CHARACTERIZATION OF INFLUENCE OF MOISTURE CONTENT ON MORPHOLOGICAL FEATURES OF SINGLE WHEAT KERNELS USING MACHINE VISION SYSTEM

BY

GANESAN RAMALINGAM

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Department of Biosystems Engineering
University of Manitoba
Winnipeg, Manitoba

THE UNIVERSITY OF MANITOBA

ABSTRACT

The main objective of this study was to quantify changes in physical features of western Canadian wheat kernels caused by moisture increase using a machine vision system. Single wheat kernels of eight western Canadian wheat classes were conditioned to 12, 14, 16, 18, and 20% (wet basis) moisture content, one after another, using headspaces above various concentrations of potassium hydroxide (KOH) solutions which regulated relative humidity.

A digital camera of 7.4 x 7.4 μm pixel resolution with an inter-line transfer charge-coupled device (CCD) image sensor was used to acquire images of individual kernels of all samples. A machine vision algorithm developed at the Canadian Wheat Board Centre for Grain Storage Research, University of Manitoba, was implemented to extract 49 morphological features from the wheat kernel images.

Of the 49 morphological features, 24, 11, 7, 21, 26, 11, 17, and 9 features of Canada Western Red Spring, Canada Western Amber Durum, Canada Prairie Spring White, Canada Prairie Spring Red, Canada Western Extra Strong, Canada Western Red Winter, Canada Western Hard White Spring, and Canada Western Soft White Spring wheat kernels, respectively, were significantly (α=0.05) different as the moisture content increased from 12 to 20%.

Generally the basic morphological features such as area, perimeter, major axis length, minor axis length, maximum radius, minimum radius, and mean radius were linearly increased with increase in moisture content. In all cases the moment and Fourier descriptor features decreased as moisture content increased from 12 to 20%.

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1. INTRODUCTION

Canada is the second largest exporter of wheat in the world with annual exports of 20 Mt (million tonnes) in 2006-07 (Agriculture and Agri-Food Canada, 2008). The prairie provinces on the western part of the country hold most wheat growing areas producing 95% of total Canadian wheat (CGC, 1998). Western Canadian wheat has been classified into eight milling classes namely: Canada Western Red Spring (CWRS), Canada Western Amber Durum (CWAD), Canada Western Extra Strong (CWES), Canada Western Red Winter (CWRW), Canada Western Hard White Spring (CWHWS), Canada Western Soft White Spring (CWSWS), Canada Prairie Spring Red (CPSR), and Canada Prairie Spring White (CPSW) based on their distinct quality and processing parameters. The movement of grain takes place from prairie farms to the export terminals via primary/transfer elevators using rail transport.

The quality of the wheat can be affected by physical, sanitary, and intrinsic factors of grain during field to port movement and steps must be taken to maintain the quality of grain during this movement. Physical factors include properties such as seed moisture content, bulk density, kernel size, kernel hardness; sanitary factors include factors such as fungal infection, mycotoxins, insects, mites, foreign material; and intrinsic factors include milling yield, oil content, viability, and protein content of wheat (Muir 2000). Information on each of the above parameters guides effective grain storage and transport.

Moisture content plays an important role in determining the quality of the grain as it has a direct relationship with spoilage. To control moisture content, drying and cooling are the two methods which are helpful in maintaining safe moisture contents of the grain bulk during storage. In addition, safe storage guidelines for wheat indicating suitable moisture content, temperature, and time parameters have been developed for longer storage periods. Thus maintaining moisture affects grade and the monetary value of the grain bulk.

Many technologies have been developed and implemented to ensure rapid, accurate, and safe grain handling and storage systems. Recently, machine vision technology has been explored as a modern tool for aiding human input in conducting operations such as grading, classification, and monitoring of the grain bulk. By rapid measurement and extraction of features of grain kernels, machine vision has proven its potential for use in the grain industry. Firatligil-Durmus et al. (2008) concluded that machine vision technology offers a simple and rapid methodology to estimate geometric features and engineering properties of lentil. Visen (2002) showed the ability of a machine vision system in automating classifications and assisting many grain handling operations.

The physical properties of the grain kernels are the basic criteria used by machine vision systems in identifying, classifying different wheat classes, and they are also important in designing and operating post-harvest machinery. Basically machine vision algorithms are intended to do operations based on the pre-defined measurements of the specific wheat classes. Based on this, the machine vision system can possibly classify, sort or count the grain bulk of all wheat classes. Any misrepresentation of the kernel values may lead to misclassification of the grain sample.

Since the grain kernels are hygroscopic in nature, moisture content of grain can potentially affect the physical properties of kernels. Consequently it becomes necessary to understand the possible change caused by moisture on the properties of wheat kernels to ensure accurate and efficient post-harvest operations.

A detailed literature research revealed that some studies have been done in the field of measuring the moisture-dependent characteristics of grain samples and establishing the relationship between moisture content and physical properties of grain. It was proposed to conduct a machine vision-based study to characterize the influence of moisture content on single western Canadian wheat kernels. Selection of individual kernels was made based on the fact that knowledge of these changes on single kernels would be more comprehensive than from bulk grain samples because changes in physical properties of bulk samples cannot be measured using machine vision.

2. OBJECTIVES

The objectives of this study were:

1. To quantify the changes in morphological features of individual kernels of eight milling classes of western Canadian wheat across the moisture range of 12-20% wet basis (w.b.) using a machine vision system.
2. To evaluate the significance of the influence of moisture content on morphological features of single wheat kernels using statistical tools.

3. LITERATURE REVIEW

3.1 Moisture content of grain

Moisture content of grain determines quality as well as storage life of the grain (Jayas 1995, Mills 1996). A grain kernel contains three types of water within microscopic tubules: absorbed water, adsorbed water, and bound water. Most methods of moisture content determination measure only absorbed and adsorbed water of kernels. Being hygroscopic in nature, grain kernels will absorb moisture from or give it to the surrounding environment until it equilibrates with the atmosphere (Pixton 1967).

In Canada, the grain movement takes place in the midst of variable weather conditions inside and outside storage facilities. As a result, there are many possibilities for moisture absorption/desorption by the wheat kernels. High moisture content of grain kernels naturally facilitates mould growth on the grain bulk which eventually leads to subsequent deterioration and loss. Moreover maintaining grain at optimum moisture content is critical in grain marketing (Uddin et al. 2006).

Safe storage moisture contents have been established along with suitable time and temperature guidelines by Mills and Sinha 1980 (rapeseed), Karunakaran et al. 2001 (wheat), Nithya 2008 (durum wheat), and Rajarammanna 2008 (rye). These studies provided time-temperature-moisture content combinations for safely storing these grains throughout the intended storage periods.

3.2 Grain moisture content and equilibrium relative humidity

Many studies have been conducted to explain the relationship between moisture content and equilibrium relative humidity of different grains. Oxley (1948) observed a general agreement out of previous published results that this relationship can be best represented by a rising sigmoid curve above 80% relative humidity. Pixton and Warburton (1971) presented moisture content and equilibrium relative humidity data using graphs for English wheat, barley, and some other cereal grains. Henderson (1987) developed a mean moisture content- equilibrium relative humidity relationship for nine varieties of wheat at 25°C (Table 1).

Table 1. Moisture content – Relative humidity relationship for nine wheat varieties

Relative humidity (%)	Adsorption equilibrium moisture content at 25°C read off the mean curves of nine wheat varieties (% wet basis)
50	11.5
60	13.0
70	14.7
80	16.9
85	18.6
90	21.0

Source: Henderson (1987)

The effect of change in temperature on the moisture content/relative humidity equilibrium relationship of Manitoba wheat was studied by Pixton (1968). The study concluded that temperature effect was greatest at low moisture contents. However, Pixton and Warburton (1971) stated that the effect of temperature could be ignored for many purposes unless there are extreme ranges of temperatures.

3.3 Control of humidity using saturated salt solutions

Solomon (1951) provided data on preparation methods of graded saturated salt solutions for accurate control of atmospheric relative humidity. Data for preparing graded KOH solutions with respective concentrations for controlling atmospheric humidity are given in Table 2.

Table 2. Preparation of KOH solutions with various density gradients

Relative Humidity (%, at 20^{o}C)	Wt % (g KOH per 100 g water)	Density (g/ml) at 15^{o}C
100	0	1.00
90	11.75	1.108
80	19.25	1.181
70	25.00	1.239
60	29.50	1.285
50	33.70	1.330

Source: Solomon (1951)

Winston and Bates (1960) confirmed that a closed container with anything over 1 L of saturated salt solutions was sufficient to control respective relative humidity in the headspace. They also suggested that a device should be provided for keeping the air in motion inside the container. However, Pixton and Warburton (1968) used headspaces over potassium hydroxide solutions to condition two varieties of wheat without a device for accelerating the equilibration process. They found that 90 per cent of the total moisture change of the wheat kernels, during an absorbing process, happened in 5-14 days.

3.4 Moisture dependence of grain kernel properties

Windham et al. (1993) studied the effect of wheat kernel moisture content on the hardness score (HS) by near-infrared reflectance, which is one of the physical factors used in grain quality determination. They considered four wheat classes namely hard red winter (HRW), hard red spring (HRS), soft red winter (SRW), and soft white winter (SWW). The wheat kernels were conditioned to different moisture contents inside saturated salt solutions-filled cabinets. They reported that the hardness scores, within each class of wheat, increased with increase in moisture content.

Lazaro et al. (2005) examined the effect of moisture on physical properties of sorghum and millet by conditioning to four different moisture contents ranging from 10.7 to 20% wet basis. The results revealed that linear dimensions, geometric mean diameter, sphericity, surface area, volume, kernel density, and porosity of sorghum and millet increased linearly with moisture content.

Isik and Unal (2007) examined the dependence of physical properties such as geometric mean diameter, true density, porosity, and static coefficient of friction of red kidney bean when conditioned to various moisture levels from 8.9-16.4% wet basis. Experimental studies by Altuntas and Yildiz (2007) suggested that the physical and mechanical properties such as length, width, thickness, geometric mean diameter, sphericity, thousand grains mass, and angle of repose of faba bean kernels increased as a result of moisture increase from 9 to 20.1% wet basis.

3.5 Machine vision in the grain industry

Machine vision has been widely explored as a modern tool for automating grain handling and quality inspection operations. Implementation of image analysis to characterize and identify wheat cultivars using morphological parameters by Keefe and Draper (1986) proved that machine vision can be potentially employed in the grain industry. Zayas et al. (1989) used image analysis for discriminating wheat and non-wheat components in grain samples which emphasized the capability of machine vision systems in solving a variety of problems in the grain industry.

Appropriate algorithms are essential to meet operational requirements of the grain handling and inspection systems that measure and extract features of grain kernels. Majumdar and Jayas (2000 a, b, c, d) developed algorithms to classify individual kernels of Canada Western Red Spring (CWRS) wheat, Canada Western Amber Durum (CWAD) wheat, barley, oats and rye based on morphological, color, and textural features of the kernels. Firatligil-Durmus et al. (2008) have developed a methodology for measuring geometrical features to analyze the size distribution of lentils. The results of their study provided increased confidence that machine vision technology can be an effective tool for determining geometrical features and engineering properties of grain kernels.

In general, machine vision algorithms for extracting grain kernel features have been developed based on mathematical models. Majumdar and Jayas (2000a) developed an algorithm capable of extracting 23 morphological features and, for instance, they calculated the perimeter, by adding Euclidean distances between all successive pairs of pixels around the circumference of the kernels. These types of measurements are made, by and large, at constant moisture content of grain kernels. However changes in moisture content (mc) of grain, may affect the working of an algorithm because of the moisture dependence of kernel morphology during a decision-making process.

Table 3. Studies on grain using machine vision technology

Objective of Study	Reference
Dockage classification for CWRS and other cereals	Nair et al. (1997)
Classification of wheat grains using statistical filters	Utku et al. (1998)
Classification of bulk grain samples	Visen et al. (2003)
Measurement of hard vitreous kernels in Durum wheat	Symons et al. (2003)
Classification of cereal grains using a flatbed scanner	Paliwal et al. (2003)
Classification and authentication of granular food products	Carter et al. (2006)

Urasa et al. (1999) demonstrated a third-order polynomial relationship that exists between moisture and pixel ratio of soybean grain kernel features. Moreover, the grain size was determined by developing an equation, and their study suggested the feasibility of using pixels to measure the volume of soybean kernels.

In addition, Tahir et al. (2001) studied the effect of moisture content on the classification accuracy when using digital image analysis, and found that moisture content had large impact when classifying bulk kernels in comparison with the individual kernels. It was suggested that use of a high resolution camera would be helpful in analyzing the individual kernels.

Shimizu et al. (2008) recently tested the feasibility of using image analysis for measuring changes in rice kernels during moisture absorbing tests and they found that both the length and width of the rice kernels increased with increase in moisture content. On the whole, the results of these studies prove that moisture content of grain can potentially affect the physical appearance and kernel morphology, which in turn can affect the grain handling properties and classification results. The studies dealing with application of machine vision for grains are summarized in Table 3.

While developing machine vision algorithms for analysis involving grain kernel features, it is important to consider the influence of moisture content on grain kernel features.

4. MATERIALS AND METHODS

4.1 Sample

One hundred individual kernels of Canada Western Red Spring (CWRS), Canada Western Amber Durum (CWAD), Canada Western Extra Strong (CWES), Canada Western Red Winter (CWRW), Canada Western Hard White Spring (CWHWS), Canada Western Soft White Spring (CWSWS), Canada Prairie Spring Red (CPSR), and Canada Prairie Spring White (CPSW) wheat were selected randomly from the composite mixture of various cultivars within each class. All the wheat samples were obtained from the Cereal Research Centre, Agriculture and Agri-Food Canada, Winnipeg. Prior to selecting the individual kernels from the respective bulk sample, all the eight wheat class samples were treated with 2% sodium hypochlorite (NaOCl) aqueous solution to prevent fungal infection, and then dried at room temperature.

4.2 Grain conditioning

Five different concentrated potassium hydroxide (KOH) solutions, more than 1 liter each in volume, were used to create different headspaces with 60, 70, 80, 85, and 90% relative humidity at 25°C (Solomon 1951), which approximately corresponded to 12, 14, 16, 18, and 20% wet mass basis moisture content of wheat kernels, respectively. The wheat kernels were conditioned from lower to higher moisture content to prevent a hysteresis effect on kernel morphology and to minimize the potential of mold growth on samples.

Equilibration period for attaining respective moisture contents was determined by measuring the mass, as well as moisture content (ASAE 2003), of 10 g samples on a daily basis until <0.01g change in mass of the samples was observed. Based on these experiments, the grain kernels required seven days to be stored in the headspace of KOH solutions to attain constant mass as well as moisture content. The grain kernels were placed individually without touching each other on a sample wire mesh holder, which was above the KOH solution stored in a plastic pail. In addition the placement of the kernel was in such a way that the kernel could be able to absorb moisture from both top and bottom surfaces.

A small fan (2.5 x 10^{-3} m^3/s airflow rate) was kept under the wire mesh inside the pail to hasten the equilibration process. The plastic pail with the KOH solution and the grain samples was closed with a tight lid and wrapped with duct tape to prevent exchange of ambient air with wheat samples. Each kernel of the samples was placed on the respective numbered space in the wire-mesh above the KOH headspace inside the pail (Figure 1). Naturally a single wheat kernel, exposing to water vapor directly, will absorb more quickly than bulk kernel samples and the air in motion will facilitate replenishing the water vapor at the respective kernel surface as fast as it is adsorbed (Babbitt 1949). A data logger (Onset Computer Corporation, Model-HoboU10, Pocasset, MA) was employed to monitor temperature and humidity inside pails. Based on this, the same 100 kernels were used for conditioning to different moisture levels by following the above procedure after each set of imaging. Thus the experimental set up helped to study the moisture effect on the same single wheat kernels.

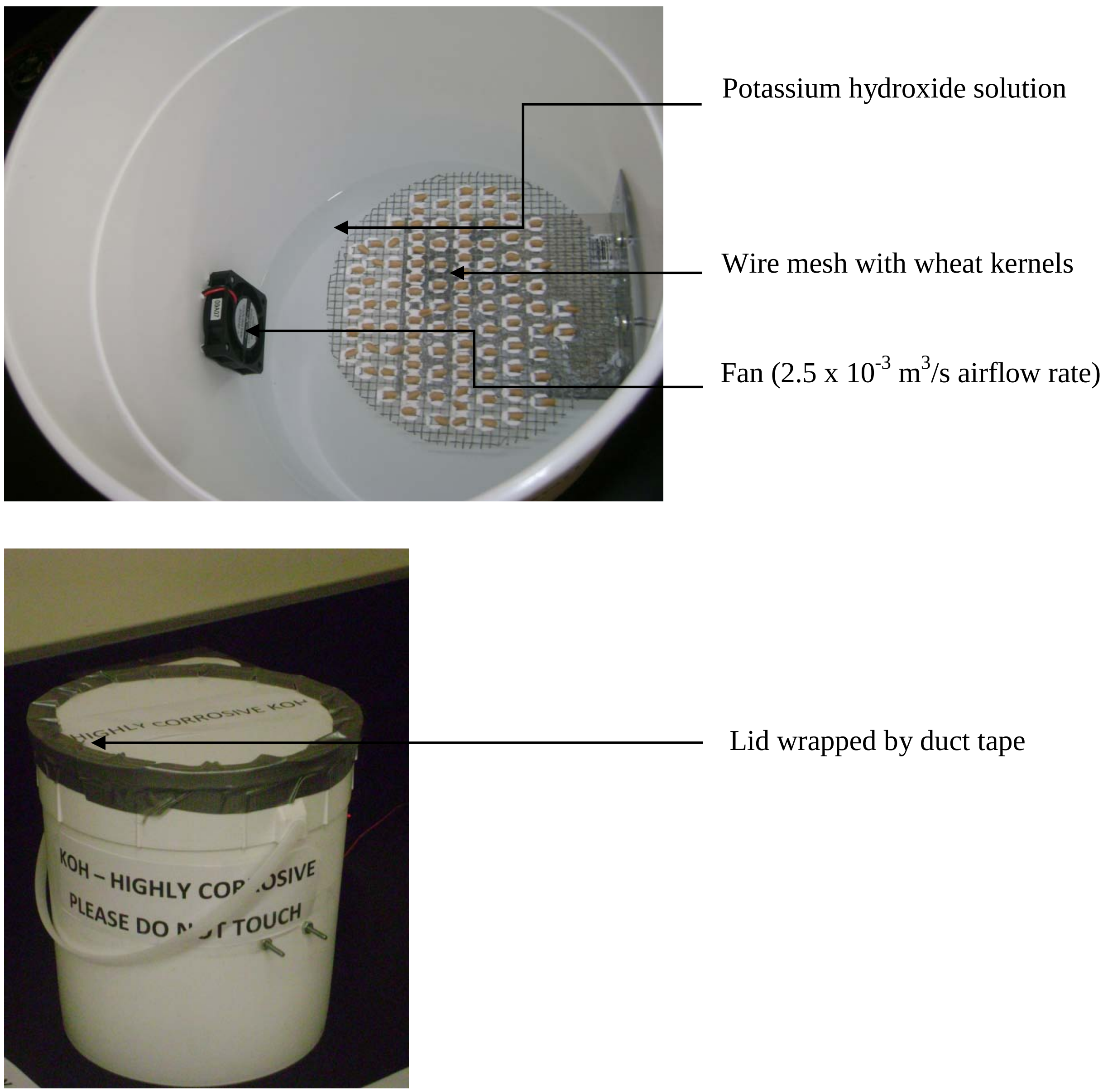
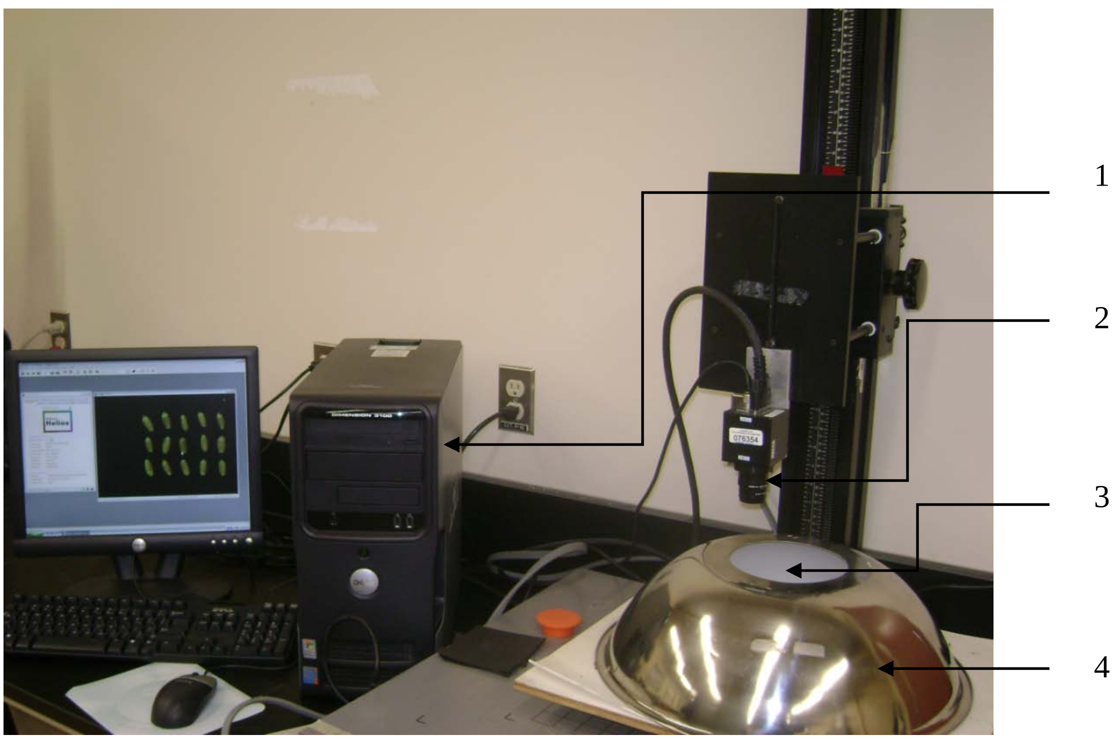


Figure 1. Grain conditioning set up

4.3 Imaging operation

A color camera of 7.4 x 7.4 µm pixel resolution (Dalsa, Model- DS-22-02M30, ON, Canada) was used. This camera used an inter-line transfer CCD image sensor to acquire images of individual kernels kept in the field of view (FOV) of the camera. A vertical copy stand (m3, Bencher Inc, Chicago, IL) was used to mount the camera over the illumination set up to fix a constant camera height from the kernels being imaged. The acquired images were stored using Helios/CL dual interface, Matrox Intellicam 8.0 (Matrox Electronic Systems Ltd, Dorval, QC) and a personal computer (Pentium IV 3.0 GHz processor). The components of machine vision system are shown in Figure 2.



1 – Processor
3 – Illumination chamber

2 - Digital camera
4 – Light diffuser

Figure 2. Machine vision system

Illumination for the images was provided by a 32 W fluorescent lamp (FC12T9, Philips Electronics Ltd, ON), and a light diffuser. The light diffuser was a dome made of steel, inside of which was painted and smoked with magnesium oxide, to uniformly illuminate the sample kernels. The power supply to the light source was controlled by a fluorescent lamp controller (Mercron Inc, Richardson, TX, USA) to ensure constant supply of voltage as well as light intensity throughout the imaging session. The lamp was switched on 30 min before imaging to make stable lighting as the lamp controller was able to stabilize the light within 0.25% of the selected light intensity.

Before imaging every sample of wheat kernels, the camera was calibrated for constant illumination settings by using a grey card. This procedure confirmed that the images of different wheat class kernels were taken under the same illumination conditions. To prevent moisture loss from kernels before imaging, samples were moved swiftly between pails and the image acquisition system. Approximately 20 min was required for each sample to be imaged. In addition, each kernel of the samples was imaged in such a way that the maximum exposure time to illumination was maintained around 2-3 min.

4.4 Feature extraction

Forty nine morphological features (Table 4) of individual kernels of all eight wheat classes were extracted using an algorithm developed at The Canadian Wheat Board Centre for Grain Storage Research group, Department of Biosystems Engineering, University of Manitoba (Visen 2002, Paliwal 2002).

Table 4. List of extracted features of single wheat kernels

Category		Features
Basic		Area, Perimeter, Maximum radius, Minimum radius, Mean radius, Major axis length, and Minor axis length
Moment		Shapemoment1 and Shapemoment2
Fourier descriptors	Radial length transform	RadialFD 1 to 20
	Perimeter coordinate transform	PeriFD 1 to 20

Information on the development of algorithm and the method of extracting 49 morphological features are given in Majumdar and Jayas (2000a), Paliwal (2002), Visen (2002), and Paliwal et al. (2003). Forty nine morphological features (Table 4) were extracted for all the 100 kernels at five moisture levels.

The algorithm determined the kernel boundary using a 4-connect technique from which area and perimeter of that kernel were calculated. The center of mass values of kernels were computed by the algorithm to determine maximum, minimum, and mean radii values of the kernels. The algorithm also calculated major and minor axis length using points on the perimeter of the wheat kernels. Shape moment and Fourier descriptor features were mainly incorporated to acquire information about shape characteristics of the wheat kernels.

4.4.1 Calibration of spatial resolution

Since the algorithm extracted all the features in pixels, the following calculation was made in order to read the values in metric units. The algorithm determined the linear dimensions of the kernel based on Euclidean distance principle where the side of a pixel and the Euclidean distance between two pixels were same (Figure 3).

Manually measured diameter (major axis length) of Canadian 25¢ coin		=24 mm
Mean value of extracted major axis length of Canadian 25¢ coin images by algorithm		=387.38 pixels
So the side of one pixel is	(24/387.38)	=0.0619 mm
		Ω 62 µm

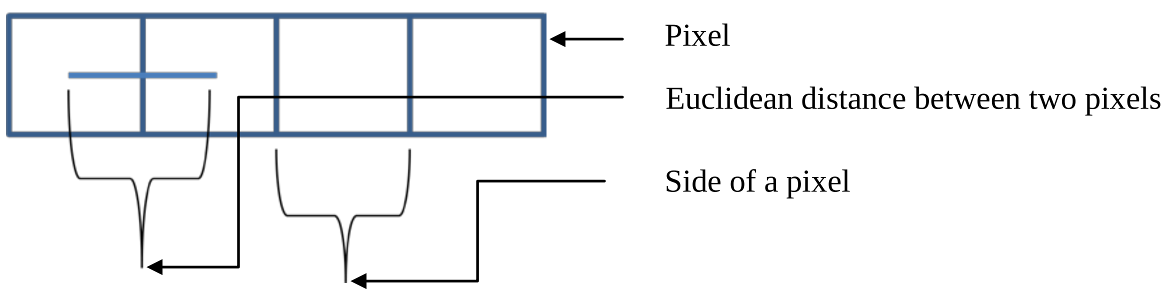


Figure 3. Spatial calibration

4.5 Data Analysis

The data of 49 morphological features of single wheat kernels of five different moisture treatments were compiled for each milling class. Significance of moisture influence was analyzed using ‘Proc Mixed’ and ‘Proc GLM’ models (SAS 9.1.3, SAS Institute Inc, NC, USA) and paired t-test results were produced by considering every kernel as a block in a randomized block design. The effects of five moisture treatments on the morphological features of every sample kernel were studied. In addition, feature measurements were predicted against different intermediate moisture levels based on the observed measurements of each feature and these findings were utilized in developing regression curves to relate moisture content with kernel morphology.

5. RESULTS AND DISCUSSION

The analysis of the morphological features by general linear models (GLM) and the mixed procedures (SAS 9.1.3) showed that 24 CWRS, 11 CWAD, 7 CPSW, 21 CPSR, 26 CWES, 11 CWRW, 17 CWHWS, and 9 CWSWS out of 49 morphological features were significantly (α=0.05) affected by the increase in moisture content from 12 to 20% wet basis. Within each milling classes, all the basic morphological features of wheat kernels were significantly increased while increasing moisture content from 12 to 20% wb.

5.1 Area

Area of all eight wheat class kernels increased with increase in moisture content (Table 5). When increasing moisture content of kernels from 12 to 14% and at 20% moisture content, the area values were significantly different, within each class, for CWRS, CWAD, CPSW, and CWHWS kernels. However, the area of CWSWS, CPSR, CWRW, and CWES wheat kernels were not significantly different during 12 to 14% moisture increase but were significantly higher at 20% mc. By and large there was no significant increase in area values between 16 and 18% moisture treatments except for CPSW and CWHWS wheat kernels. Regression curves were drawn to explain the relationship between moisture content and kernel area values of the eight milling classes of western Canadian wheat kernels. In general, the area of wheat kernels increased linearly as the moisture content increases with R^2 ranging from 0.6 to 0.8 for the eight classes (Figure D. 1 in appendix).

Table 5: Statistical grouping of mean area values of 100 kernels of eight western Canadian wheat samples at five different moisture contents (values with same letter, within each milling class, indicate that they were not significantly different at α = 0.05 using t-test).

Feature	Wheat Class	Moisture Contents					Least Significant Difference (LSD$^{\phi}$)
		12%	14%	16%	18%	20%	
Area*	CWHWS	1879.42_{a}	1922.84_{b}	1960.71_{b}	2023.45_{c}	2097.71_{d}	38.71
	CPSW	2391.99_{a}	2465.26_{b}	2521.56_{c}	2580.46_{d}	2643.78_{e}	50.98
	CWRS	1912.48_{a}	1973.78_{b}	2045.30_{c}	2058.45_{c}	2094.41_{d}	21.71
	CWAD	2304.24_{a}	2201.19_{b}	2329.58_{ac}	2353.23_{c}	2404.20_{d}	42.99
	CWRW	1849.13_{a}	1877.38_{ab}	1914.58_{b}	1914.67_{b}	1922.25_{b}	49.51
	CWES	2314.22_{a}	2361.89_{ab}	2407.08_{bc}	2463.66_{cd}	2489.62_{d}	59.38
	CPSR	2242.77_{a}	2230.08_{a}	2345.79_{b}	2364.18_{b}	2403.61_{b}	61.57
	CWSWS	2057.77_{a}	2097.44_{a}	2091.66_{a}	2081.07_{a}	2215.96_{b}	62.08

*****Area values are in pixels (1 pixel = 0.0038 mm^2); ϕLSD values are in pixels and were calculated using standard error and critical t-value

5.2 Perimeter

The perimeter of all eight western Canadian wheat samples also increased with an increase in moisture content of kernels (Table 6). Increase in moisture content from 12 to 14% resulted in significant increment, within each class, for perimeter values of CPSW, CWAD, CWRS, and CWHWS wheat samples. However CPSR, CWRW, CWES, and CWSWS kernels were not significantly different during the same moisture change. At 20% moisture content, the perimeter values of CWHWS, CPSW, CWAD, and CWSWS significantly increased from other at moisture treatment values. During mid-range moisture treatments, the perimeter had a similar trend as area values of the respective wheat samples because area and perimeter are inter-related features. The general linear increasing trend with moisture content has been shown in the appendix (Figure D. 2 in appendix).

Table 6: Statistical grouping of mean perimeter values of 100 kernels of eight western Canadian wheat samples at five different moisture contents (values with same letter, within each milling class, indicate that they were not significantly different at $\alpha = 0.05$ using t-test).

Feature	Wheat Class	Moisture Contents					Least Significant Difference (LSD$^{\phi}$)
		12%	14%	16%	18%	20%	
Perimeter*	CWHWS	174.84_{a}	176.93_{b}	178.63_{b}	182.01_{c}	185.57_{d}	1.99
	CPSW	207.30_{a}	210.25_{b}	212.13_{b}	214.67_{c}	218.53_{d}	2.39
	CWRS	183.38_{a}	186.26_{b}	188.91_{c}	189.14_{c}	191.59_{d}	1.29
	CWAD	208.250_{a}	203.48_{b}	208.736_{a}	209.307_{a}	213.109_{c}	2.41
	CWRW	178.10_{a}	178.99_{ab}	180.61_{bc}	180.99_{bc}	182.00_{c}	2.43
	CWES	207.66_{a}	209.41_{ab}	211.44_{bc}	213.91_{cd}	214.80_{d}	2.77
	CPSR	201.48_{a}	200.96_{a}	204.96_{b}	206.65_{bc}	208.31_{c}	2.82
	CWSWS	182.98_{a}	185.19_{a}	184.42_{a}	183.91_{a}	191.30_{b}	2.68

*****Perimeter values are in pixels (1 pixel = 0.062 mm); ϕLSD values are in pixels and were calculated using standard error and critical t-value

5.3 Radius and Length

The extracted axial and radial features of eight western Canadian wheat class kernels such as maximum radius, minimum radius, mean radius, major axis length, and minor axis length increased with an increase in moisture content from 12 to 20% (Tables 7 and 8). Generally there was a significant increase in the radial feature values of CWHWS, CWRW, CWAD, and CPSW wheat kernels while increasing moisture content from 12 to 14%, followed by a statistically constant feature values at 14, 16 and 18% mc, and a final significant increase at 20% mc. Minimum radius of CWRW wheat class was not significantly affected due to moisture increase where the value remained almost constant across the range of moisture contents. For CWSWS, CPSR, CWES, and CWRW wheat kernels, the radial features were not significantly different at 12 and 14% moisture treatment but were significantly different at lowest and highest moisture treatments.

Table 7: Statistical grouping of mean radius values of 100 kernels of CWHWS, CPSW, CWRS, and CWAD wheat samples at five different moisture contents (values with same letter indicate that they were not significantly different at $\alpha = 0.05$ using t-test).

Wheat Class	Feature*	Moisture Contents 12%	14%	16%	18%	20%	Least Significant Difference (LSD$^{\Phi}$)
CWHWS	MaxRad	33.89_{a}	34.3_{b}	34.58_{b}	35.13_{c}	35.70_{d}	0.40
	MeanRad	24.43_{e}	24.71_{f}	24.95_{f}	25.36_{g}	25.84_{h}	0.25
	MinRad	16.50_{i}	16.69_{ij}	16.91_{j}	17.24_{k}	17.64_{l}	0.24
CPSW	MaxRad	42.62_{a}	43.28_{b}	43.71_{c}	44.11_{d}	44.85_{e}	0.38
	MeanRad	28.18_{e}	28.62_{f}	28.91f	29.26_{g}	29.66_{h}	0.30
	MinRad	16.61_{i}	16.87_{i}	17.17_{j}	17.42_{jk}	17.55_{k}	0.28
CWRS	MaxRad	37.13_{a}	37.47_{b}	37.85_{c}	37.85_{c}	38.04_{c}	0.28
	MeanRad	25.03_{e}	25.42_{f}	25.83_{g}	25.91_{g}	26.12_{h}	0.14
	MinRad	15.09_{i}	15.45_{j}	15.97_{jk}	16.08_{kl}	16.24_{l}	0.19
CWAD	MaxRad	42.83_{a}	42.05_{b}	42.83_{a}	42.99_{a}	43.67_{c}	0.56
	MeanRad	28.00_{e}	27.40_{f}	28.13_{e}	28.24_{e}	28.62_{g}	0.28
	MinRad	15.57_{i}	15.18_{j}	15.78_{ik}	15.92_{kl}	16.08_{l}	0.25

MaxRad- Maximum Radius; MeanRad- Mean Radius; MinRad- Minimum Radius.*Radii are in pixels (1 pixel = 0.062 mm)

ϕLSD values are in pixels and were calculated using standard error and critical t-value

Table 8: Statistical grouping of mean radius values of 100 kernels of CWES, CPSR, CWSWS, and CWRW wheat samples at five different moisture contents (values with same letter indicate that they were not significantly different at α = 0.05 using t-test).

Wheat Class	Feature*	Moisture Contents					Least Significant Difference (LSD$^{\phi}$)
		12%	14%	16%	18%	20%	
CWES	MaxRad	43.19_{a}	43.40_{ab}	43.87_{bc}	44.13_{c}	44.34_{c}	0.61
	MeanRad	27.91_{e}	28.16_{ef}	28.43_{fg}	28.72_{gh}	28.87_{h}	0.35
	MinRad	16.10_{i}	16.45_{j}	16.53_{jk}	16.79_{kl}	16.98_{l}	0.29
CPSR	MaxRad	41.40_{ab}	41.20_{a}	41.90_{bc}	42.37_{c}	42.50_{c}	0.62
	MeanRad	27.30_{e}	27.21_{e}	27.85_{f}	28.00_{f}	28.21_{f}	0.37
	MinRad	15.85_{i}	15.82_{i}	16.38_{j}	16.47_{j}	16.66_{j}	0.30
CWSWS	MaxRad	36.30_{a}	36.77_{a}	36.54_{a}	36.54_{a}	37.55_{b}	0.49
	MeanRad	25.61_{e}	25.88_{e}	25.83_{e}	25.76_{e}	26.60_{f}	0.37
	MinRad	17.06_{i}	17.31_{i}	17.27_{i}	17.17_{i}	17.84_{j}	0.38
CWRW	MaxRad	35.40_{a}	35.60_{ab}	36.03_{bc}	36.08_{bc}	36.23_{c}	0.52
	MeanRad	24.49_{e}	24.66_{ef}	24.91_{fg}	24.93_{fg}	24.99_{g}	0.32

MaxRad- Maximum Radius; MeanRad- Mean Radius; MinRad- Minimum Radius. *Radii are in pixels (1 pixel = 0.062 mm)

ϕLSD values are in pixels and were calculated using standard error and critical t-value

Regarding length features of all wheat samples, the major and minor axis lengths increased as the wheat kernels absorbed moisture from the headspace of the KOH solutions. The statistical grouping for length feature was similar to radial features of the respective wheat class kernels. Regression curves showing the linear increasing relationship between the axial and radial features and moisture content are given in the appendix (Figure D.3-7). A similar increase was attained in area, radius and length dimensions of three popular varieties of Iranian wheat when they mechanically measured the effect of moisture content (Karimi et al. 2009). A linear relationship was also proven between mechanical measurements of various properties of green wheat and moisture content (Al-Mahasneh and Rababah 2007).

All the basic morphological feature values were, by and large, significantly different during initial increment on moisture content (12 to 14%) which was followed by almost statistically constant value during intermediate moisture treatments (16 and 18%) for all eight western Canadian wheat samples. This is because moisture-holding forces of a grain kernel decrease as moisture content increases (Pixton and Warburton 1968) which in turn produced statistically insignificant changes during intermediate moisture treatments on the basic morphological features such as area, perimeter, radial and axial dimensions of wheat kernels. However, further increase in moisture content to 20% established significant increment on the basic morphological features for almost all eight western wheat Canadian class samples.

Table 9: Statistical grouping of mean length values of 100 kernels of CWHWS, CPSW, CWRS, and CWAD wheat samples at five different moisture contents (values with same letter, within each milling class, indicate that they were not significantly different at α = 0.05 using t-test).

Wheat Class	Feature*	Moisture Contents					Least Significant Difference (LSD$^{\phi}$)
		12%	14%	16%	18%	20%	
CWHWS	MajAxLength	66.58_{a}	67.40_{b}	67.85_{b}	69.04_{c}	69.99_{d}	0.73
	MinAxLength	34.76_{e}	35.24_{f}	35.69_{g}	36.13_{h}	37.14_{i}	0.43
CPSW	MajAxLength	82.97_{a}	84.11_{b}	84.89_{bc}	85.82_{c}	87.24_{d}	1.07
	MinAxLength	34.97_{e}	35.56_{f}	36.15_{g}	36.59_{gh}	36.87_{h}	0.52
CWRS	MajAxLength	72.79_{a}	73.36_{b}	74.08_{c}	74.16_{c}	74.71_{d}	0.50
	MinAxLength	31.71_{e}	32.57_{f}	33.60_{g}	33.92_{gh}	34.16_{h}	0.36
CWAD	MajAxLength	83.96_{a}	82.51_{b}	84.19_{a}	84.34_{a}	85.77_{c}	1.06
	MinAxLength	33.19_{e}	32.04_{f}	33.35_{eg}	33.75_{gh}	33.91_{h}	0.49

MajAxLength – Major axis length; MinAxLength – Minor axis length; * Length measurements are in pixels (1 pixel = 0.062 mm)

ϕLSD values are in pixels and were calculated using standard error and critical t-value

Table 10: Statistical grouping of mean length values of 100 kernels of CWES, CPSR, CWSWS, and CWRW wheat samples at five different moisture contents (values with same letter, within each milling class, indicate that they were not significantly different at α = 0.05 using t-test).

Wheat Class	Feature*	Moisture Contents					Least Significant Difference (LSD$^{\phi}$)
		12%	14%	16%	18%	20%	
CWES	MajAxLength	84.08_{a}	84.55_{ab}	85.42_{bc}	85.97_{c}	86.40_{c}	1.11
	MinAxLength	33.80_{e}	34.41_{f}	34.69_{f}	35.40_{g}	35.74_{g}	0.56
CPSR	MajAxLength	80.32_{ab}	79.90_{a}	81.35_{bc}	81.95_{c}	82.34_{c}	1.17
	MinAxLength	33.64_{e}	33.57_{e}	34.80_{fg}	34.68_{f}	35.30_{g}	0.61
CWSWS	MajAxLength	71.16_{a}	71.93_{a}	71.52_{a}	71.50_{a}	73.58_{b}	0.94
	MinAxLength	36.11_{e}	36.39_{e}	36.29_{e}	36.10_{e}	37.44_{f}	0.75
CWRW	MajAxLength	69.10_{a}	69.36_{ab}	70.29_{bc}	70.25_{bc}	70.69_{c}	0.98
	MinAxLength	32.02_{e}	32.47_{ef}	32.73_{f}	32.74_{f}	32.88_{f}	0.56

MajAxLength – Major axis length; MinAxLength – Minor axis length; * Length measurements are in pixels (1 pixel = 0.062 mm)

ϕLSD values are in pixels and were calculated using standard error and critical t-value

5.4 Moment and Fourier descriptor features

In all cases of wheat kernels, the moment and Fourier descriptor features decreased as moisture content increased from 12 to 20 % and all those feature values were significantly different between 12 and 20% moisture treatments. At mid-range of moisture contents, the values were either similar to values at 12% moisture content or to values at 20% moisture content (Table 11). Moreover, the Fourier descriptor features of CPSW, CWSWS, CWAD, and CWRW were not as much affected as for the other four wheat class kernels when increasing moisture content from 12 to 20%.

The decrease in the moment and Fourier descriptor features correlated with the increase in axial and radial dimensions of the kernels, as both happened at about the same moisture levels. The lower frequency descriptors intend to acquire general shape information whereas the higher frequency descriptors give smaller/finer information about the object. From the results, it can be understood that moisture content had higher impact on the general shape features than the features intended to extract finer shape details of the wheat kernels (Table D. 1-4 in appendix).

Table 11: Statistical grouping of some moment and Fourier descriptor mean values of 100 kernels of western Canadian wheat kernels at five different moisture contents (values with same letter, within each milling class, indicate that they were not significantly different at α = 0.05 using t-test).

Wheat Class	Features*	Moisture Contents					Least Significant Difference (LSD$^{\phi}$)
		12%	14%	16%	18%	20%	
CWSWS	PeriFD 8	0.62_{a}	0.600_{ab}	0.54_{bc}	0.56_{abc}	0.53_{c}	0.0623
	RadialFD 8	0.50_{ef}	0.51_{e}	0.47_{ef}	0.46_{ef}	0.45_{f}	0.0586
CWHWS	PeriFD 3	1.24_{a}	1.19_{ab}	1.11_{b}	1.10_{b}	1.12_{b}	0.102
	RadialFD 2	15.55_{e}	15.54_{e}	15.47_{ef}	15.54_{e}	15.23_{f}	0.2608
CWRS	PeriFD 2	20.12_{a}	19.64_{b}	19.15_{c}	18.95_{c}	18.87_{c}	0.2872
	Shapemoment 2	0.020_{e}	0.019_{f}	0.018_{g}	0.017_{g}	0.017_{g}	0.0007
CWES	RadialFD 7	0.43_{a}	0.40_{a}	0.41_{a}	0.38_{ab}	0.34_{b}	0.0553
	PeriFD 3	2.03_{e}	1.95_{e}	1.92_{ef}	1.92_{ef}	1.80_{f}	0.1317
	Shapemoment 2	0.026_{i}	0.025_{j}	0.025_{j}	0.024_{k}	0.024_{k}	0.0008
CPSR	PeriFD2	20.99_{a}	20.91_{a}	20.53_{b}	20.57_{b}	20.48_{b}	0.3037
	RadialFD1	1.17_{e}	1.19_{e}	1.09_{ef}	0.96_{f}	1.00_{f}	0.1313
	Shapemoment 1	0.22_{i}	0.22_{i}	0.21_{j}	0.21_{j}	0.21_{j}	0.0019
CWAD	RadialFD 5	0.77_{ab}	0.79_{a}	0.70_{ab}	0.69_{b}	0.70_{b}	0.0901
	PeriFD 6	2.55_{ef}	2.66_{e}	2.49_{f}	2.45_{f}	2.53_{ef}	0.1397

PeriFD- perimeter coordinate transform; RadialFD – radial length transform; ϕLSD values were calculated using standard error and critical t-value

Being the most contributing parameter in machine vision-based single kernel classification, the changes in the morphological features need to be considered during grain handling operations (Tahir et al. 2007). This single kernel study demonstrated significant difference on area and perimeter features of CWRS and CWAD wheat kernels when the same kernels were conditioned to increasing moisture contents. However the effects of moisture content on area and perimeter of single CWRS and CWAD kernels were not significantly different in a study by Tahir et al. (2007) when they randomly picked kernels from different grain bulks conditioned to 12, 14, 16, 18, and 20% mc.

Regarding mould prevention, moulds will normally develop above 75% relative humidity on grain kernels during storage (Pixton and Warburton 1971). The pre-treatment of wheat kernels with NaOCl solution helped to keep wheat samples mould-free. The effect of fan on the relative humidity of the headspace was found to be negligible with this experimental set up (Figure B. 1-5).

6. CONCLUSION

The influence of moisture content on the morphological features of eight milling classes of western Canadian wheat kernels has been characterized using the machine vision algorithm. The statistical analysis demonstrated that 24 (CWRS), 11 (CWAD), 7 (CPSW), 21 (CPSR), 26 (CWES), 11 (CWRW), 17 (CWHWS), and 9 (CWSWS) morphological features were significantly (α=0.05) different as the moisture content increased from 12 to 20%.

Generally the basic morphological features such as area, perimeter, major axis length, minor axis length, maximum radius, minimum radius, and mean radius increased linearly with an increase in moisture content. In all cases the moment and Fourier descriptor features decreased as moisture content increased from 12 to 20%. Statistical grouping has been developed for the significant influence of change in moisture content from 12 to 20% on physical features of individual kernels of all eight western Canadian wheat classes.

This machine vision study reveals the significant influence of moisture content on area, perimeter, axial and radial features of single wheat kernels in the range of 12-20% wet basis regardless of their milling classes. These results would be helpful in deciding aperture size based on the moisture content of the grain bulk used in post-harvest machinery such as grain cleaning systems. It also provides a comprehensive picture on the changes in the morphological features of individual western Canadian wheat kernels due to their moisture change, which may also be useful in optimizing machine vision algorithms to deal with grains of changing moisture contents.

7. RECOMMENDATIONS FOR FUTURE WORK

- A model can be developed to express the relationship between single wheat kernel morphology and moisture content using a large number of sample kernels and a three-dimensional, high resolution machine vision system which would serve as a tool for optimizing machine vision algorithms. The given results will be useful in choosing features for this study.
- This study can be extended to other physical features such as textural and color features to characterize the influence of moisture content on single wheat kernels for Canadian western wheat classes as well as milling classes of eastern Canadian wheat.

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APPENDIX A: Equilibration Study

Table A. 1. Time required for 10 g CWRS wheat kernels to attain equilibrium with relative humidity of the headspace when using KOH solution responsible for creating 80% relative humidity.

Day	Mass of Sample 1 (g)	Mass of Sample 2 (g)	Average Mass (g)
0	10	10	10
3	10.46	10.466	10.463
6	10.504	10.509	**10.507***
9	10.505	10.511	**10.508***
11	10.504	10.509	10.507
12	10.502	10.510	10.506
13	10.503	10.511	10.507
14	10.502	10.506	10.504

* Equilibrium reached after six days

Table A. 2. Time required for 10 g CWRS wheat kernels to attain equilibrium with relative humidity of the headspace when using KOH solution responsible for creating 90% and 80% relative humidity.

Relative humidity of KOH solution	Day	Mass of Sample 1 (g)	Mass of Sample 2 (g)	Mass of Sample 3 (g)	Average Mass (g)
	0	10	10	10	10
90 %	4	10.975	10.984	10.964	*10.974*
	7	10.975	10.974	10.974	*10.975*
	0	10	10	-	10
	4	10.507	10.503	-	*10.505*
80%	5	10.499	10.504	-	*10.502*
	6	10.495	10.504	-	*10.500**

***** Mean moisture content of the sample at the end of 6^{th} day was 16.02%

APPENDIX B: Relative humidity and temperature data

Table B. 1. Mean relative humidity and temperature achieved through the KOH solution in the experiment

Weight % (g KOH/100 g of solution)	Density (g/ml) at 15° C	Achieved mean relative humidity and temperature inside pail, (%,°C)
29.50	1.285	57.0±0.3 at 25.2±0.66
25.00	1.239	65.7±0.5 at 25.7±0.3
19.25	1.181	78.4±0.7 at 25.7±0.2
15.80	1.147	83.1±0.6 at 25±0.5
11.75	1.108	88.6±0.7 at 23.0±1.7

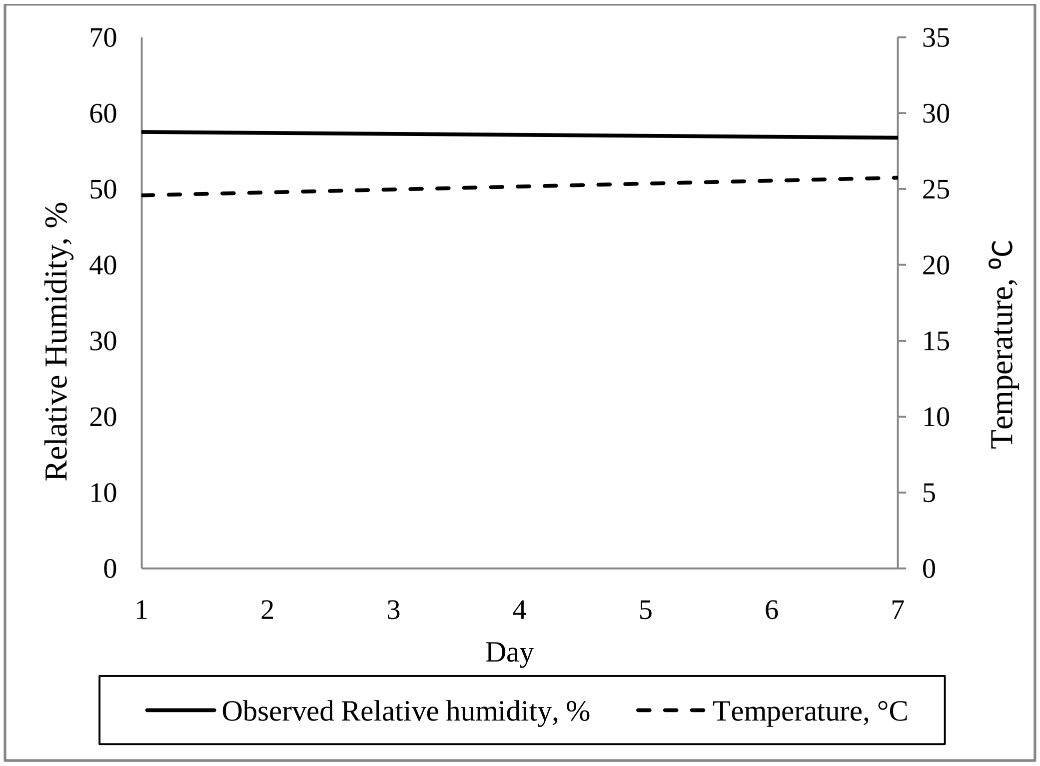


Figure B. 1. Relative humidity and temperature data of headspace above KOH solution to condition the kernels to 12% moisture content in the experimental set up.

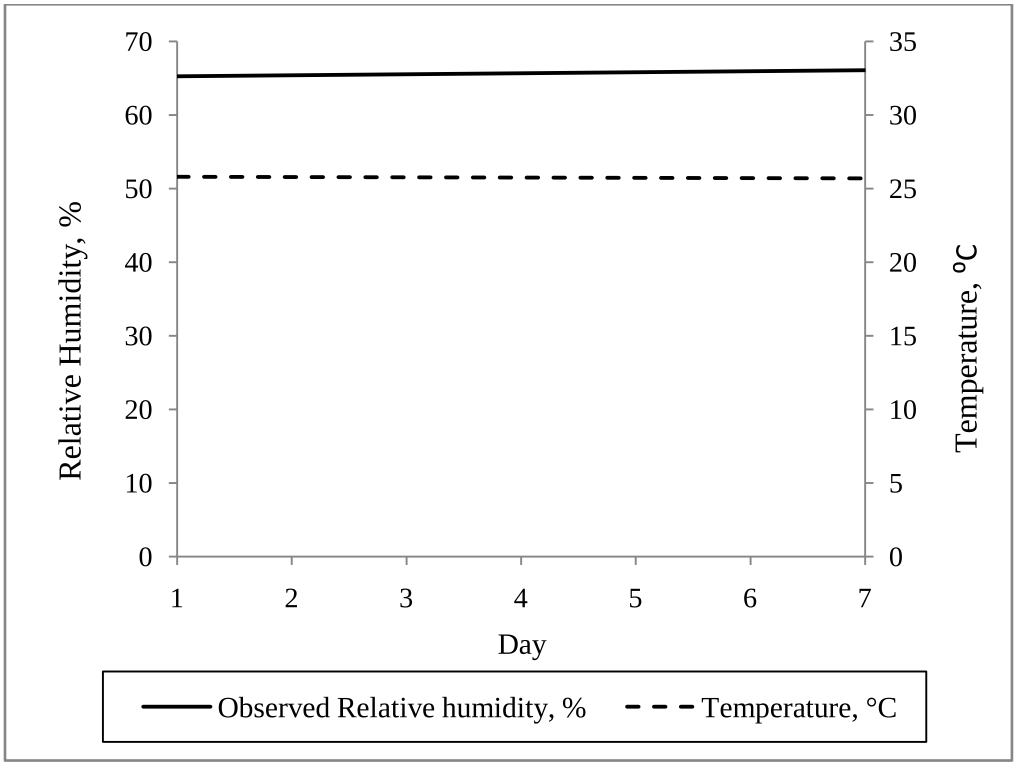


Figure B. 2. Relative humidity and temperature data of headspace above KOH solution to condition the kernels to 14% moisture content in the experimental set up.

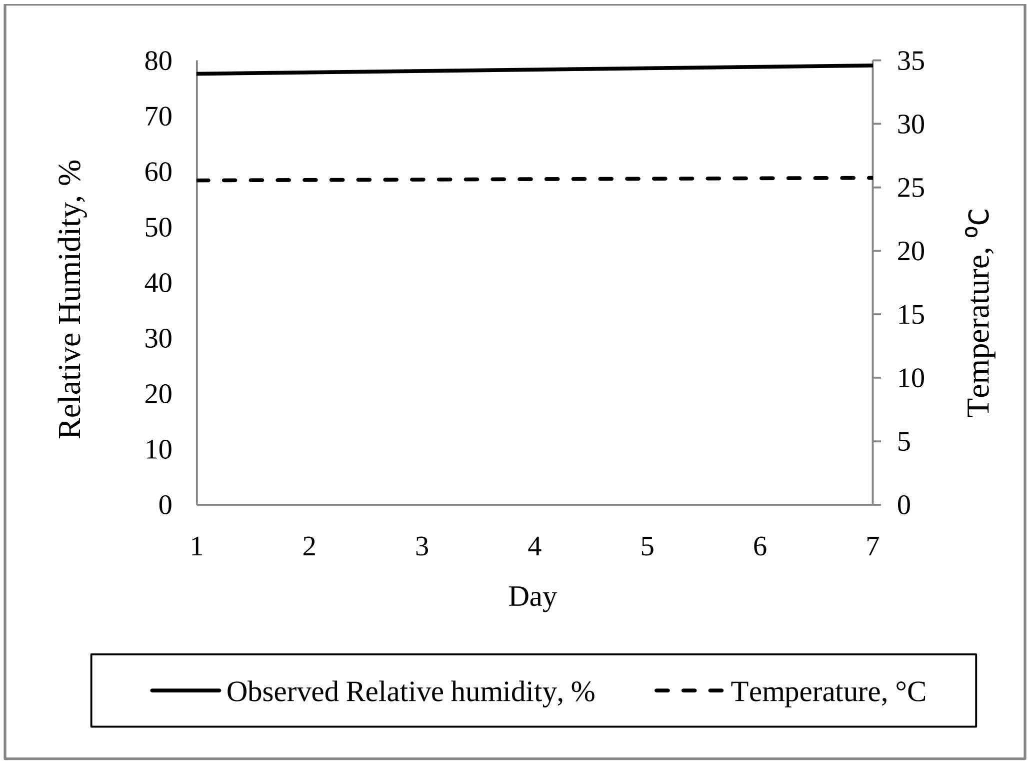


Figure B. 3. Relative humidity and temperature data of headspace above KOH solution to condition the kernels to 16% moisture content in the experimental set up.

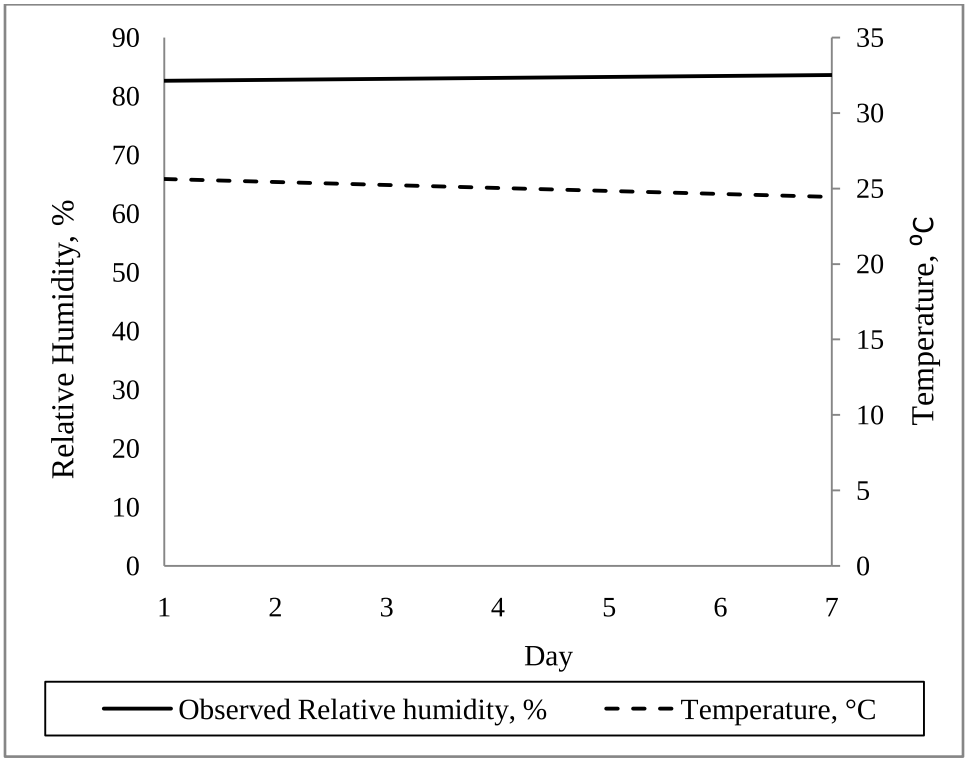


Figure B. 4. Relative humidity and temperature data of headspace above KOH solution to condition the kernels to 18% moisture content in the experimental set up.

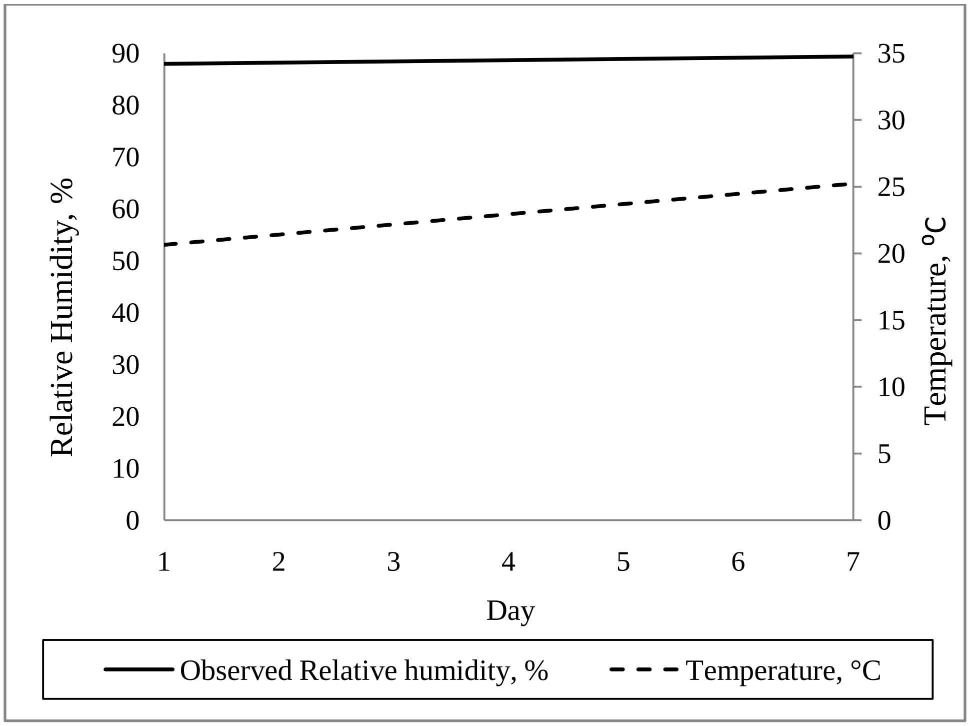


Figure B. 5. Relative humidity and temperature data of headspace above KOH solution to condition the kernels to 20% moisture content in the experimental set up.

APPENDIX C: SAS programs

C. 1. Typical SAS program for analyzing the effect of moisture content on morphological features of CWHWS wheat kernels

```
Data CWHWS;
        Input Kernel @;
                MC='12'; Input Area@; Output;
                MC='14'; Input Area@; Output;
                MC='16'; Input Area@; Output;
                MC='18'; Input Area@; Output;
                MC='20'; Input Area@; Output;
Datalines;
```

1	2088	2112	2146	2199	2271
2	2010	2047	2097	2130	2198
3	2447	2029	2057	2548	2644
4	1838	1875	2527	2060	1971
5	1878	2489	1906	1916	2060
6	1966	1916	1933	1964	2166
7	2124	2175	2227	1925	2345
8	2264	2335	1856	2276	1993
9	1791	1848	2369	2402	2482
10	1552	1593	1644	1681	2168
11	1946	2010	2033	2110	1721
12	1652	1660	1696	1745	1805
13	1755	1816	1843	1914	1963
14	1479	1913	1950	1994	2052
15	1885	1803	1856	1888	1934
16	1745	1520	1540	1591	1628
17	1851	1933	1927	2010	2055

18	1504	1443	1522	1543	1547
19	1863	1930	1962	1760	2066
20	2175	2280	1670	2072	1808
21	1627	1616	2309	2414	2497
22	1663	1617	1706	1786	1809
23	1601	1680	1723	1813	1801
24	2217	2378	2356	2464	2504
25	1983	1935	2013	2065	2120
26	1820	1853	1833	1923	1981
27	1769	1801	1880	1849	2165
28	1981	1992	2037	2096	1938
29	2234	1988	2305	2360	2461
30	1951	2276	2010	2061	2157
31	1968	2008	1897	2076	2097
32	1808	1868	2042	1953	2028
33	2088	2097	2097	2195	2294
34	2011	2041	2152	2218	2200
35	1880	1921	1966	2016	2133
36	1885	1957	1993	2029	1971
37	1722	1802	1810	1913	2085
38	1536	2069	1851	2167	2247
39	1785	1796	2097	1906	1980
40	1986	1615	1672	1688	1749
41	1814	1863	1912	2013	2072
42	1857	1888	1912	1982	2025
43	1555	1597	1609	1693	1710
44	2056	2120	2184	2273	2291

46	1961	2008	1959	2046	2012
47	1884	1684	1723	1792	2067
48	1804	2176	2054	2156	1851
49	1637	1811	1864	1966	2617
50	2037	2047	2099	2161	2265
51	2090	2110	2124	2098	2245
53	1567	1591	2081	2191	1821
54	1946	2279	1981	2206	2131
55	2260	1956	2327	2342	2462
56	2110	2108	2139	1980	2321
57	2101	2122	2140	2204	2334
58	1562	1888	1612	1974	1668
59	1871	1556	1919	1687	2076
60	1638	1694	1719	1801	1871
61	1830	1877	1916	1984	1807
62	1619	1655	1666	1703	2132
63	1591	1658	1691	1767	1812
64	1510	2093	2131	2200	2290
65	2084	1553	1864	1896	2025
66	1902	1817	1542	1600	1731
67	1789	1949	1974	2066	2113
68	2015	2032	2054	1928	2203
69	1767	1812	1840	2127	2008
70	1766	1803	1867	1913	1972
71	1649	1697	1906	1824	1855
72	1816	1856	1732	2009	2067
74	1925	2073	2032	2216	2208

75	2013	1994	2068	2001	2291
76	2040	2073	2110	2169	1907
77	2072	1775	1780	1837	2224
78	1726	2100	2128	2143	2270
79	2108	2132	2155	2213	2279
80	2064	2101	2162	2162	2226
81	2140	2161	2204	2260	2378
82	2195	2220	2227	2324	2396
83	1984	1962	2057	2266	2358
84	2104	2147	2205	2146	2239
85	1992	2027	2075	1937	2027
86	1828	1763	1883	2180	2306
87	1785	1845	1779	1997	2074
88	1886	1878	2006	1887	2178
89	1722	1946	1915	2103	1941
90	1937	1586	2032	2091	2185
91	1552	1971	1631	1699	1793
92	1838	1962	1977	2033	2176
93	1810	1774	1888	1931	2066
94	1740	1832	1823	1899	1960
95	1851	1887	1932	2010	2041
96	1809	1846	2292	1979	2090
97	2185	2232	1877	2388	2482
98	1719	1882	1812	1871	1983
100	1983	2087	2127	2207	2354

;

```
Proc GLM Data=CWHWS;

Class Moisturecontent Kernel;

Model Area = MC Kernel/Solution;

Random kernel;

Means Moisturecontent/Scheffe LSD;

Estimate 'MC 12 vs MC 14' MC 1 -1 0 0 0;

Estimate 'MC 12 vs MC 16' MC 1 0 -1 0 0;

Estimate 'MC 12 vs MC 18' MC 1 0 0 -1 0;

Estimate 'MC 12 vs MC 20' MC 1 0 0 0 -1;

Estimate 'MC 14 vs MC 16' MC0 1 -1 0 0;

Estimate 'MC 14 vs MC 18' MC 0 1 0 -1 0;

Estimate 'MC 14 vs MC 20' MC 0 1 0 0 -1;

Estimate 'MC 16 vs MC 18' MC 0 0 1 -1 0;

Estimate 'MC 16 vs MC 20' MC 0 0 1 0 -1;

Estimate 'MC 18 vs MC 20' MC 0 0 0 1 -1;

Quit;
```

OUTPUT

The GLM Procedure

Class Level Information

Class	Levels	Values
MC	5	12 14 16 18 20
Kernel	96	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 46 47 48 49 50 51 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 100

Number of Observations Read	480
Number of Observations Used	480

Dependent Variable: Area

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	99	16506856.40	166735.92	8.96	<.0001
Error	380	7069552.90	18604.09		
Corrected Total	479	23576409.30			

R-Square	Coeff Var	Root MSE	Area Mean
0.700143	6.899791	136.3968	1976.825

Source	DF	Type I SS	Mean Square	F Value	Pr > F
MC	4	2827063.90	706765.98	37.99	<.0001
Kernel	95	13679792.50	143997.82	7.74	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
MC	4	2827063.90	706765.98	37.99	<.0001
Kernel	95	13679792.50	143997.82	7.74	<.0001

Parameter		Estimate		Standard Error	t Value	Pr > |t|
Intercept		2272.483333	B	62.25633597	36.50	<.0001
MC	12	-218.291667	B	19.68718204	-11.09	<.0001
MC	14	-174.864583	B	19.68718204	-8.88	<.0001
MC	16	-137.000000	B	19.68718204	-6.96	<.0001
MC	18	-74.260417	B	19.68718204	-3.77	0.0002
MC	20	0.000000	B	.	.	.
Kernel	1	11.600000	B	86.26490959	0.13	0.8931
Kernel	2	-55.200000	B	86.26490959	-0.64	0.5226
Kernel	3	193.400000	B	86.26490959	2.24	0.0255

Kernel	4	-97.400000	B	86.26490959	-1.13	0.2596
Kernel	5	-101.800000	B	86.26490959	-1.18	0.2387
Kernel	6	-162.600000	B	86.26490959	-1.88	0.0602
Kernel	7	7.600000	B	86.26490959	0.09	0.9298
Kernel	8	-6.800000	B	86.26490959	-0.08	0.9372
Kernel	9	26.800000	B	86.26490959	0.31	0.7562
Kernel	10	-424.000000	B	86.26490959	-4.92	<.0001
Kernel	11	-187.600000	B	86.26490959	-2.17	0.0303
Kernel	12	-440.000000	B	86.26490959	-5.10	<.0001
Kernel	13	-293.400000	B	86.26490959	-3.40	0.0007
Kernel	14	-274.000000	B	86.26490959	-3.18	0.0016
Kernel	15	-278.400000	B	86.26490959	-3.23	0.0014
Kernel	16	-546.800000	B	86.26490959	-6.34	<.0001
Kernel	17	-196.400000	B	86.26490959	-2.28	0.0234
Kernel	18	-639.800000	B	86.26490959	-7.42	<.0001
Kernel	19	-235.400000	B	86.26490959	-2.73	0.0067
Kernel	20	-150.600000	B	86.26490959	-1.75	0.0817
Kernel	21	-59.000000	B	86.26490959	-0.68	0.4944
Kernel	22	-435.400000	B	86.26490959	-5.05	<.0001
Kernel	23	-428.000000	B	86.26490959	-4.96	<.0001
Kernel	24	232.200000	B	86.26490959	2.69	0.0074
Kernel	25	-128.400000	B	86.26490959	-1.49	0.1375
Kernel	26	-269.600000	B	86.26490959	-3.13	0.0019
Kernel	27	-258.800000	B	86.26490959	-3.00	0.0029
Kernel	28	-142.800000	B	86.26490959	-1.66	0.0987
Kernel	29	118.000000	B	86.26490959	1.37	0.1722

Kernel	30	-60.600000	B	86.26490959	-0.70	0.4828
Kernel	31	-142.400000	B	86.26490959	-1.65	0.0996
Kernel	32	-211.800000	B	86.26490959	-2.46	0.0145
Kernel	33	2.600000	B	86.26490959	0.03	0.9760
Kernel	34	-27.200000	B	86.26490959	-0.32	0.7527
Kernel	35	-168.400000	B	86.26490959	-1.95	0.0517
Kernel	36	-184.600000	B	86.26490959	-2.14	0.0330
Kernel	37	-285.200000	B	86.26490959	-3.31	0.0010
Kernel	38	-177.600000	B	86.26490959	-2.06	0.0402
Kernel	39	-238.800000	B	86.26490959	-2.77	0.0059
Kernel	40	-409.600000	B	86.26490959	-4.75	<.0001
Kernel	41	-216.800000	B	86.26490959	-2.51	0.0124
Kernel	42	-218.800000	B	86.26490959	-2.54	0.0116
Kernel	43	-518.800000	B	86.26490959	-6.01	<.0001
Kernel	44	33.200000	B	86.26490959	0.38	0.7006
Kernel	46	-154.400000	B	86.26490959	-1.79	0.0743
Kernel	47	-321.600000	B	86.26490959	-3.73	0.0002
Kernel	48	-143.400000	B	86.26490959	-1.66	0.0973
Kernel	49	-172.600000	B	86.26490959	-2.00	0.0461
Kernel	50	-29.800000	B	86.26490959	-0.35	0.7299
Kernel	51	-18.200000	B	86.26490959	-0.21	0.8330
Kernel	53	-301.400000	B	86.26490959	-3.49	0.0005
Kernel	54	-43.000000	B	86.26490959	-0.50	0.6184
Kernel	55	117.800000	B	86.26490959	1.37	0.1729
Kernel	56	-20.000000	B	86.26490959	-0.23	0.8168
Kernel	57	28.600000	B	86.26490959	0.33	0.7404

Kernel	58	-410.800000	B	86.26490959	-4.76	<.0001
Kernel	59	-329.800000	B	86.26490959	-3.82	0.0002
Kernel	60	-407.000000	B	86.26490959	-4.72	<.0001
Kernel	61	-268.800000	B	86.26490959	-3.12	0.0020
Kernel	62	-396.600000	B	86.26490959	-4.60	<.0001
Kernel	63	-447.800000	B	86.26490959	-5.19	<.0001
Kernel	64	-106.800000	B	86.26490959	-1.24	0.2165
Kernel	65	-267.200000	B	86.26490959	-3.10	0.0021
Kernel	66	-433.200000	B	86.26490959	-5.02	<.0001
Kernel	67	-173.400000	B	86.26490959	-2.01	0.0451
Kernel	68	-105.200000	B	86.26490959	-1.22	0.0055
Kernel	70	-287.400000	B	86.26490959	-3.33	0.0009
Kernel	71	-365.400000	B	86.26490959	-4.24	<.0001
Kernel	72	-255.600000	B	86.26490959	-2.96	0.0032
Kernel	74	-60.800000	B	86.26490959	-0.70	0.4814
Kernel	75	-78.200000	B	86.26490959	-0.91	0.3652
Kernel	76	-91.800000	B	86.26490959	-1.06	0.2879
Kernel	77	-214.000000	B	86.26490959	-2.48	0.0135
Kernel	78	-78.200000	B	86.26490959	-0.91	0.3652
Kernel	79	25.800000	B	86.26490959	0.30	0.7650
Kernel	80	-8.600000	B	86.26490959	-0.10	0.9206
Kernel	81	77.000000	B	86.26490959	0.89	0.3726
Kernel	82	120.800000	B	86.26490959	1.40	0.1622
Kernel	83	-26.200000	B	86.26490959	-0.30	0.7615
Kernel	84	16.600000	B	86.26490959	0.19	0.8475
Kernel	85	-140.000000	B	86.26490959	-1.62	0.1054

Kernel	86	-159.600000	B	86.26490959	-1.85	0.0651
Kernel	87	-255.600000	B	86.26490959	-2.96	0.0032
Kernel	88	-184.600000	B	86.26490959	-2.14	0.0330
Kernel	89	-226.200000	B	86.26490959	-2.62	0.0091
Kernel	90	-185.400000	B	86.26490959	-2.15	0.0323
Kernel	91	-422.400000	B	86.26490959	-4.90	<.0001
Kernel	92	-154.400000	B	86.26490959	-1.79	0.0743
Kernel	93	-257.800000	B	86.26490959	-2.99	0.0030
Kernel	94	-300.800000	B	86.26490959	-3.49	0.0005
Kernel	95	-207.400000	B	86.26490959	-2.40	0.0167
Kernel	96	-148.400000	B	86.26490959	-1.72	0.0862
Kernel	97	81.200000	B	86.26490959	0.94	0.3472
Kernel	98	-298.200000	B	86.26490959	-3.46	0.0006
Kernel	100	0.000000	B	.	.	.

NOTE: The X'X matrix has been found to be singular, and a generalized inverse was used to solve the normal equations. Terms whose estimates are followed by the letter 'B' are not uniquely estimable.

Source	Type III Expected Mean Square
MC	Var (Error) + Q (MC)
Kernel	Var (Error) + 5 Var (Kernel)

t Tests (LSD) for Area

NOTE: This test controls the Type I comparison wise error rate, not the experiment wise error rate. Means with the same letter are not significantly different

Alpha	0.05
Error Degrees of Freedom	380
Error Mean Square	18604.09
Critical Value of t	1.96623
Least Significant Difference	38.709

t Grouping	Mean	N	MC
A	2097.71	96	20
B	2023.45	96	18
C	1960.71	96	16
C			
C	1922.84	96	14
D	1879.42	96	12

Scheffe's Test for Area

NOTE: This test controls the Type I experiment wise error rate. Means with the same letter are not significantly different.

Alpha	0.05
Error Degrees of Freedom	380
Error Mean Square	18604.09
Critical Value of F	2.39543
Minimum Significant Difference	60.94

Scheffe Grouping		Mean	N	MC
	A	2097.71	96	20
	B	2023.45	96	18
	C	1960.71	96	16
	C			
D	C	1922.84	96	14
D				
D		1879.42	96	12

Parameter	Estimate	Standard Error	t Value	Pr > |t|
MC 12 vs MC 14	-43.427083	19.6871820	-2.21	0.0280
MC 12 vs MC 16	-81.291667	19.6871820	-4.13	<.0001
MC 12 vs MC 18	-144.031250	19.6871820	-7.32	<.0001
MC 12 vs MC 20	-218.291667	19.6871820	-11.09	<.0001
MC 14 vs MC 16	-37.864583	19.6871820	-1.92	0.0552
MC 14 vs MC 18	-100.604167	19.6871820	-5.11	<.0001
MC 14 vs MC 20	-174.864583	19.6871820	-8.88	<.0001
MC 16 vs MC 18	-62.739583	19.6871820	-3.19	0.0016
MC 16 vs MC 20	-137.000000	19.6871820	-6.96	<.0001
MC 18 vs MC 20	-74.260417	19.6871820	-3.77	0.0002

C. 2. Typical SAS program for generating regression curves by predicting area values across five different moisture treatments from the observed area values of CWHWS wheat kernels

```
Data CWHWS;
    Input Kernel @;
        MC='12'; Input Area@; Output;
        MC='14'; Input Area@; Output;
        MC='16'; Input Area@; Output;
        MC='18'; Input Area@; Output;
        MC='20'; Input Area@; Output;

Datalines;
1   2088   2112   2146   2199   2271
2   2010   2047   2097   2130   2198
3   2447   2029   2057   2548   2644
4   1838   1875   2527   2060   1971
5   1878   2489   1906   1916   2060
6   1966   1916   1933   1964   2166
7   2124   2175   2227   1925   2345
8   2264   2335   1856   2276   1993
9   1791   1848   2369   2402   2482
10  1552   1593   1644   1681   2168
11  1946   2010   2033   2110   1721
12  1652   1660   1696   1745   1805
13  1755   1816   1843   1914   1963
14  1479   1913   1950   1994   2052
15  1885   1803   1856   1888   1934
```

16	1745	1520	1540	1591	1628
17	1851	1933	1927	2010	2055
18	1504	1443	1522	1543	1547
19	1863	1930	1962	1760	2066
20	2175	2280	1670	2072	1808
21	1627	1616	2309	2414	2497
22	1663	1617	1706	1786	1809
23	1601	1680	1723	1813	1801
24	2217	2378	2356	2464	2504
25	1983	1935	2013	2065	2120
26	1820	1853	1833	1923	1981
27	1769	1801	1880	1849	2165
28	1981	1992	2037	2096	1938
29	2234	1988	2305	2360	2461
30	1951	2276	2010	2061	2157
31	1968	2008	1897	2076	2097
32	1808	1868	2042	1953	2028
33	2088	2097	2097	2195	2294
34	2011	2041	2152	2218	2200
35	1880	1921	1966	2016	2133
36	1885	1957	1993	2029	1971
37	1722	1802	1810	1913	2085
38	1536	2069	1851	2167	2247
39	1785	1796	2097	1906	1980
40	1986	1615	1672	1688	1749
41	1814	1863	1912	2013	2072
42	1857	1888	1912	1982	2025

43	1555	1597	1609	1693	1710
44	2056	2120	2184	2273	2291
46	1961	2008	1959	2046	2012
47	1884	1684	1723	1792	2067
48	1804	2176	2054	2156	1851
49	1637	1811	1864	1966	2617
50	2037	2047	2099	2161	2265
51	2090	2110	2124	2098	2245
53	1567	1591	2081	2191	1821
54	1946	2279	1981	2206	2131
55	2260	1956	2327	2342	2462
56	2110	2108	2139	1980	2321
57	2101	2122	2140	2204	2334
58	1562	1888	1612	1974	1668
59	1871	1556	1919	1687	2076
60	1638	1694	1719	1801	1871
61	1830	1877	1916	1984	1807
62	1619	1655	1666	1703	2132
63	1591	1658	1691	1767	1812
64	1510	2093	2131	2200	2290
65	2084	1553	1864	1896	2025
66	1902	1817	1542	1600	1731
67	1789	1949	1974	2066	2113
68	2015	2032	2054	1928	2203
69	1767	1812	1840	2127	2008
70	1766	1803	1867	1913	1972
71	1649	1697	1906	1824	1855

72	1816	1856	1732	2009	2067
74	1925	2073	2032	2216	2208
75	2013	1994	2068	2001	2291
76	2040	2073	2110	2169	1907
77	2072	1775	1780	1837	2224
78	1726	2100	2128	2143	2270
79	2108	2132	2155	2213	2279
80	2064	2101	2162	2162	2226
81	2140	2161	2204	2260	2378
82	2195	2220	2227	2324	2396
83	1984	1962	2057	2266	2358
84	2104	2147	2205	2146	2239
85	1992	2027	2075	1937	2027
86	1828	1763	1883	2180	2306
87	1785	1845	1779	1997	2074
88	1886	1878	2006	1887	2178
89	1722	1946	1915	2103	1941
90	1937	1586	2032	2091	2185
91	1552	1971	1631	1699	1793
92	1838	1962	1977	2033	2176
93	1810	1774	1888	1931	2066
94	1740	1832	1823	1899	1960
95	1851	1887	1932	2010	2041
96	1809	1846	2292	1979	2090
97	2185	2232	1877	2388	2482
98	1719	1882	1812	1871	1983
100	1983	2087	2127	2207	2354

;

```
Proc Mixed Data=CWHWS;

Class Kernel;

Model Area = MC;

Random kernel;

Estimate 'Intercept' Intercept 1;

Estimate 'Linear coefficient' MC 1;

Data CWHWSLine;


/*

                                   Standard

   Label                Estimate   Error       DF    t Value   Pr > |t|


   Intercept            1512.84    41.7529     95     36.23    <.0001

   Linear coefficient   28.9993    2.3744      383    12.21    <.0001


*/


 Do MC=12 to 20 by 1;

     PredArea=1512.84+28.9993*MC;

     Output;

     End;

Datalines;

Proc Plot data=CWHWSLine;

     Plot PredArea*MC;

Data CWHWS_Plus_Line;
```

```
    Set CWHWS CWHWSLine;
Datalines;
Proc Plot data=CWHWS_Plus_Line;
    Plot Area*MC='*' PArea*MC='p'/overlay;
Quit;
```

OUTPUT

The Mixed Procedure

Model Information

Data Set	WORK.CWHWS
Dependent Variable	Area
Covariance Structure	Variance Components
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Containment

Class Level Information

Class	Levels	Values
Kernel	96	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 46 47 48 49 50 51 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 100

Dimensions

Covariance Parameters	2
Columns in X	2
Columns in Z	96
Subjects	1
Max Obs per Subject	480

Number of Observations

Number of Observations Read	480
Number of Observations Used	480
Number of Observations Not Used	0

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	6476.28434814	
1	1	6264.32789249	0.00000000

Convergence criteria met.

Covariance Parameter Estimates

Cov Parm	Estimate
Kernel	25080
Residual	18597

Fit Statistics

-2 Res Log Likelihood	6264.3
AIC (smaller is better)	6268.3
AICC (smaller is better)	6268.4
BIC (smaller is better)	6273.5

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
MC	1	383	149.16	<.0001

Estimates

Label	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept	1512.84	41.7529	95	36.23	<.0001
Linear coefficient	28.9993	2.3744	383	12.21	<.0001

APPENDIX D: Data Analysis

Table D. 1. List of features of CWRS and CWAD kernels which were significantly influenced by moisture increase from 12 to 20% wet basis

Wheat Class	Basic morphological features	Moment and Fourier descriptor features
CWRS	Area, Perimeter, Maximum radius, Minimum radius, Mean radius, Major axis length and Minor axis length	Shapemoment 1, Shapemoment 2, PeriFD 2, PeriFD 3, PeriFD 4, PeriFD5, PeriFD 6, PeriFD 16, PeriFD17, PeriFD 18, PeriFD 19, PeriFD 20, RadialFD1, RadialFD 2, RadialFD 4, RadialFD5, and RadialFD 6
CWAD	Area, Perimeter, Maximum radius, Minimum radius, Mean radius, Major axis length and Minor axis length	PeriFD 3, PeriFD4, PeriFD19, and RadialFD 5

Table D. 2. List of features of CWHWS and CWSWS kernels which were significantly influenced by moisture increase from 12 to 20% wet basis

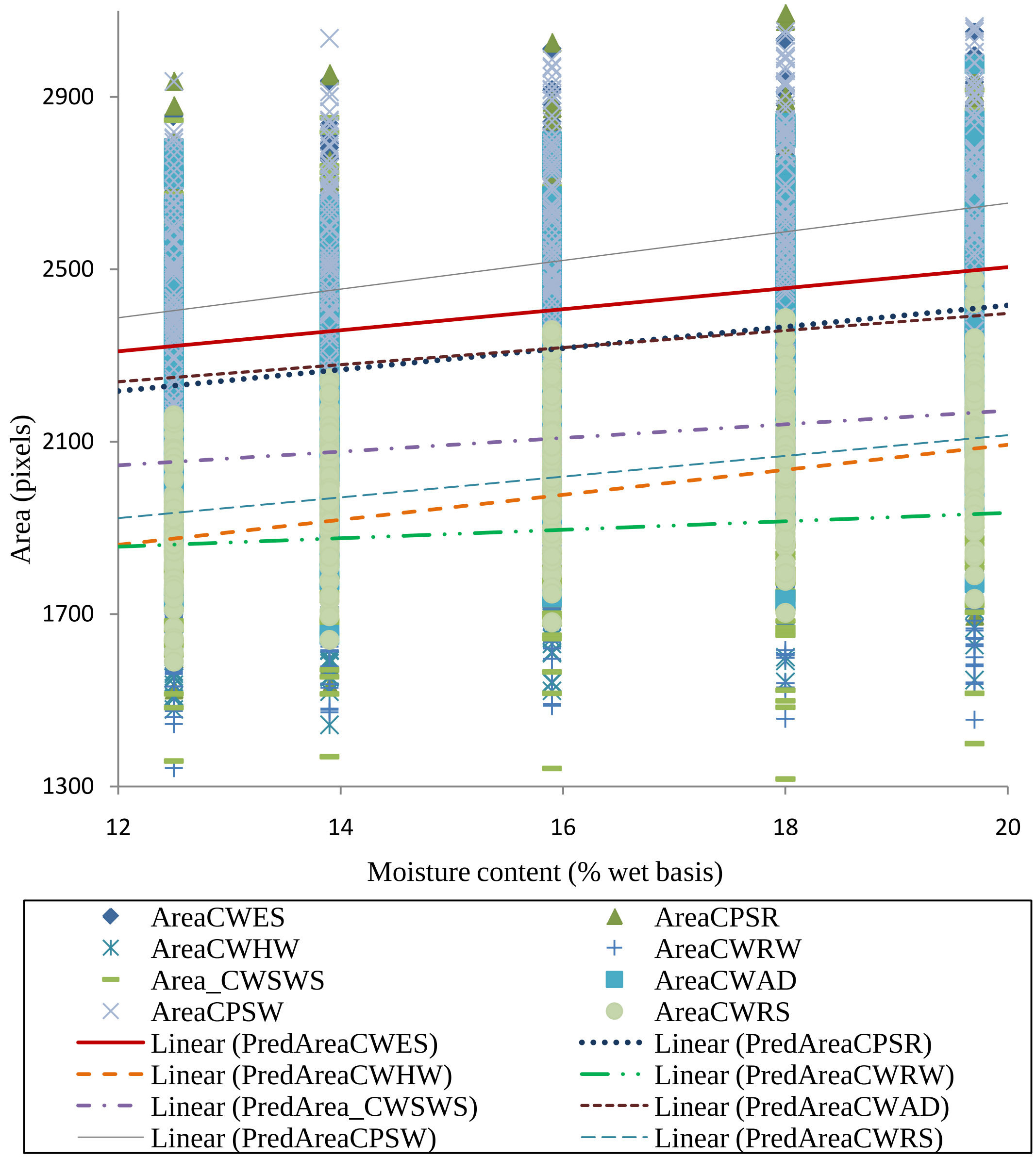
Wheat Class	Basic morphological features	Moment and Fourier descriptor features
CWHWS	Area, Perimeter, Maximum radius, Minimum radius, Mean radius, Major axis length, and Minor axis length	Shapemoment 1, Shapemoment 2, PeriFD 2, PeriFD 3, PeriFD 4, PeriFD 16, PeriFD 19, PeriFD 20, RadialFD 2, and RadialFD 3,
CWSWS	Area, Perimeter, Maximum radius, Minimum radius, Mean radius, Major axis length, and Minor axis length	PeriFD 8, and RadialFD 8

Table D. 3. List of features of CPSR and CPSW kernels which were significantly influenced by moisture increase from 12 to 20% wet basis

Wheat Class	Basic morphological features	Moment and Fourier descriptor features
CPSR	Area, Perimeter, Maximum radius, Minimum radius, Mean radius, Major axis length, and Minor axis length	Shapemoment 1, Shapemoment 2, PeriFD 1, PeriFD 2, PeriFD 3, PeriFD 4, PeriFD 6, PeriFD 16, PeriFD 18, PeriFD 20, RadialFD 1, RadialFD 2, RadialFD 4, and RadialFD6
CPSW	Area, Perimeter, Maximum radius, Minimum radius, Mean radius, Major axis length, and Minor axis length	-

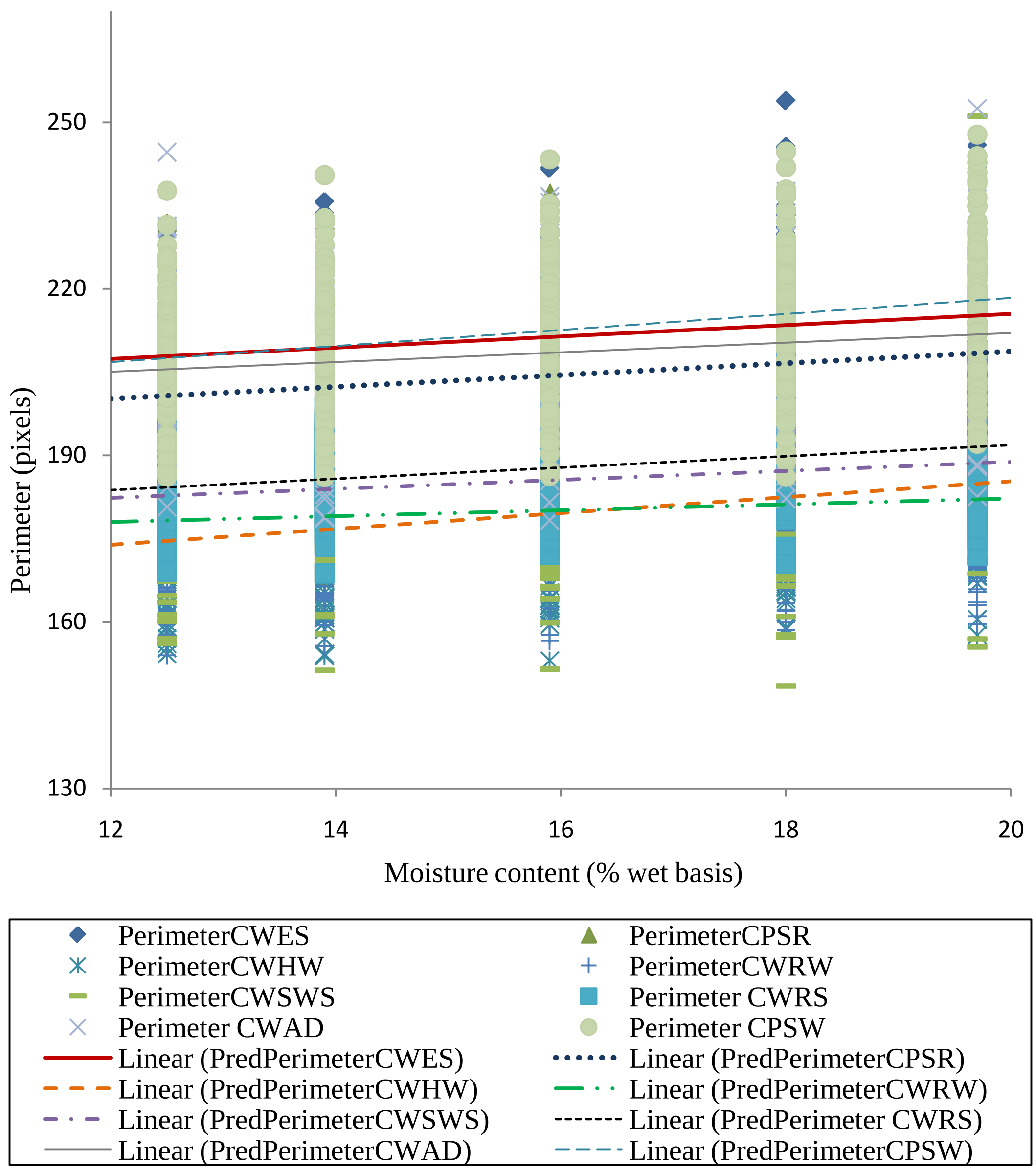
Table D. 4. List of features of CPSR and CPSW kernels which were significantly influenced by moisture increase from 12 to 20% wet basis

Wheat Class	Basic morphological features	Moment and Fourier descriptor features
CWRW	Area, Perimeter, Maximum radius, Mean radius, Major axis length, and Minor axis length	PeriFD 8, PeriFD 13, PeriFD 14, RadialFD 7, and RadialFD 20
CWES	Area, Perimeter, Maximum radius, Minimum radius, Mean radius, Major axis length, and Minor axis length	Shapemoment 1, Shapemoment 2, PeriFD 2, PeriFD 3, PeriFD 4, PeriFD 5, PeriFD 6, PeriFd7, PeriFD15, PeriFD 16, PeriFD17, PeriFD 18, PeriFD 19, PeriFD 20, RadialFD 2, RadialFD 4, RadialFD 5, RadialFD6, RadialFD7



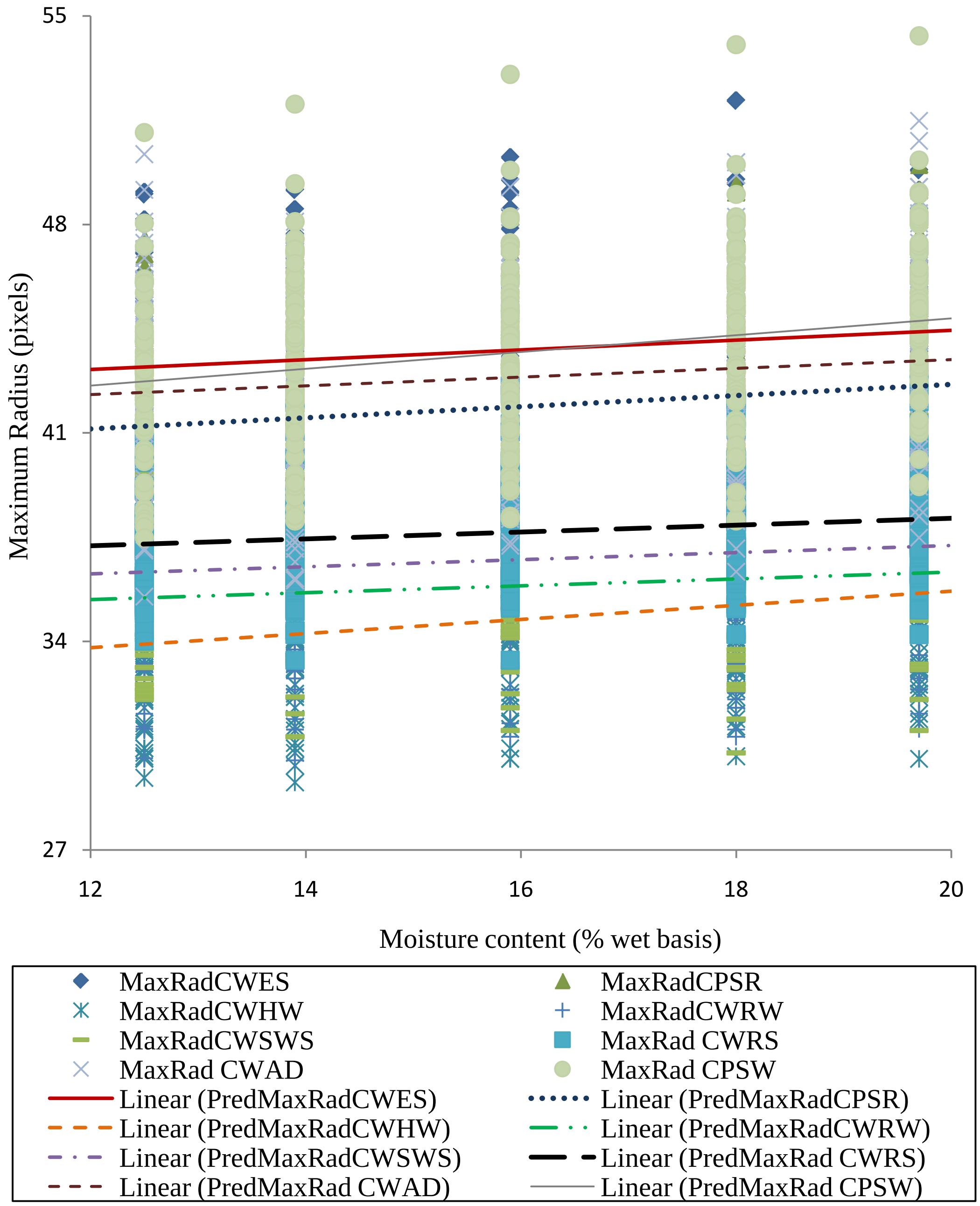
Pred - Predicted

Figure D. 1. Observed and predicted values of area of eight milling classes of western Canadian wheat kernels at different moisture contents.



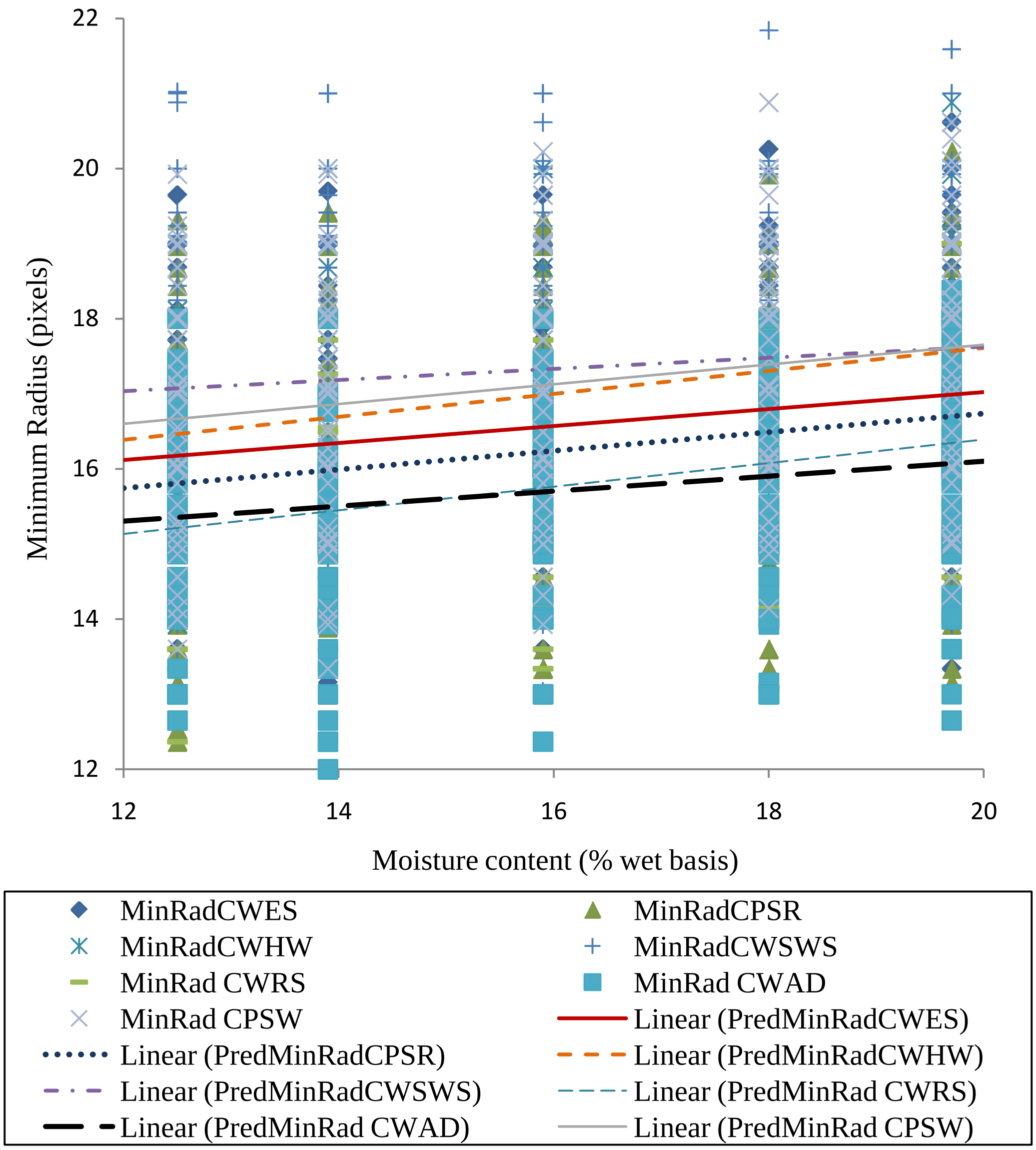
Pred - Predicted

Figure D. 2. Observed and predicted values of perimeter of eight milling classes of western Canadian wheat kernels at different moisture contents.



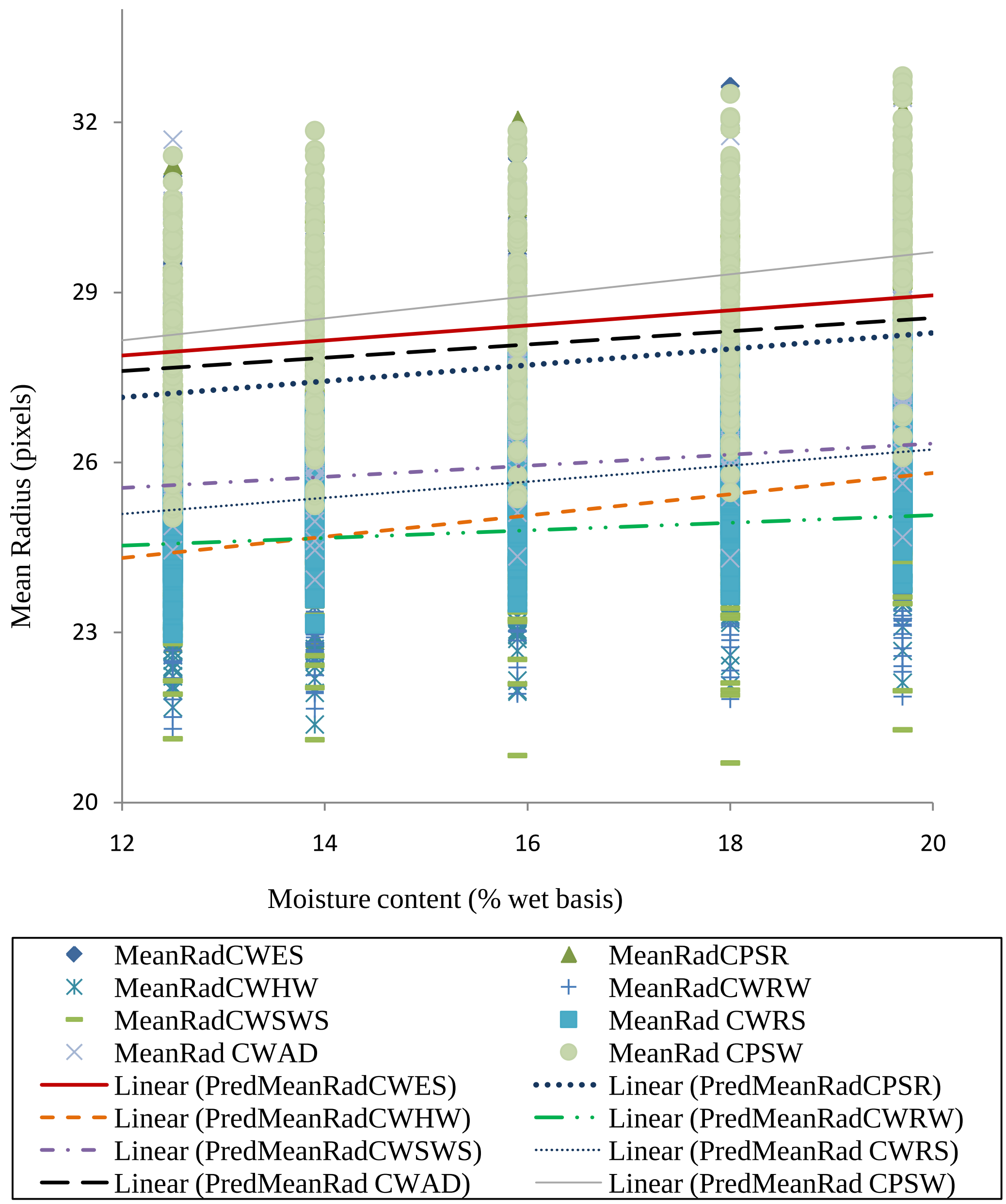
Pred - Predicted

Figure D. 3. Observed and predicted values of maximum radius of eight milling classes of western Canadian wheat kernels at different moisture contents.



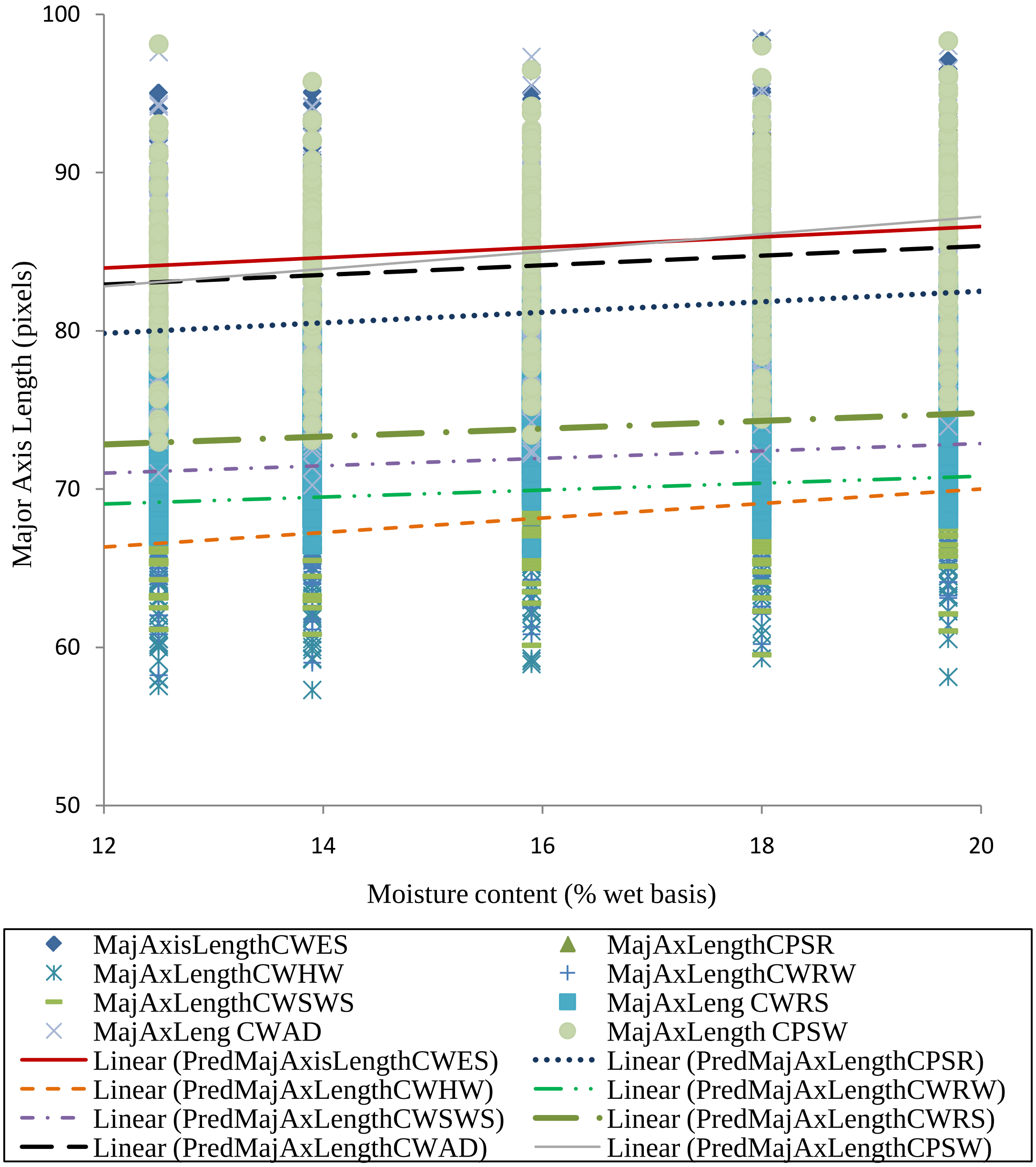
Pred – Predicted

Figure D. 4. Observed and predicted values of minimum radius of seven milling classes of western Canadian wheat kernels at different moisture contents.



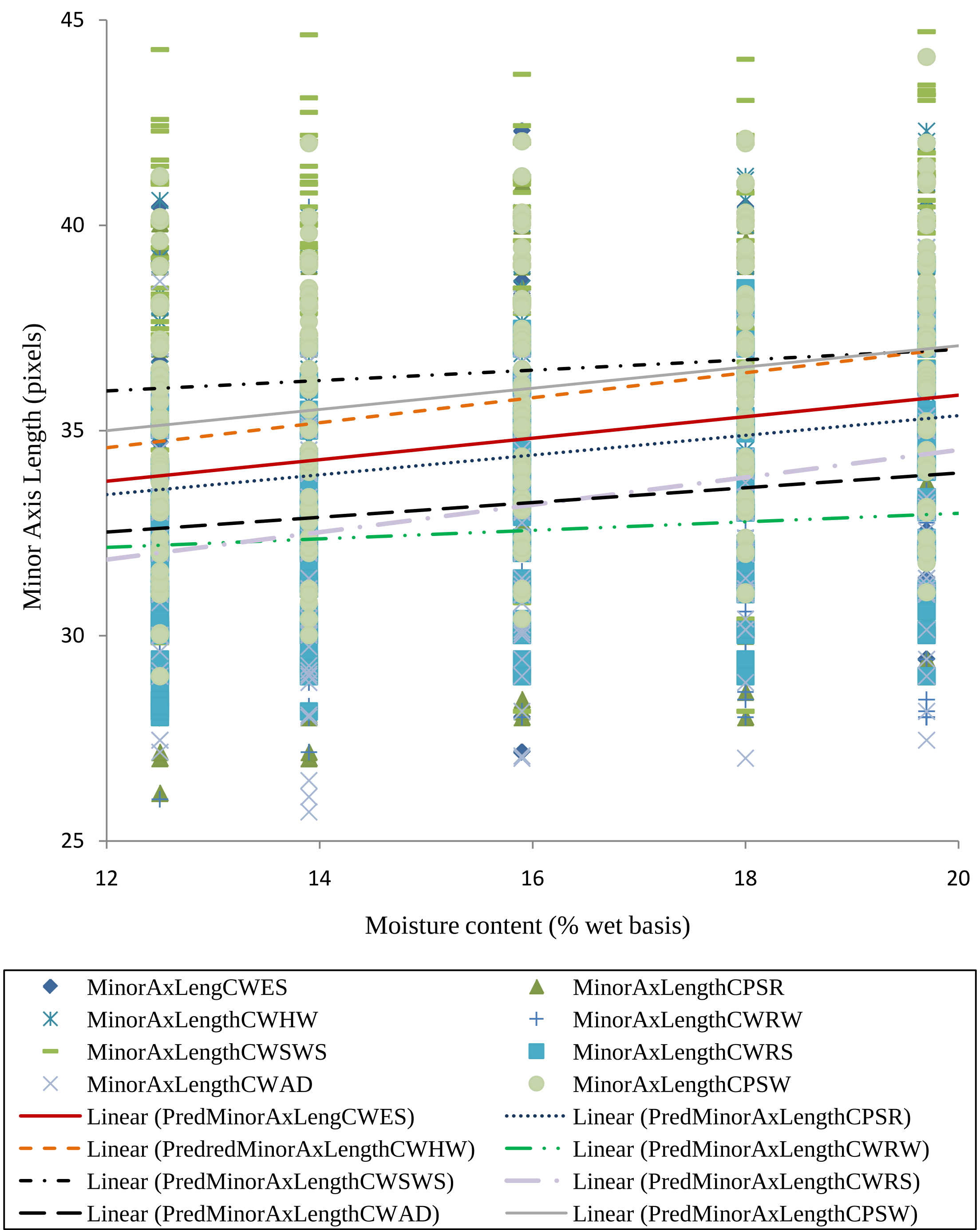
Pred – Predicted

Figure D. 5. Observed and predicted values of mean radius of eight milling classes of western Canadian wheat kernels at different moisture contents.



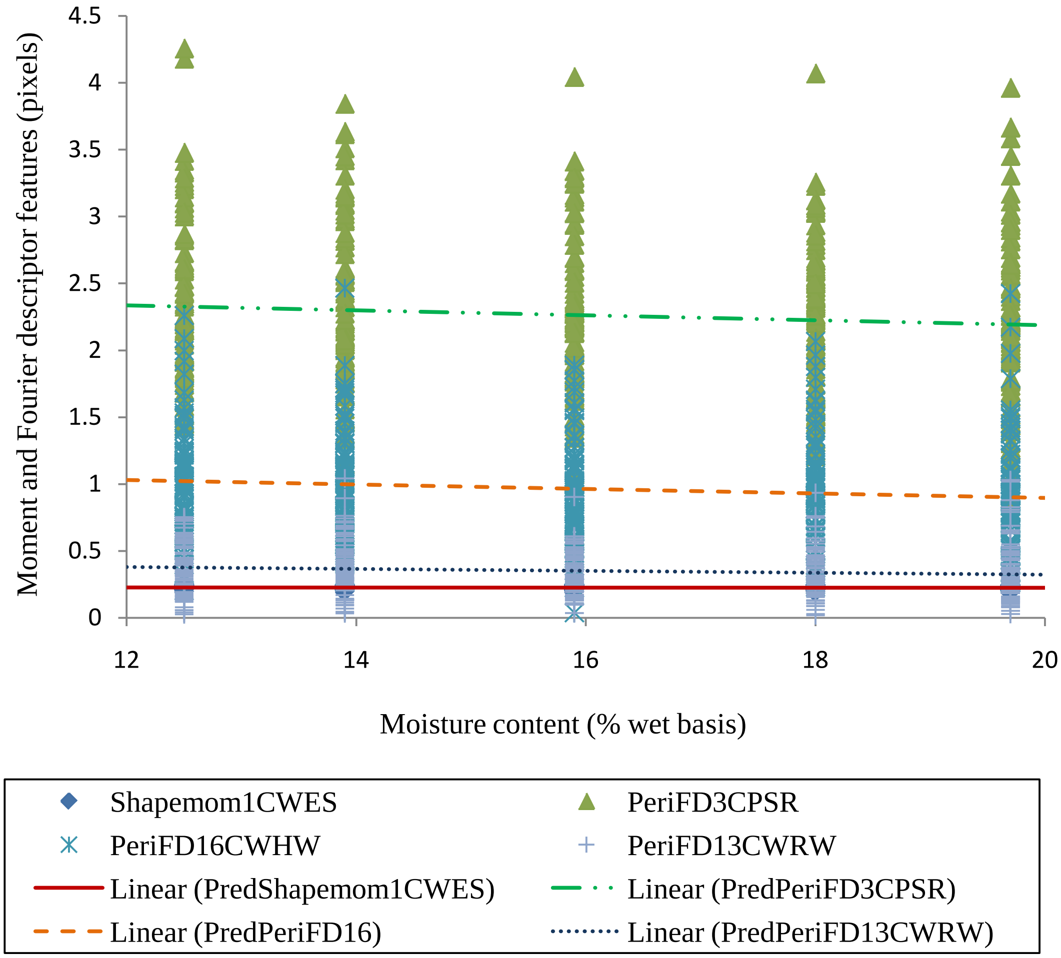
Pred – Predicted

Figure D. 6. Observed and predicted values of major axis length of eight milling classes of western Canadian wheat kernels at different moisture contents.



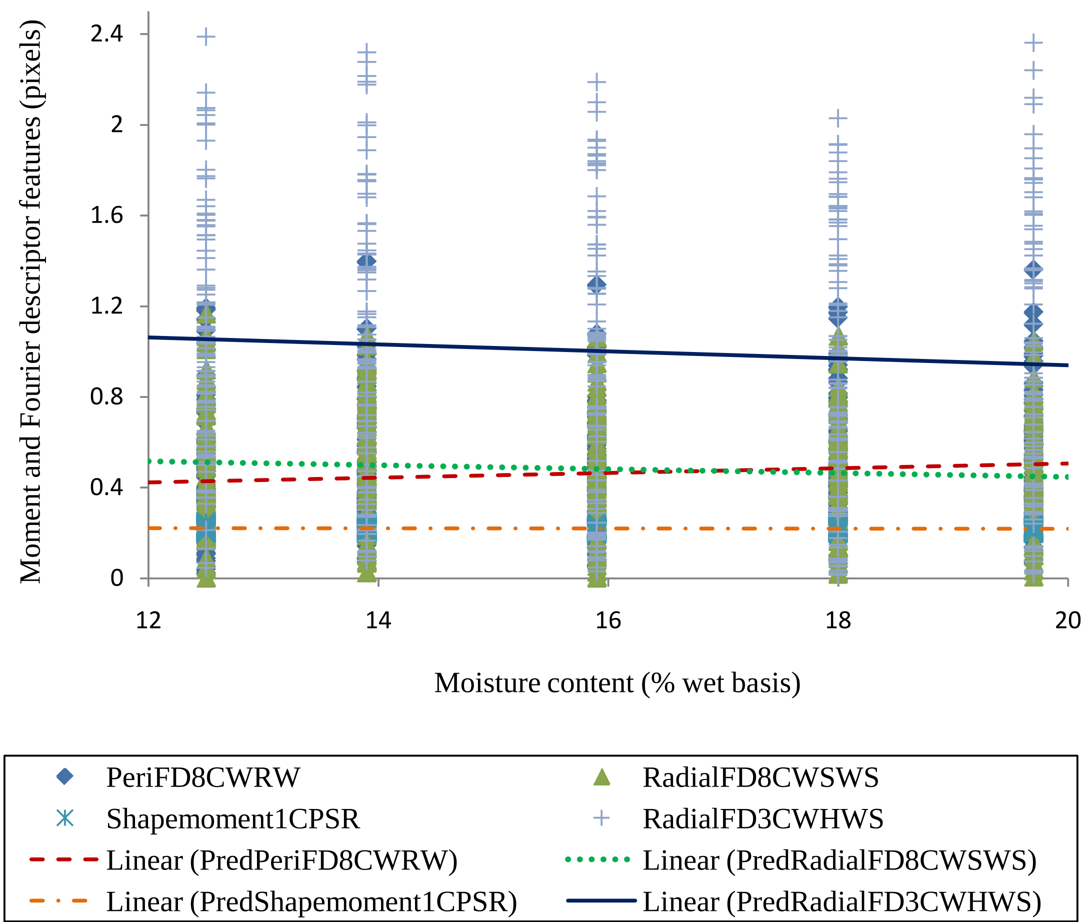
Pred – Predicted

Figure D. 7. Observed and predicted values of minor axis length of eight milling classes of western Canadian wheat kernels at different moisture contents.



Pred – Predicted

Figure D. 8. Observed and predicted values of some of the moment and Fourier descriptor features of CWES, CPSR, CWHWS, and CWRW wheat kernels at different moisture contents.



Pred – Predicted

Figure D. 9. Observed and predicted values of some of the moment and Fourier descriptor features of CWRW, CPSR, CWSWS, and CWHWS wheat kernels at different moisture contents.