment of mechanical and stink bug damage in soybean seed using X-ray analysis test. *Seed Science and Technology, 37*(1), 110–120.

Pinto, T. L. F., Mondo, V. H. V., Gomes-Junior, F. G., & Cicero, S. M. (2012). Image analysis for evaluating mechanical damages in soybean seeds. *Pesquisa Agropecuária Tropical, 42*(3), 310–316.

Ramakrishnan, N., Babu, B. S., & Babu, T. R. (2012). Standardization of X-ray radiography methodology for the detection of hidden infestation in pulses*. *Indian Journal of Plant Protection, 40*(1), 12–18.

Sabins, F. F. (1999). Remote sensing for mineral exploration. *Ore Geology Reviews, 14*(3), 157–183.

Sakai, N., & Yonekawa, S. (1992). Three-dimensional image analysis of the shape of soybean seed. *Journal of Food Engineering, 15*(3), 221–234.

Shahin, M. A., & Symons, S. J. (2001a). A machine vision system for grading lentils. *Canadian Biosystems Engineering, 43*, 7.7–7.14.

Shahin, M. A., & Symons, S. J. (2001b). *Lentil seed size distribution with machine vision*. Paper presented at the ASAE Annual International Meeting, Sacramento.
Shahin, M. A., & Symons, S. J. (2003a). Color calibration of scanners for scanner-independent grain grading. *Cereal Chemistry, 80*(3), 285–289.
Shahin, M. A., & Symons, S. J. (2003b). Lentil type identification using machine vision. *Canadian Biosystems Engineering, 45*, 3.5–3.11.
Shahin, M. A., & Symons, S. J. (2005). Seed sizing from images of non-singulated grain samples. *Canadian Biosystems Engineering, 47*(3), 49–55.
Shahin, M. A., Symons, S. J., Annie, X., & Meng, M. (2004). *Seed sizing with image analysis*. Paper presented at the ASAE Annual International Meeting-Biological Cybernetics, Ottawa. ASAE Annual Meeting retrieved from.
Shahin, M. A., Symons, S. J., & Poysa, V. W. (2006). Determining soya bean seed size uniformity with image analysis. *Biosystems Engineering, 94*(2), 191–198.
Shahin, M. A., Symons, S. J., Schepdael, L., & Tahir, A. (2006). *Three dimensional seed shape and size measurement with orthogonal cameras*. Paper presented at the Annual International Meeting of the American Society of Agricultural and Biological Engineers.
Shahin, M. A., Symons, S. J., & Wang, N. (2012). Predicting dehulling efficiency of lentils based on seed size and shape characteristics measured with image analysis. *Quality Assurance and Safety of Crops & Foods, 4*(1), 9–16.
Singh, N. I., & Chauhan, J. (2010). Quality prediction of carry-over soybean seed. *Researcher, 2*(3), 66–69.
Singh, C. B., Jayas, D. S., Paliwal, J., & White, N. D. G. (2009). Detection of insect-damaged wheat kernels using near-infrared hyperspectral imaging. *Journal of Stored Products Research, 45*(3), 151–158.
Singh, C. B., Jayas, D. S., Paliwal, J., & White, N. D. G. (2010). Identification of insect-damaged wheat kernels using short-wave near-infrared hyperspectral and digital colour imaging. *Computers and Electronics in Agriculture, 73*(2), 118–125.
Smail, V. W., Fritz, A. K., & Wetzel, D. L. (2006). Chemical imaging of intact seeds with NIR focal plane array assists plant breeding. *Vibrational Spectroscopy, 42*(2), 215–221.
Smykalova, I., Grillo, O., Bjelkova, M., Hybl, M., & Venora, G. (2011). Morpho-colorimetric traits of *Pisum* seeds measured by an image analysis system. *Seed Science and Technology, 39*(3), 612–626.
Sun, D.-W. (2004). Computer vision––an objective, rapid and non-contact quality evaluation tool for the food industry. *Journal of Food Engineering, 61*(1), 1–2.
Tiwari, R. K. (2012). *Soybeans grading and marking rules* (Subsection(i) vide notification number G.S.R. 41(E)). Gazette of India, Extraordinary.
Uno, Y., Prasher, S., Lacroix, R., Goel, P., Karimi, Y., Viau, A., et al. (2005). Artificial neural networks to predict corn yield from Compact Airborne Spectrographic Imager data. *Computers and Electronics in Agriculture, 47*(2), 149–161.
Vadivambal, R., & Jayas, D. S. (2011). Applications of thermal imaging in agriculture and food industry—a review. *Food and Bioprocess Technology, 4*(2), 186–199.
Vance, C. P. (2001). Symbiotic nitrogen fixation and phosphorus acquisition. Plant nutrition in a world of declining renewable resources. *Plant Physiology, 127*(2), 390–397.
Van der Meer, F., & de Jong, S. M. (2001)*Imaging spectrometry: Basic principles and prospective applications, Vol. 4*. Springer.
Venora, G., Grillo, O., Ravalli, C., & Cremonini, R. (2007). Tuscany beans landraces, on-line identification from seeds inspection by image analysis and linear discriminant analysis. *Agrochimica, 51*(4–5), 254–268.
Venora, G., Grillo, O., Ravalli, C., & Cremonini, R. (2009). Identification of Italian landraces of bean (*Phaseolus vulgaris* L.) using an image analysis system. *Scientia Horticulturae, 121*(4), 410–418.
Venora, G., Grillo, O., Shahin, M., & Symons, S. (2007). Identification of Sicilian landraces and Canadian cultivars of lentil using an image analysis system. *Food Research International, 40*(1), 161–166.
Vinogradova, I., & Falaleev, O. (2012). Formation of the vascular system of developing bean (*Phaseolus limensis* L.) seeds according to nuclear magnetic resonance microtomography. *Russian Journal of Developmental Biology, 43*(1), 25–34.
Wojtyla, L., Garnczarska, M., Zalewski, T., Bednarski, W., Ratajczak, L., & Jurga, S. (2006). A comparative study of water distribution, free radical production and activation of antioxidative metabolism in germinating pea seeds. *Journal of plant physiology, 163*(12), 1207–1220.
Wong, W. K., Tan, P. N., Loo, C. K., & Lim, W. S. (3–5 April 2009). *An effective surveillance system using thermal camera*. Paper presented at the International Conference on Signal Acquisition and Processing (ICSAP) Kuala Lumpur.
Wood, K., Gulian, A., Fritz, G., & VanVechten, D. (2002). A QVD detector for focal plane hyperspectral imaging in astronomy. *Bulletin of the American Astronomical Society, 34*, 1241, (201st AAS Meeting, #82.14).
Xingwei, H., Xianchang, T., & Jianchun, W. (1999). *The comparison of five determination methods for hidden insect infestation*. Paper presented at the Stored Product Protection: Proceedings of the 7th International Working Conference on Stored-product Protection" Chengdu, China.
Zhang, L., & McCarthy, M. J. (2013). NMR study of hydration of navy bean during cooking. *LWT-Food Science and Technology, 53*(2), 402–408.