Available online at www.sciencedirect.com

SCIENCE DIRECT®

Computers and Electronics in Agriculture 53 (2006) 71–78

Computers and electronics in agriculture

www.elsevier.com/locate/compag

Classification of vitreousness in durum wheat using soft X-rays and transmitted light images

S. Neethirajan[a], C. Karunakaran[b,1], S. Symons[c], D.S. Jayas[d,*]

[a] *Department of Biosystems Engineering, University of Manitoba, Winnipeg, MB, Canada R3T 2N2*
[b] *Department of Biosystems Engineering, University of Manitoba, Winnipeg, MB, Canada R3T 2N2*
[c] *Image Analysis Grain Research Laboratory, Canadian Grain Commission, Winnipeg, MB, Cannada R3C 3G8*
[d] *Distinguished Professor, and Canada Research Chair in Stored-Grain Ecosystems, University of Manitoba, Winnipeg, MB, Canada R3T 2N2*

Received 29 December 2005; accepted 13 April 2006

Abstract

Hardness is a kernel characteristic that influences both milling and processing characteristics of wheat. It is one characteristic that is used for segregating wheat to meet the needs for various products. Kernel virteousness is a visual marker for hardness and is the characteristic assessed during the grading process. The potential of classifying vitreous and non-vitreous durum wheat kernels, in crease-down position, using imaging systems based on real time soft X-rays or transmitted light was assessed in this study. Durum wheat kernels at 14, 15 and 16% moisture contents were used as samples in this study. Image features modeling gray level distribution, textural and shape moments were measured and used to develop a classification system for vitreous and non-vitreous durum wheat kernels. The classification accuracies were 76% for vitreous kernels and 82% for non-vitreous kernels at 16% moisture content using the soft X-ray system but for the transmitted light system, the classification accuracies were 86% for vitreous and 93% for non-vitreous kernels. Moisture content had no effect on classifying vitreous or non-vitreous kernels by the transmitted light system but the classification accuracies increased with moisture content for non-vitreous kernels by the soft X-ray system.

Keywords: Vitreous kernels; Non-vitreous kernels; Soft X-ray images; Transmitted light images; Image analysis

1. Introduction

Wheat is the dominant grain of world commerce and a staple food of millions of people. Annual global wheat production was about 624 million tonnes in the year 2004 (Food Outlook, 2005). Kernel hardness is one of the most important factors in determining the functionality of wheat. Hardness is a characteristic often used in the milling industry to identify wheat varieties according to the desirability for milling and bread making properties. Wheat kernel hardness is also related to protein content and the flour water absorption factor (Dexter et al., 1989).

Durum wheat has a very hard endosperm that fragments into large chunks during milling. These endosperm chunks are sized in the mill to produce semolina or couscous, depending upon size. Non-vitreous durum wheat kernels give a higher yield of flour in comparison to semolina during milling. This is undesirable, since flour is a low value

* Corresponding author. Tel.: +1 204 474 6860; fax: +1 204 474 7568.
E-mail address: digvir_jayas@umanitoba.ca (D.S. Jayas).
1 Present address: Canadian Light Source Inc., University of Saskatchewan, 101 Perimeter Road, SK, Canada S7N 0X4.

0168-1699/$ – see front matter
doi:10.1016/j.compag.2006.03.001

by-product in this process. Vitreous kernels are glassy and translucent in appearance while non-vitreous kernels are starchy or may have chalky spots. Presently, wheat is graded visually for vitreous kernel content by inspectors. This method is somewhat subjective and it can be time consuming and tedious. The other commonly used methods for determining wheat hardness are particle size index test and near-infrared reflectance method (AACC, 2003). These standard techniques for classifying wheat hardness are preferred in a processing environment where a laboratory facility is available. They are also destructive, i.e., they require grinding or crushing of wheat samples. A single-kernel characterization system (SKCS) was developed by Martin et al. (1993) to determine wheat hardness by crushing individual kernels and using algorithms based on the force-deformation profile values. However, the SKCS instrument data are inaccurately influenced by kernel moisture content and kernel size (Gaines et al., 1996). There is a need for a measurement technique that is objective, non-destructive, rapid and accurate.

Dobraszczyk et al. (2002) used compression, indentation and wedge fracture methods to prove that the soft durum wheat kernels have broader mean distribution of densities compared to narrower mean densities of hard durum wheat. Glenn and Saunders (1990) demonstrated that intracellular space exists around the starch granules of soft, but not hard wheat, forming a discontinuity in the starch-protein mix. Hard vitreous kernels appear as translucent due to compact internal structure while the starchy non-vitreous kernels are opaque (Dexter et al., 1989).

Symons et al. (2003) used transmitted light images for classifying non-vitreous kernels from vitreous kernels. They concluded that the machine vision based transmitted light system is a fast and accurate procedure to segregate top grades of durum wheat of diverse origin. Xie et al. (2004) used reflectance and transmittance light images to determine vitreousness in durum wheat and concluded that using both the images improves the classification accuracy. Techniques such as X-ray, magnetic resonance imaging (MRI) and near-infrared imaging (NIR) have been explored to determine quality based on indicators not visible on the surface of the product (Chen and Sun, 1991). In recent years, X-ray based systems have increasingly been used effectively as a research tool for the detection of internal defects in agricultural products. X-ray imaging has been successfully applied in detecting insects in wheat and quality evaluation of almonds (Karunakaran et al., 2004; Kim and Schatzki, 2001).

The physical discontinuity of protein in the non-vitreous wheat kernel, and the difference in distribution of densities between the non-vitreous and vitreous wheat kernels can be used in the soft X-ray image analysis to identify the kernel types. When an object is subjected to X-ray imaging, the X-rays interact with matter and an exponential decrease in the total energy of the X-ray beam occurs as it traverses through the object. This phenomenon is called attenuation (Curry et al., 1990). The non-vitreous wheat kernel is expected to have a different attenuation coefficient than the vitreous kernel.

Since the vitreous kernels are hard, glassy and translucent and the non-vitreous kernels are soft, starchy and opaque, the ability to transmit or reflect light must be different for the vitreous and non-vitreous kernels. This principle can be used in the transmitted light image analysis for classifying vitreous from the non-vitreous kernels.

The objectives of this research were:

- to determine the potential of the soft X-ray and the transmitted light systems to classify vitreous and non-vitreous durum wheat kernels,
- to determine the classification percentages of vitreous and non-vitreous durum wheat kernels from the X-ray images and the transmitted light images using statistical classifiers, and
- to compare the efficiency of the soft X-ray and transmitted light systems in identifying wheat hardness.

2. Materials and methods

2.1. Sample preparation

Durum wheat kernel (*Triticum turgidum L. var. durum*) samples collected from terminal elevators at Moose Jaw and Thunder Bay in Canada were used in this study (Fig. 1). The samples collected were of the same grade and were mixed prior to being separated into three sets and conditioned to 14, 15 and 16% moisture contents (wet basis) from initial moisture content of 10%. Kernels were manually separated into vitreous and non-vitreous sets based upon a visual assessment. Care was taken to avoid the weathered and bleached kernels in the sample set. A total of 9000 kernels with 3 replicates of 500 vitreous and 500 non-vitreous kernels in each set were used for this study. The same kernels were scanned using both the soft X-ray and transmitted light systems.

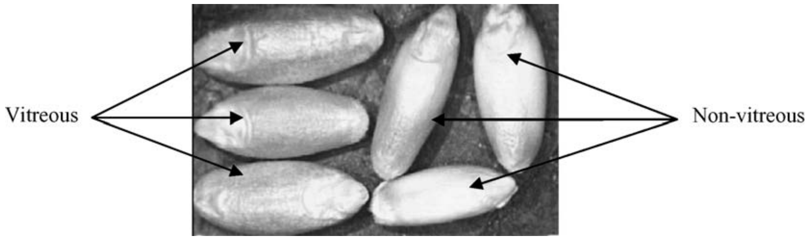

Fig. 1. Photographic image of vitreous and non-vitreous durum wheat kernels.

2.2. Image acquisition

X-ray images of wheat kernels were acquired using a Lixi fluoroscope that has 62.5 μm resolution detection screen (Model: LX-85708, Lixi Inc., Downers Grove, IL). A preliminary analysis of X-ray images for classification of vitreous kernels in durum wheat showed that 17 kV potential provided a balance of contrast between vitreous and non-vitreous kernels with a reasonable quality of image at 65 μA current. Therefore, wheat kernels were placed manually, crease down, on Saran Wrap on the sample platform and single kernels were X-rayed at 17 kV potential and 65 μA current for 3–5 s. The X-ray images of wheat kernels were digitized into 8-bit gray scale images at a resolution of 60 pixels mm^{-1}.

Transmitted light images of wheat kernels, placed crease down, were captured using a NC-70× Camera (Dage-MTI, Michigan, IN) fitted with a 60 mm macro lens (Carl Zeiss, Germany). The camera and lens were mounted on an Illuma light table (Bencher, Wood Dale, IL) to capture the trans-illuminated kernel images. The intensity of the substage lamp (600 W) was controlled through a vario-stat and the 120 V power supply with a constant voltage transformer. Baffles in the light table allowed only the light reflected from the sides of the lamp chamber to impinge on the kernels. Sets of 35 kernels were imaged from a surface of 9 cm × 10 cm. The transmitted light images of wheat kernels were digitized into 8-bit gray scale images at 85 μm resolution.

2.3. Feature extraction and classification

2.3.1. X-ray image analysis

A simple thresholding procedure was used to segment wheat kernels from the background (Saran Wrap). The normalized histogram obtained for each kernel was grouped into 50 bins, i.e equal width of 5 gray scale units. Other features extracted were: kernel area (Σ pixels), total gray value (Σ gray values in kernel), mean gray value (Σ gray values/Σ pixels), inverted gray value, and standard deviation of the gray levels.

X-ray images of 9 sets of 500 hard kernels were grouped into a ‘Vitreous’ class and 9 sets of 500 starchy soft kernels were grouped into a ‘Non-Vitreous’ class at three different moisture contents (14, 15 and 16%) for classification purposes. The 55 extracted features were used to identify vitreous and non-vitreous wheat kernels using statistical classifiers. The cross validation and hold-out methods of the parametric (linear function) and non-parametric classifiers using the DISCRIM procedure were used for classification (SAS, 2000).

Classification accuracies were determined by randomly selecting the training and testing sets three times. One-fourth of the sample was used as training and remaining three-fourth as the independent test sets and the average of the three trials was calculated as the mean classification accuracy. The significant differences between the histogram group values of different classes were determined using the Duncan’s multiple range test at 5% significance level (SAS, 2000).

2.3.2. Transmitted light image analysis

The KS400 imaging software package (Carl Zeiss Vision GmbH, Hallergmoos, Germany) was used for the analysis of transmitted light images of wheat kernels. Densitometric and textural features (Haralick, 1979) were extracted for the wheat kernel images. The main features extracted were kernel area, skewness of gray level, kurtosis of gray level, standard deviation and mean gray values.

A total of 10 densitometric and 22 Haralick textural features were extracted for use in the classifier functions provided in KS400 to develop a linear Bayes classifier (Duda and Hart, 1973). This classifier was applied directly to all the features extracted from the image, resulting in real-time classification. Cross validation gave 95% classi-

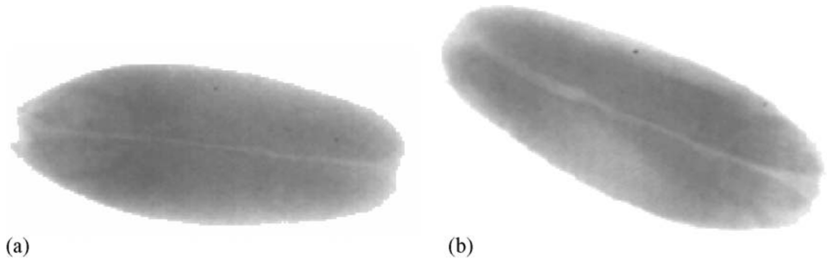

Fig. 2. X-ray images of durum wheat kernels (a) vitreous (b) non-vitreous (brighter regions indicates accumulated starch).

fication in the training data set. A training macro was designed to classify images into vitreous and non-vitreous kernels.

The morphologic, densitometric and Haralick texture features were combined together to determine the classification percentages of vitreous and non-vitreous kernels from the transmitted light images using the Bayes classifier.

3. Results and discussion

3.1. X-ray images

The X-ray images of a vitreous and a non-vitreous kernel are shown in Fig. 2. Non-vitreous regions in kernels were recorded as brighter regions in the X-ray images. Fig. 3 shows the gray level distribution from X-ray images of vitreous and non-vitreous kernels. The brighter non-vitreous regions in kernels cause a shift in gray values of the X-ray images towards numerically higher values in comparison to vitreous kernels. The means of the total gray value of the vitreous kernel class were significantly higher than for the non-vitreous kernel class, as expected due to the less starchy area represented by brighter pixels with high gray values in the non-vitreous kernels.

The normalized histogram values of vitreous and non-vitreous durum wheat kernels at 14% moisture content (m.c.) are shown in Fig. 4. The histogram group values from 135 to 165 of vitreous kernels were significantly higher than those of the non-vitreous kernels. Since the protein matrix is discontinuous in the non-vitreous kernels, the X-rays are passed through the non-vitreous kernels with less attenuation than the vitreous kernels creating brighter regions in the non-vitreous image.

Differences in the histogram values for kernels at different moisture contents can be observed when the area under the curve is viewed at 15 and 16% m.c. (Fig. 5). The mean total gray values were significantly higher for vitreous than the non-vitreous kernels for both 15% and 16% m.c. The histogram groups from 110 to 225 of vitreous kernels were significantly higher than the non-vitreous kernels (Fig. 5).

The histogram features were combined together (55 features) to determine the classification percentages of vitreous and non-vitreous kernels. The classification accuracies determined using 55 features by the quadratic-function parametric statistical classifier for all three moisture contents of the samples are shown in Table 1.

Moisture content had no effect in classifying vitreous kernels but the classification accuracies significantly increased with increasing moisture content for non-vitreous kernels. The results from this study show the potential of the soft X-ray method to differentiate vitreous and non-vitreous durum wheat kernels. Further testing for classifying vitreous and non-vitreous kernels using dual energy X-ray images by the soft X-ray system may give higher classification accuracies.

Table 1
Classification accuracies of vitreous and non-vitreous durum wheat kernels using all 55 features by the quadratic-function parametric statistical classifier from the X-ray images

Moisture content (%)	Vitreous kernel (% classification)	Non-vitreous kernel (% classification)
14	74	74
15	75	78
16	75	82

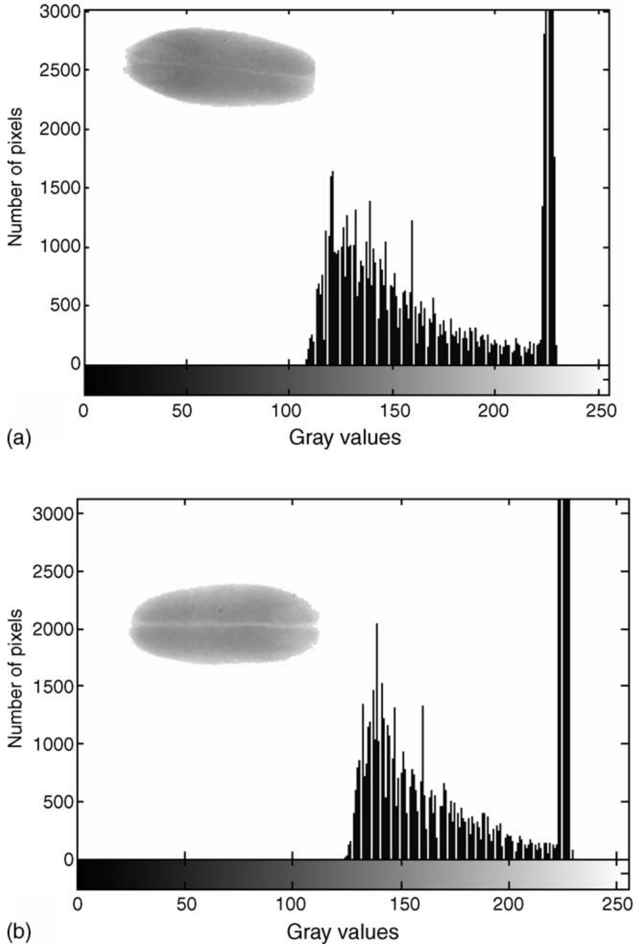

Fig. 3. Histograms of durum wheat kernel X-ray images (a) vitreous (b) non-vitreous (0 represents black and 255 represents white in the *X*–axes).

3.2. Transmitted light images

The transmitted light images of the vitreous and the non-vitreous kernels are shown in Fig. 6. Vitreous kernels allowed the transmitted light to pass through while the non-vitreous kernels absorbed more light. Therefore, the vitreous kernel images appear lighter due to higher gray values and the starchy kernel images appear darker due to the lower gray values.

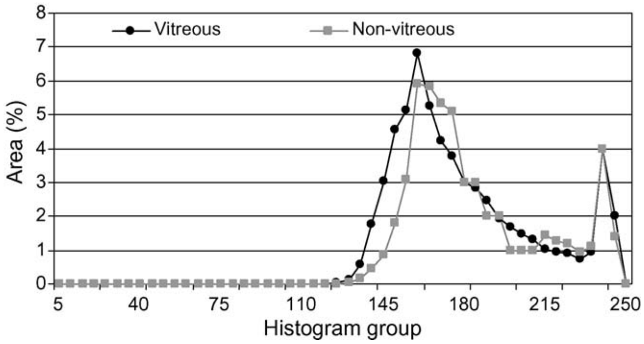

Fig. 4. Histogram of vitreous and non-vitreous durum wheat kernels at 14% moisture content.

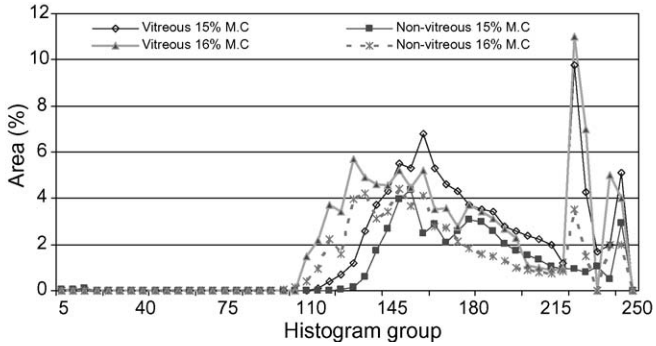

Fig. 5. Histogram of vitreous and non-vitreous durum wheat kernels at 15% and 16% moisture content.

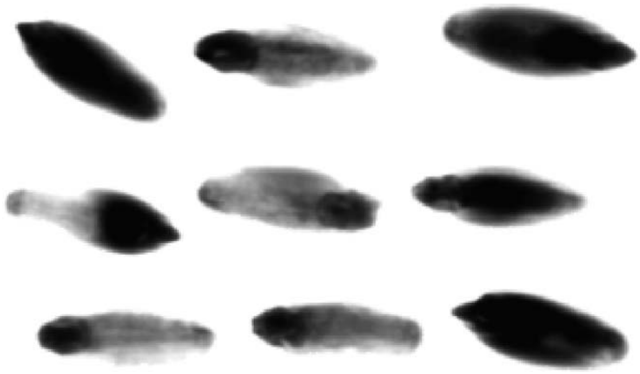

Fig. 6. Transmitted images of durum wheat kernels. Darker kernels are non-vitreous and the lighter kernels are vitreous kernels.

Table 2
Classification accuracies of vitreous and non-vitreous durum wheat kernels using all 32 features by the linear Bayesian statistical classifier from the transmitted light system images

Moisture content	Vitreous kernel (% classification)	Non-vitreous kernel (% classification)
14	84	92
15	86	93
16	86	93

Fig. 7 shows the gray level distribution of a vitreous and a non-vitreous kernel transmitted light image. Non-vitreous kernels have more optically dense regions than the translucent vitreous kernels. This results in the histogram group values of vitreous kernels being numerically higher reflecting the brighter kernels. The non-vitreous kernels tend towards numerically lower values due to their optically dense characteristics.

The classification accuracies determined using 32 features by the Bayes classifier are shown in Table 2. Moisture content had no effect in classifying vitreous or non-vitreous kernels. The results from this study show that the transmitted light system has greater potential in differentiating vitreous and non-vitreous durum wheat kernels and is moisture content independent.

4. Comparison of soft X-ray system and the transmitted light system

The classification accuracy for differentiating vitreous and non-vitreous kernels using transmitted light system is higher than the soft X-ray system. The transmitted light system is inexpensive compared to the soft X-ray system. The transmitted light system scanned multiple kernels simultaneously (35 kernels per image) in comparison to single kernel imaging by the soft X-ray system. Soft X-ray system has the potential to identify insect infestations in wheat

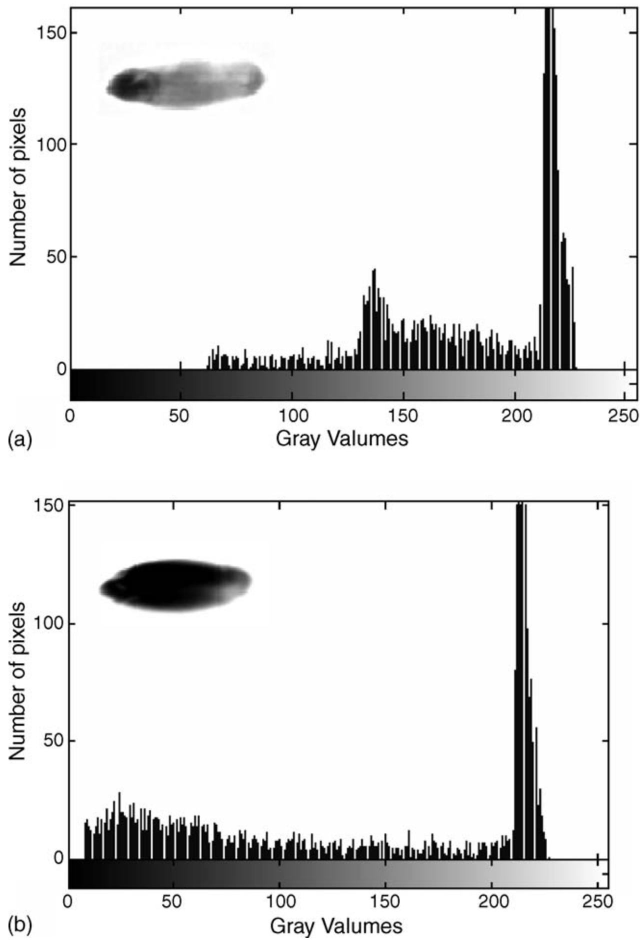

Fig. 7. Histogram of durum wheat kernel transmitted light images (a) vitreous, (b) non-vitreous. (0 represents black and 255 represents white in the *X*–axes).

(Karunakaran et al., 2004). Hence, the soft X-ray system can be effectively used at terminal elevators to classify hardness in wheat in addition to detection of insect infestation.

During scanning, kernels were oriented crease down in both the transmitted light system and in the soft X-ray system. In a transmitted light system, kernels can be randomly dropped and a high accuracy of classification can be achieved (Symons, unpublished data). With respect to soft X-ray system, future study is required to check the effect of orientation of kernels on classification during imaging. Dual energy X-ray imaging is a demonstrated technique in evaluating bone density with much more details than the conventional X-ray imaging. Future work is needed to study the classification of vitreous and non-vitreous kernels using dual energy X-ray images to enhance classification accuracy.

5. Conclusions

The soft X-ray system and the transmitted light system have the potential to classify vitreous and non-vitreous kernels in durum wheat. The quadratic-function parametric classifier correctly identified 82% of non-vitreous kernels and 75% of vitreous kernels at 16% moisture content from the soft X-ray images. The Bayesian classifier correctly classified 93% of the non-vitreous kernels and 86% of the vitreous kernels at 16% moisture content from transmitted light images. The classification accuracy for differentiating vitreous and non-vitreous kernels is higher by the transmitted light system than the soft X-ray system.

Acknowledgements

The authors gratefully thank the Canada Research Chairs Program and the Natural Sciences and Engineering Research Council of Canada for their financial support for this study. The authors also thank the Industry Services Division of the Canadian Grain Commission for providing durum wheat samples.

References

AACC, 2003. Approved Methods of the American Association of Cereal Chemists, 10 ed. American Association of Cereal Chemists, ISBN 1891127128.

Chen, P., Sun, Z., 1991. A review of non-destructive methods for quality evaluation and sorting of agricultural products. J. Agric. Eng. Res. 73 (4), 323–330.

Curry, T.S., Dowdey, J.E., Murry, R.C., 1990. Christensen's Physics of Diagnostic Radiology, vol. 4. Lippincott Williams & Wilkins, Philadelphia, USA.

Dexter, J.E., Marchylo, B.A., MacGregor, A.W., Tkachuk, R., 1989. The structure and protein composition of vitreous, piebald and starchy durum wheat kernels. J. Cereal. Sci. 10, 19–32.

Dobraszczyk, B.J., Whitworth, M.B., Vincent, J.F.V., Khan, A.A., 2002. Single kernel wheat hardness and fracture properties in relation to density and the modelling of fracture in wheat endosperm. J. Cereal. Sci. 35 (3), 245–263.

Duda, R.O., Hart, P.E. (Eds.), 1973. Pattern classification and scene analysis. Wiley & Sons, New York.

Food Outlook, 2005. Global information and early warning system on food and agriculture, FAO Corporate Document Depository, United Nations, Rome, Italy.

Gaines, C.S., Finney, P.F., Fleege, L.M., Andrews, L.C., 1996. Predicting a hardness measurement using the single-kernel characterization system. Cereal. Chem. 73 (2), 278–283.

Glenn, G.M., Saunders, R.M., 1990. Physical and structural properties of wheat endosperm associated with grain structure. Cereal. Chem. 67, 176–182.

Haralick, R.M., 1979. Statistical and structural approaches to texture. Proc. IEEE 67 (5), 786–804.

Karunakaran, C., Jayas, D.S., White, N.D.G., 2004. Identification of wheat kernels damaged by the red flour beetle using X-ray images. Biosys. Eng. 87 (3), 267–274.

Kim, S., Schatzki, T.F., 2001. Detection of pinholes in almonds through X-ray imaging. Trans. ASAE 44 (4), 997–1003.

Martin, C.R., Rousser, R., Brabec, D.L., 1993. Development of a single-kernel wheat characterization system. Trans. ASAE 36 (5), 1399–1404.

SAS, 2000. SAS User's Guide, Statistics. SAS Institute Inc., Cary, North Carolina.

Symons, S.J., Van Schepdael, L., Dexter, J.E., 2003. Measurement of hard vitreous kernels in durum wheat by machine vision. Cereal. Chem. 80 (5), 511–517.

Xie, F., Pearson, T., Dowell, F.E., Zhang, N., 2004. Detecting vitreous kernels using reflectance and transmittance image analysis. Cereal. Chem. 81 (5), 594–597.