

# Optical characterization of free-falling mold-damaged wheat kernels

Stephen R. Delwiche

USDA-ARS, Beltsville Agricultural Research Center

Food Safety Laboratory, Building 303

Beltsville, Maryland 20705-2350 USA

Stephen.Delwiche@ars.usda.gov : phone 301-504-8450 fax 301-504-9466

## ABSTRACT

One of the most common molds that infects the seeds of small cereals worldwide, such as wheat, is *Fusarium Head Blight* (FHB). The mycotoxin, deoxynivalenol (also known as DON or vomitoxin) is often produced by this mold, which, upon ingestion, causes health problems to not only livestock (especially non-ruminants), but to humans as well. In the United States, the FDA has established advisory levels for DON in food and feeds, a practice that is likewise conducted by most countries of the world. Our previous research has shown that commercial high-speed optical sorters are on average 50 percent efficient at the removal of mold-damaged kernels; however, under more careful control in the laboratory, this efficiency can rise to 95 percent or better. Ongoing research is examining the potential to achieve the higher efficiencies at conditions that are more akin to those of commercial processing. For example, multispectral information is collected on single kernels in freefall at the sub-millisecond level. Knowledge gained from this research will provide design criteria for improvement of high-speed optical sorters for reduction of DON in raw cereals commodities, as well as in finished food products.

**Keywords:** *Fusarium Head Blight*, deoxynivalenol, DON, high-speed sorting

---

Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply endorsement or recommendation by the USDA.

## 1. INTRODUCTION

In the United States, official inspection of grain for official grade is conducted by the USDA Grain Inspection, Packers and Stockyards Administration. For wheat, the act of inspection (which is a requirement for exported grain) consists of the certification of wheat class and grade. Each wheat class (there are eight U.S. classes) is subdivided into six grades: U.S. No. 1, U.S. No. 2, ..., U.S. No. 5, and U.S. Sample grade. Among other factors that define grade, the level of damaged kernels is evaluated, such that Grades 1 through 5 can contain no more than the following respective percentages by weight of damage: 2.0, 4.0, 7.0, 10.0, and 15.0. Damage itself can occur by heat, frost, insect, pre-harvest sprouting, and, of prime interest in the current study, mold. One of the most prevalent forms of mold is called scab, which is caused by the fungus, *Fusarium graminearum*. Also known as *Fusarium Head Blight*, this disease is a worldwide problem that affects temperate climates in which small grains (wheat, barley, corn, etc.) are grown. Often coincident with scab is the mycotoxin, deoxynivalenol, or vomitoxin or DON, that is produced by the mold. In the United States regulation of DON is codified in the Federal Food, Drug and Cosmetic Act, which places authority with the Food and Drug Administration (FDA). For DON, regulation by the FDA is done at an advisory level<sup>1</sup>. The permissible level of DON ranges from 1 mg/kg for finished wheat products for human consumption to as high as 10 mg/kg for ruminating beef and feedlot cattle older than 4 months and for chickens, in which the diet of the moldy wheat does not exceed 50% of their feed. Regulation elsewhere in the world, with more than 100 countries having established guidelines, can be even more stringent<sup>2</sup>. For example, in the European Union, the human food limit is set at 0.5 mg/kg for finished products and 0.75 mg/kg for raw material<sup>3</sup>. Additional information on the food safety concerns of DON and other trichothecenes is contained in a review by Dexter and Nowicki<sup>4</sup>.

*Fusarium Head Blight* is not a newly discovered disease, as noted by its focus of study since the late 1800's<sup>5</sup>. However, in the past 20 years, coincident, though not fully proven, with the increased popularity of minimum tillage and corn in the crop rotation, FHB has become a recurring problem of the wheat growing regions of the U.S., with outbreaks

occurring in the mid-1990s<sup>6</sup>, and on through the current decade, such as in the soft red winter wheat growing areas of the eastern United States in 2003 and 2004. The current year, 2007, has been affected by this disease in the Central Plains region, owing to the unusual amount of rain during the early summer season. A conventional post harvest method for reduction of DON is grain blending, in which the contaminant is diluted through combination with a cleaner lot. This practice could be banned in the United States should the FDA decide to regulate DON with an action level. Removal of *Fusarium*-damaged kernels can be accomplished at the various sequential stages of the wheat handling, such as by increasing the fan velocity of the combine to remove the generally lighter *Fusarium*-damaged kernels (at the risk of also losing sound kernels), and also at the mill through the use of either aspiration or density separation equipment<sup>7,8</sup>. In the latter case, specific gravity tables, which rely on a difference in density of sound and *Fusarium*-damaged kernels, are very expensive, energy intensive, and limited in throughput. Hence, the removal of *Fusarium*-damaged kernels by optical sorting technology is under consideration as an alternative to current mechanical practices.

The current study is a continuation of the author's work on optical methods for wheat scab detection that have taken place over the past several years. Optical measurement techniques fall into two general categories, spectroscopy-based (visible or NIR) and image analysis. The first category, spectroscopy, was first examined by Dowell et al.<sup>9</sup> In recent years, research has also addressed *Fusarium*-damaged kernel (FDK) detection by optical measurement. Both image analysis and near-infrared (near-IR) spectroscopy have been utilized. In the second category, kernel morphology and color characteristics were the primary features used to distinguish damaged from healthy kernels<sup>10,11</sup>, with the *Fusarium* damage characterized by kernels having a white or pinkish color and being shriveled<sup>12</sup>. In the author's own studies<sup>13-15</sup>, which involved visible and NIR spectroscopy on individual kernels, identification of *Fusarium*-damaged kernels of hard red winter wheat could be achieved at an accuracy of 95 to 97 percent with as few as two wavelengths. However, these studies were conducted under controlled laboratory conditions, in which each kernel was scanned at rest while placed in a machined trough on a black plate. Two analytical spectrometers were used, one based on a 512-element silicon photodiode array (operating range of 380 to 879 nm), the other based on a 128-element indium gallium arsenide array (1000 to 1700 nm usable range). From these studies, the best one or two wavelengths from each wavelength region (visible and NIR) were determined from exhaustive searches of all possible wavelength combinations. The goal of wavelength selection was for this information to be used in selection of filters (or other means of light dispersion) in the operation of a high-speed bichromatic commercial sorting device. The restriction on the number of wavelengths not exceeding two was enacted with the recognition of design of these high-speed devices that achieve high throughput rates (> 1kg/min-lane) because of their relatively simple optical design.

In a later study by the author, in which a commercial sorter was used, commercial wheat samples of varying degrees of *Fusarium* damage were sorted biochromatically by utilizing a broad visible waveband (675 nm) and a broad NIR waveband (1480 nm)<sup>16</sup>. With operating conditions set at a feed-rate of 0.33 kg/(min-channel) and a preset mass rejection rate of 10% for 43 samples ranging in DON concentration from low (< 1.0 mg/kg) to very high (> 20 mg/kg), the researchers found that upon one pass through the sorting machine only about one-half of the *Fusarium*-damaged kernels were removed. This is in contrast to the >95% accuracy that was previously demonstrated as achievable under controlled laboratory conditions. Therefore, the current study was designed to examine the gulf between the laboratory and high-speed environments, with the goal of developing new design criteria for high-speed (1 to 2 ms per kernel) sorting devices in order to reach the goal of 95% sorting accuracy.

The objective of the present research is to establish the optical design parameters and classification algorithms that will permit high-speed sorting of wheat for *Fusarium* damage at high accuracy (>95%) and high throughput [> 500 kernels / (channel-s)]. Visible/near-infrared spectroscopy analysis techniques and very fast detectors are considerations to improve upon the accuracy of existing high-speed sorting technology. This report provides details on some initial efforts at measuring reflected light from free-falling kernels for the purpose of separating normal from *Fusarium*-damaged kernels.

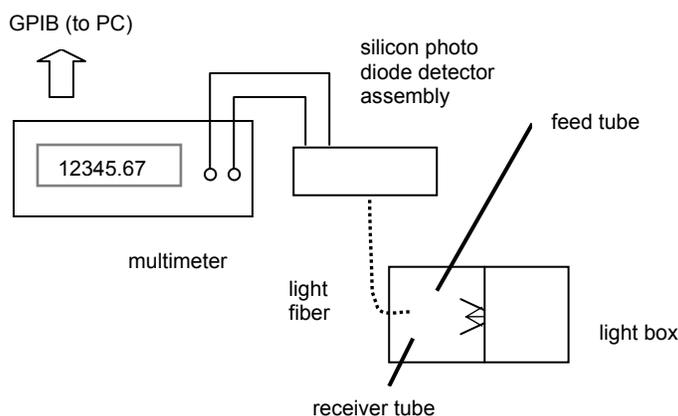


Fig. 1. Schematic of apparatus used in single kernel inspection of mold damage in free-fall.

## 2. MATERIALS AND METHODS

### 2.1 Wheat

*Acrylic Balls* – Solid acrylic balls of 3.175-mm diameter (Engineering Laboratories, Inc., Oakland, NJ), were used to verify the operation of the free-falling system. Fifty ‘olive’ and fifty ‘red’ balls were used.

*Fusarium-Damaged Set* – Breeders’ advance lines and commercial releases of soft red winter wheat were grown near Blacksburg, Virginia and harvested in summer 2005. Of more than 60 samples provided, 20 were selected at random. From each sample, equal numbers of healthy and Fusarium-damaged kernels were hand-selected based on human visual inspection. Fusarium-damaged kernels were identified from their faded, white appearance and shriveled texture. Altogether, a total of 24 healthy and 24 Fusarium-damaged kernels were selected from each sample.

*Red vs. White Set* – This set of samples, initially postulated to be a less challenging set (compared to the Fusarium-damaged set), was obtained from the USDA Grain Marketing and Production Research Center (Manhattan, KS). The set consisted of commercial releases or advanced breeders lines of 10 red and 9 white genotypes, as follows: Reds = FGIS57570, ‘Waverly’, ‘Kulm’, ‘Sharpbristol’, ‘TAM 105’, ‘Len’, ‘Dodge’, ‘Seward’, ‘Nekota’, and an unknown genotype from Berthoud, CO.; Whites = ID0604, ‘Otis’, ‘Blanca Grande’ (two independent samples), ‘Nufrontier’, ‘Klasic’, ‘Arlin’, ‘Snow White’, ‘Nuhorizon’, and ‘Rio Blanco’. Harvest year and growing location were unavailable.

### 2.2 Equipment

A sketch of the apparatus for real-time inspection of free-falling kernels is shown in Figure 1. This device consists of a stainless steel tube (914 mm length x 6.3 mm ID) inclined at a 70 degree angle with respect to the horizontal. The inclination angle of the tube is slightly greater than that for an open channel of a commercial sorter because of the need to provide a greater gravitational force on the kernel to overcome the interaction of the kernel with the tube’s interior wall. The lower end of the tube terminates in a plastic electronics assembly box (120 mm width x 64 mm height x 40 mm depth) whose two opposing faces were open. A small stub of ½-inch (OD) stainless steel tubing protrudes through the bottom of the assembly box and is used to receive the free-falling kernels. A distance of approximately 30 mm, as measured along a straight line path between the feed and receiver tubes, forms the region for kernel illumination and reflectance capture by a fiber bundle. The terminal end of the multi-fiber bundle, with internal diameter of 5 mm, is

oriented in a perpendicular direction to the trajectory path of the kernel. The opposite end of the fiber bundle is connected by SMA connector to a silicon detector/amplifier assembly (Hamamatsu, Model C6386-01). The analog signal from this amplifier is digitized and stored by a multimeter (Hewlett Packard, Model 3458A). Digital data from the multimeter is ported to a personal computer (PC) across a GPIB interface.

For the purpose of comparing the classification accuracy of the free-falling apparatus with expectations (from previous studies) of accuracies that could be achieved under controlled laboratory, kernel-at-rest conditions, the kernels of each sample were also scanned by a 512-element silicon photodiode array, whereupon readings were interpolated to a uniform increment of 1 nm at whole wavelengths between 380 and 879 nm, as described in Delwiche<sup>13</sup>. A 250-ms integration time, with 10 successive scans per spectrum, was used for each kernel. Dark-current adjusted, referenced (against a tile of polytetrafluoroethylene, *i.e.*, 'spectralon') energy readings were stored as  $\log(1/R)$ , and later converted back to reflectance during the analysis of the data.

### 2.3 Operation

A Visual Basic (version 6) program was written to send command instructions to the multimeter. Sampling rate (40,000 / s) and number of sample points (1000) were selected to capture sufficient data from the free-falling kernel while in the field of view of the fiber probe, which lasted approximately 4 to 12 ms. Control of data collection was performed by the PC, using the multimeter's command set of instructions. The start of data capture was controlled by the multimeter's internal trigger. Each kernel or ball was released by hand at the upper opening of the inclined tube. The acrylic balls ( $n = 50$  reds, 50 olives) were processed in alternating sequence (*i.e.*, red, olive, red, ..., olive). For the Fusarium-damaged set, kernels within each sample ( $n = 48$  kernels, equally divided between normal and Fusarium-damaged) were sequentially dropped by alternating between the two categories (normal and Fusarium-damaged). For the red vs. white set, all kernels within a variety ( $n = 30$  kernels) were processed entirely before processing started for the next variety. The varieties were sequenced in alternating fashion, (*i.e.*, red, white, red, ..., white). The Fusarium-damaged samples were scanned over a three day period, while the red vs. white samples were scanned over a two day period. Following the free-falling kernel measurements of all wheat samples in a set, the kernels were scanned at rest by the diode array spectrometer.

### 2.4 Data Analysis

Upon initial processing, a total of 50 reflectance readings under red light illumination (nominal criteria:  $\lambda_{\text{peak}} = 627$  nm, 20 nm FWHM) and an equal number of readings under green light illumination ( $\lambda_{\text{peak}} = 530$  nm, 35 nm FWHM) were available, which represented a 25-ms time window. However, depending on the velocity and length of the kernel, the actual number of readings in which the kernel was in the field of view of the fiber bundle probe was typically between 15 and 25. From this set of paired responses, for each kernel, the red light responses were linearly regressed onto the green light responses. Two results from the regression analysis—the slope of the line of best fit and the coefficient of determination ( $r^2$ )—were used as input parameters in a linear discriminant analysis (LDA) model for classifying the categories (*i.e.*, normal vs. Fusarium-damaged, red vs. white). It was postulated that the slope, which encapsulates the relationship between the reflected energies under two wavelengths of visible light illumination (red and green) would be sensitive to color variation between kernel classes (normal vs. Fusarium-damaged, red vs. white). The coefficient of determination, on the other hand, was postulated to be sensitive to surface textural differences between kernel classes. Given these hypotheses, one would expect that the coefficient of determination would have a greater role in classification of normal vs. Fusarium-damaged wheat, compared to red vs. white wheat. Classification accuracy was reported as the percentages of kernels in each category correctly classified, based on a leave-one-out cross validation. Data reduction and classification analyses were preformed in the SAS (version 9) environment, using the procedure, 'Discrim'<sup>17</sup>, for the LDA.

The data in parallel from the diode array spectrometer were also processed in SAS. Spectral data were first transformed back to reflectance, whereupon a Gaussian waveform of 20 nm (FWHM) was convolved onto each spectrum for the purpose of mimicking the illumination conditions of the free-falling kernel setup. From this convolved spectrum, the reflectance value centered at 627 nm ( $R_{627 \text{ nm}}$ ) was selected. This procedure was repeated, using a Gaussian waveform of

35 nm, in order to select a reflectance value centered at 530 nm ( $R_{530 \text{ nm}}$ ). Classification by LDA was subsequently performed using these two reflectances as input parameters.

### 3. RESULTS AND DISCUSSION

#### 3.1 Raw Data

Typical time-of-flight responses of two free-falling Fusarium-damaged kernels from one sample are depicted in Figure 2. These two kernels were purposely selected to demonstrate the large kernel-to-kernel variation in captured reflected energy. Not only is the peak level of energy different between the two kernels, but the shapes of time-domain traces is also different, with the kernel in the upper graph (A) demonstrating a symmetrical shape under both red and green illumination, compared to the kernel's trace in the lower graph (B) having much less symmetry, though still possessing some degree of correlation between red and green responses. Similar overall curve shapes were observed for the normal kernels of this set and also for the kernels of the red and white wheat set, such that sample traces of these kernels are not shown.

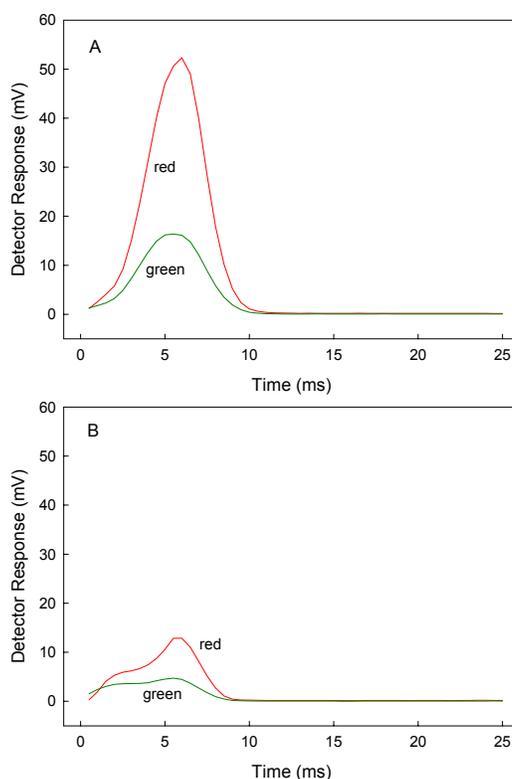


Fig. 2. Examples of reflected energy responses of two free-falling Fusarium-damaged wheat kernels subjected to red (peak = 627 nm) and green light (peak = 530 nm).

For the purpose of comparison, the diode array spectra of the same two kernels at rest are shown in Figure 3. As with the free-falling kernel traces, spectra of normal kernels and spectra of kernels from the red and white wheat set were similar in overall shape as those shown in Figure 3; therefore such spectra are not shown.

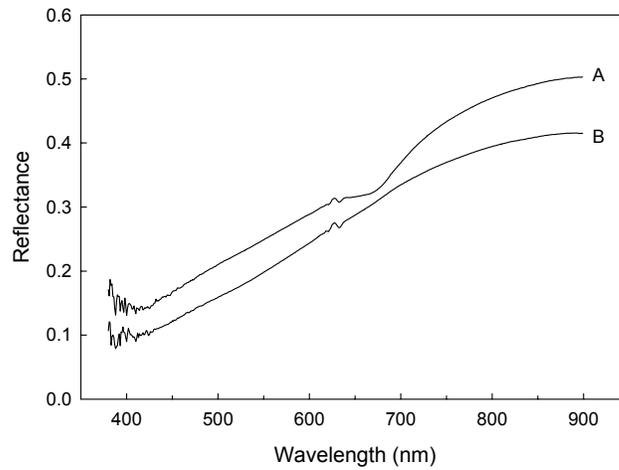


Fig. 3. Reflected energy spectra of the kernels plotted in Figure 2. A = same kernel as shown in upper graph of Figure 2, B = same kernel as shown in lower graph of Figure 2.

### 3.2 Acrylic Balls

The responses of the red and olive acrylic balls (50 of each category) are shown in Figure 4. Clearly, the slope of the regression line ( $y$ -axis), which relates the reflected energy under red light illumination to the reflected energy under green light illumination, was sufficient to discriminate the two colors, with perfect accuracy. With this demonstration of the rudimentary capabilities of the free-falling system for discriminating between uniformly shaped objects of two starkly different colors, the focus was turned to wheat kernels.

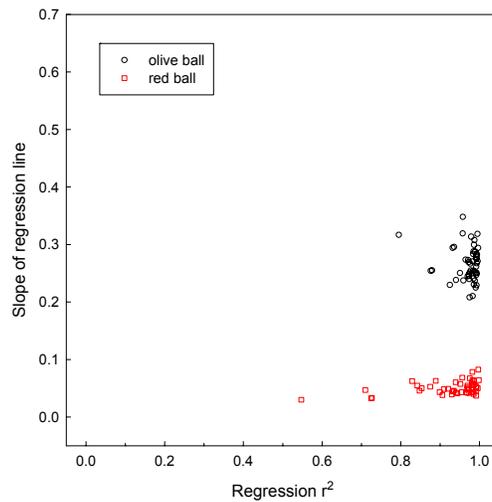


Fig. 4. Plot of classification parameters from the free-falling apparatus for acrylic ball set, consisting of 50 olive and 50 red 3.175-mm diameter acrylic balls.

### 3.3 Fusarium-Damaged Wheat

A scatter plot of the two free-falling classification parameters of all normal and Fusarium-damaged ( $n = 480$  kernels, each) is shown in Figure 5. Unlike the responses of the acrylic balls, there are no distinct regions that perfectly isolate the normal and Fusarium-damaged kernels.

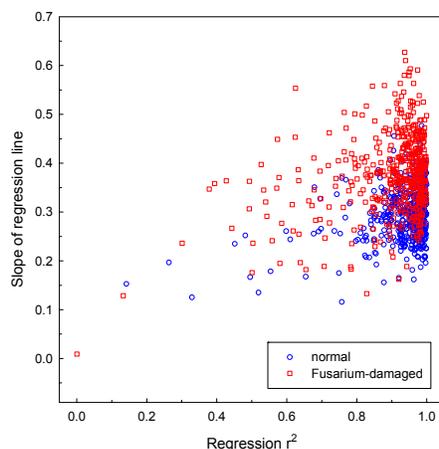


Fig. 5. Plot of classification parameters from the free-falling apparatus of the Fusarium-damaged set, which consisted of 20 varieties or lines of soft red winter wheat, from which 24 Fusarium-damaged and 24 normal kernels were selected at random from each variety/line. The classification parameters are the slope of the linear regression equation and coefficient of determination arising from the regression of the red light response onto the green light response.

Using these two parameters in LDA, the cross-validation accuracy was 83% and 72% for normal and Fusarium-damaged categories, respectively, yielding an average accuracy of 78% (Table 1). Of the two parameters, the slope, with an average classification accuracy of 75%, was much better at discriminating between the two categories (compared to an average accuracy of 56% for the coefficient of determination as a sole classification parameter). Thus, color, rather than texture, as sensed by the free-falling apparatus, is the dominant classifier. To gauge the margin for improvement if the free-falling system were to be refined, the classification accuracies arising from LDA using the reflectances at two wavelengths ( $R_{530\text{ nm}}$ ,  $R_{627\text{ nm}}$ ) when the kernel was at rest are also listed in Table 1. These accuracies, averaging 95% when both wavelengths are used, were on par with the author’s earlier published results<sup>15</sup>. A scatter plot of the stationary-kernel reflectance at two wavelengths is shown in Figure 6. This plot shows a more distinct separation of the two categories than the free-falling plot of Figure 5.

**Table 1. Summary of accuracies of linear discriminant analysis (LDA) models for classification of normal and Fusarium-damaged wheat kernels.**

State of Kernel	Parameters Used in LDA Model	Percentage of Correctly Classified Kernels by LDA Cross-Validation		
		Normal	Fusarium-Damaged	Average
Free-falling	Slope, S	79.4	71.2	75.3
	Coefficient of determination, $r^2$	76.5	35.6	56.0
	S, $r^2$	82.7	72.5	77.6

**Table 1 (continued)**

Stationary	$R_{530 \text{ nm}}$	77.1	65.8	71.5
	$R_{627 \text{ nm}}$	60.2	55.2	57.7
	$R_{530 \text{ nm}}, R_{627 \text{ nm}}$	95.6	94.8	95.2

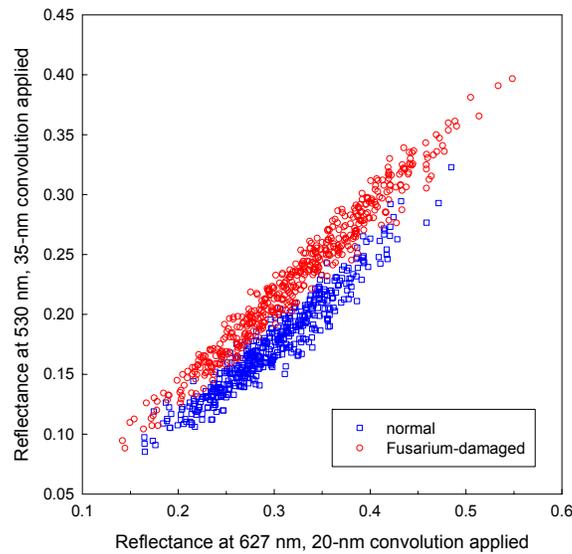


Fig. 6. Plot of classification parameters from stationary, diode array apparatus for the same kernels described in Fig. 5. The classification parameters are reflectances at 530 and 627 nm.

### 3.4 Red and White Wheat

Similar to the scatter plot of Figure 5, the plot contained in Figure 7 shows that the two free-falling classification parameters provided a certain degree of separation of the red and white wheat color classes; however, this separation was not perfect, as it had been with the two colors of acrylic balls. A scatter plot of the at-rest reflectances of these same kernels is shown in Figure 8, along with a summary of the LDA classification results listed in Table 2. Apparent from the scatter plots, and confirmed by the tabulated accuracies, red and white kernels were more difficult to distinguish than normal and Fusarium-damaged kernels. The classification accuracy from the free-falling system averaged 76% for the red vs. white set, compared to 78% for the normal vs. Fusarium-damaged set. Consistent with this ranking, the stationary system accuracy was also lower for the red vs. white (92%) than for the normal vs. Fusarium-damaged set (95%). As with the other two sets of data, the slope of the regression equation was the more useful parameter in the classification model, such that, by itself, slope yielded an average classification accuracy of slightly less than 76%.

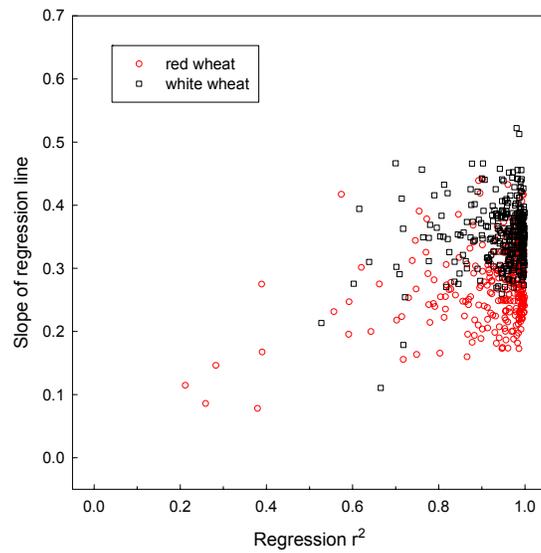


Fig. 7. Plot of classification parameters from the free-falling apparatus of the red vs. white wheat set, which consisted of 10 varieties or lines of red wheat and 10 varieties or lines of white wheat, in which, for each variety/line, 30 kernels were examined. The classification parameters are the slope of the linear regression equation and coefficient of determination arising from the regression of the red light response onto the green light response.

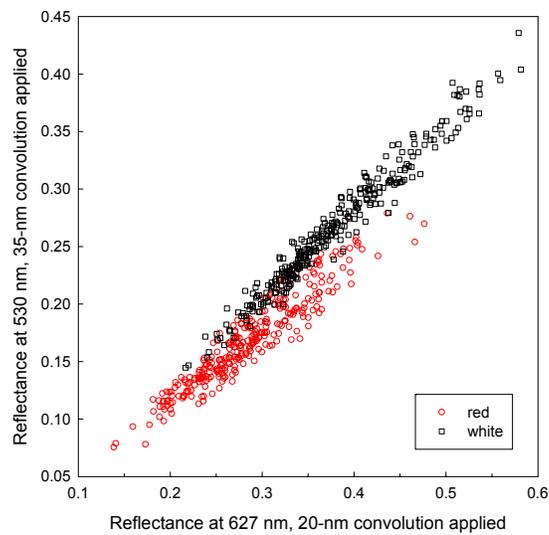


Fig. 8. Plot of classification parameters from the stationary, diode array apparatus for the same kernels described in Fig. 7. The classification parameters are reflectances at 530 and 627 nm.

**Table 2. Summary of accuracies of linear discriminant analysis (LDA) models for classification of red and white wheat kernels.**

State of Kernel	Parameters Used in LDA Model	Percentage of Correctly Classified Kernels by LDA Cross-Validation		
		Red	White	Average
Free-falling	Slope, S	75.0	76.7	75.8
	Coefficient of determination, $r^2$	31.0	75.0	53.0
	S, $r^2$	74.7	77.7	76.2
Stationary	$R_{530\text{ nm}}$	86.7	80.0	83.3
	$R_{627\text{ nm}}$	78.0	71.7	74.8
	$R_{530\text{ nm}}$ , $R_{627\text{ nm}}$	92.3	92.7	92.5

### 3.5 Discussion

As shown in the results of the current study, the ability to correctly identify free-falling wheat kernels, be it normal vs. Fusarium-damaged or red vs. white, is substantially lower than at-rest wheat kernels. These results are in general agreement with the author's previous studies that demonstrated a 95% accuracy of correctly identifying Fusarium-damaged kernels at rest, using two wavelengths<sup>15</sup>, and a corresponding 50% accuracy for high-speed bichromatic sorting<sup>16</sup>. Encouragingly, the present research demonstrates an improvement in damaged kernel detection, with more than 70% of the Fusarium-damaged kernels in free-fall correctly identified. The aim of ongoing research is to enact changes to either lighting or probe placement in order to improve the accuracy to 95% or better. Considering that the literature documents cases of 99% accuracy for red vs. white wheat kernel identification by visible/NIR spectroscopy (albeit with reliance on a broad wavelength region, reduced in mathematical dimension by partial least squares analysis)<sup>18</sup>, there appears to be the likely possibility of reaching similar levels of accuracy through design modifications of the free-falling system.

## 5. CONCLUSIONS

Based on the author's research of the past several years on the feasibility of utilizing high-speed optical sorting technologies (conventional and the author's innovative design), the following insights are noted: 1) An accuracy of 95% or better can be achieved for recognition of Fusarium-damaged individual wheat kernels through the implementation of reflectance readings at two wavelengths of visible light (530 nm and 627 nm). However, these accuracies are reached only under controlled laboratory conditions in which the kernel is at rest, rather than in free-fall. 2) Conventional high-speed optical bichromatic sorting under free-fall conditions results in the correct identification and removal of approximately one-half of the Fusarium-damaged kernels. 3) With a newly devised lighting, electronic, and data processing design for identifying Fusarium-damaged kernels in free-fall, an accuracy level of 72% has been reached. Research to improve this level to approach that of the stationary condition is currently ongoing.

## ACKNOWLEDGMENTS

Professor C. Griffey, Department Crop and Soil Environmental Sciences, Virginia Polytechnic Institute and State University, contributed the *Fusarium*-damaged samples. Dr. F. Dowell, USDA Grain Marketing and Production Research Center, Manhattan, KS, contributed the red and white wheat samples. B. Stetzler collected all of the data

## REFERENCES

1. U.S. Food and Drug Administration. 1993. Letter from Ronald Chesemore to State Agricultural Directors, State Feed Control Officials, and Food, Feed and Grain Trade Organizations on Advisory Levels for DON (vomitoxin) in Food and Feed. U.S. Department of Health and Human Services, Public Health Service. September 16<sup>th</sup>, Rockville, MD.
2. FAO. 2004. Worldwide regulations for mycotoxins in food and feed in 2003. Food and Nutrition Paper 81, Food and Agriculture Organization of the United Nations, Rome, Italy.
3. Codex. 2003. Discussion paper on deoxynivalenol. Codex Committee on Food Additives and Contaminants, 35<sup>th</sup> Session (Arusha, Tanzania, March 17-21, 2003). Codex Alimentarius Commission, FAO/WHO, Rome, Italy.
4. Dexter, J.E., and Nowicki, T.W. 2003. Safety assurance and quality assurance issues associated with *Fusarium* head blight in wheat. Pages 420-460 in: *Fusarium Head Blight of Wheat and Barley*. K.J. Leonard and W.R. Bushnell, eds. American Phytopathological Society, St. Paul, MN.
5. Stack, R.W. 2003. History of *Fusarium* head blight with emphasis on North America. Pages 1-34 in: *Fusarium Head Blight of Wheat and Barley*. K.J. Leonard and W.R. Bushnell, eds. The American Phytopathological Society, St. Paul, MN.
6. Hart, L.P. 1998. Variability of vomitoxin in truckloads of wheat in a wheat scab epidemic year. *Plant Dis.* 82:625-630.
7. Seitz, L.M., Eustace, W.D., Mohr, H.E., Shogren, M.D., and Yamazaki. 1986. Cleaning, milling, and baking tests with hard red winter wheat containing deoxynivalenol. *Cereal Chem.* 63:146-150.
8. Tkachuk, R., Dexter, J.E., Tipples, K.H., and Nowicki, T.W. 1991. Removal by specific gravity table of tombstone kernels and associated tricothecenes from wheat infected with *Fusarium* head blight. *Cereal Chem.* 68:428-431.
9. Dowell, F.E., Ram, M.S., and Seitz, L.M. 1999. Predicting scab, vomitoxin, and ergosterol in single wheat kernels using near-infrared spectroscopy. *Cereal Chem.* 76:573-576.
10. Luo, X., Jayas, D.S., and Symons, S.J. 1999. Identification of damaged kernels in wheat using a colour machine vision system. *J. Cereal Sci.* 30:49-59.
11. Ruan, R., Ning, S., Song, A., Ning, A., Jones, R., and Chen, P. 1998. Estimation of *Fusarium* scab in wheat using machine vision and a neural network. *Cereal Chem.* 75:455-459.
12. Atanasoff, D. 1920. *Fusarium*-blight (scab) of wheat and other cereals. *J. Agr. Res.* 20:1-32.
13. Delwiche, S.R. 2003. Classification of scab- and other mold-damaged wheat kernels by near-infrared reflectance spectroscopy. *Trans. ASAE* 46:731-738.
14. Delwiche, S.R., and Hareland, G.A. 2004. Detection of scab damaged hard red spring wheat kernels by near-infrared reflectance. *Cereal Chem.* 81:643-649.
15. Delwiche, S.R., and Gaines, C.S. 2005. Wavelength selection for monochromatic and bichromatic sorting of *Fusarium*-damaged wheat. *Appl. Eng. Agric.* 21:681-688.
16. Delwiche, S.R., Pearson, T.C., and Brabec, D.L. 2005. High-speed optical sorting of soft wheat for reduction of deoxynivalenol. *Plant Disease* 89:1214-1219.
17. SAS. 1988. Proc Discrim. In: *Statistics Guide*, SAS Institute (Cary, NC).
18. Dowell, F.E. 1998. Automatic color classification of single wheat kernels using visible and near-infrared reflectance. *Cereal Chem.* 75:142-144.