*Evaluation of Canning Quality Traits in Black Beans (*Phaseolus vulgaris* L.) by Visible/Near-Infrared Spectroscopy*

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Evaluation of Canning Quality Traits in Black Beans (*Phaseolus vulgaris* L.) by Visible/Near-Infrared Spectroscopy

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Abstract Black bean (*Phaseolus vulgaris* L.) processing presents unique challenges because of discoloration, breakage, development of undesirable textures, and off-flavors during canning and storage. These quality issues strongly affect processing standards and consumer acceptance for beans. In this research, visible and near-infrared (Vis/NIR) reflectance data for the spectral region of 400–2,500 nm were acquired from intact dry beans for predicting five canning quality traits, i.e., hydration coefficient (HC), visual appearance (APP) and color (COL), washed drained coefficient (WDC), and texture (TXT), using partial least squares regression (PLSR). A total of 471 bean samples harvested and canned in 2010, 2011, and 2012 were used for analysis. PLSR models based on the Vis/NIR data showed low predictive performance, as measured by correlation coefficient for prediction (R_{pred}) for APP (R_{pred}=0.275–0.566) and TXT (R_{pred}=0.270–0.681), but better results for predicting HC (R_{pred}=0.517–0.810), WDC (R_{pred}=0.420–0.796), and COL (R_{pred}<0.533–0.758). In comparison, color measurements from a colorimeter on drained canned beans showed consistently good predictions for COL (R_{pred}=0.796–0.907). In spite of the low or relatively poor agreement among the sensory panelists as determined by multirater Kappa analysis (K_{free} of 0.20 for APP and 0.18 for COL), a linear discriminant model using the Vis/NIR data was able to classify the canned bean samples into two sensory quality categories of "acceptable" and "unacceptable", based on panelists' ratings for APP and COL traits of canning beans, with classification accuracies of 72.6 % or higher. While Vis/NIR technique has the potential for assessing bean canning quality from intact dry beans, improvements in sensing and instrumentation are needed in order to meet the application requirements.

Keywords Black beans · Canning quality · Color · Vis/NIR spectroscopy · Visual assessment

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Introduction

Black beans (*Phaseolus vulgaris* L.) are commonly consumed as a canned product. During canning and processing, they are prone to loss of seed color and firmness and skin breakage (Bushey and Hosfield 2007). During processing, beans are generally soaked and must be cooked to render the seeds palatable, inactivate heat labile antinutrients, and permit the digestion and assimilation of protein and starch (Deshpande et al. 1983). The preparation conditions cause structural changes in cells that have a bearing on consumer and processor preferences and requirements for the soaked and cooked seeds. The bean canning industry and bean breeders need nondestructive, preprocessing methods and techniques to predict how well beans withstand the canning process (canning quality).

Canning quality in black beans is influenced by genetics, production environment, and seed handling (Uebersax and Bedford 1980; Wassimi et al. 1990; Wright and Kelly 2011). Phenotypic selection for superior canning quality has been successfully employed in cultivar development (Hosfield and Uebersax 1990). Hosfield and Uebersax (1980) and Hosfield

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et al. (1984) developed a small-scale canning protocol and various physical and chemical tests for phenotypic selection that were related to canning quality and differentiated samples. Today, these tests are routinely used by bean breeders to determine canning quality (Kelly and Cichy 2012). Processors seek beans that expand rapidly and uniformly in the can during processing, leave no sludge at the bottom of the container, have acceptable drained weights and texture after cooking, and cook to tenderness rapidly and uniformly (Deshpande et al. 1983). However, consumers are most conscious of the wholesomeness and quality of black beans including organoleptic aspects such as color, general appearance, and firmness. Beans are an inexpensive source of protein, minerals, vitamins, and plant phytochemicals. They are low in fat and high in fiber. Hence, improved consumer acceptance will enhance health-promoting aspects of the diet and further increase the black bean production opportunities for farmers and processors.

Among quality traits, color is the first sensation that the consumer perceives and is used as an indicator for the acceptance or rejection of raw and cooked beans. In fact, color represents a fundamental physical property of any food, since it has been widely demonstrated that it correlates well with physical, chemical, and sensorial indicators of product quality (Mendoza et al. 2006). Color retention is an integral component of canning quality in black beans. Anthocyanins are a class of flavonoids present in the seed coat and responsible for the black color. Since anthocyanins are water soluble, they readily leach out of seeds during soaking and thermal processing, and the cooked or canned product no longer appears black, but instead appears a shade of brown, which affects consumer acceptance of the canned black beans. There is significant genetic variability for color leaching in black beans, making it possible to improve this trait through breeding and selection. Water uptake during soaking is also an important consideration in bean improvement. The ideal bean from a processor's perspective is one with rapid and even seed expansion during soaking. Water uptake rate affects swelling capacity, which affects the number of cans of beans that can be produced from raw product (known as canner yield) (Hosfield 1991). Thus, the quality of canned beans is determined not only by the canning process but also by the genetics of the raw dry beans used for processing which influences their chemical composition and structural and biological characteristics (Kelly and Cichy 2012).

Hence, evaluation of the canning quality of black dry beans presents unique challenges because of the nature of black bean color and its impact on the sensory attributes after processing. Evaluation of the canning quality is costly and requires specialized equipment as well as at least 100 g of dry seed. It would be very useful to bean breeders to be able to determine the canning quality of breeding lines more efficiently and earlier in the breeding process when less seed is available. A noninvasive optical sensor method such as near-infrared spectroscopy (NIRS) has a potential to be used as an alternative screening method. Based on the relationships between spectral, compositional, or/and organoleptic properties of a set of samples, NIRS coupled with appropriate multivariate statistical methods can accurately and rapidly determine the chemical composition and/or sensorial quality of samples (Mendoza et al. 2012). This technique has several well-known advantages (e.g., speed of analysis, no sample preparation required, low cost per test, analysis of multiple constituents, small-sample size requirements, nondestructive, and potential to plant seed after analysis) over conventional laboratory methods. Additionally, NIRS technology has been successfully used for rapidly determining the composition of a wide variety of foods including intact dried pulses and beans (Hacisalihoglu et al.2010; Plans et al. 2012) and also for assessing physical and sensorial properties of other foods (Nicolaï et al. 2007).

The overall objective of this research was, therefore, to assess the feasibility of visible and near-infrared (Vis/NIR) spectroscopy for predicting five important canning quality traits (i.e., hydration coefficient, visual appearance and color ratings, washed drained coefficient, and texture) from intact dry beans based on partial least squares regression (PLSR) models. In this study, we collected the Vis/NIRS spectra of intact dry beans harvested in three consecutive seasons (2010, 2011, and 2012). In parallel, measurements with the conventional colorimeter were also made for drained canned beans and used in further comparisons.

Materials and Methods

Bean Samples and Processing

Dry beans for this study were obtained from an experimental field of Michigan State University's (MSU) Saginaw Valley Research and Extension Center in Saginaw, Michigan. A total of 471 bean samples harvested in 2010 (259 samples), 2011 (142 samples), and 2012 (70 samples) seasons were used. The samples included 140 unique genotypes (see "Supplemental Table"). The bulk of the genotypes were recombinant inbred lines (RILs) that were developed by crossing two black bean cultivars with contrasting canning quality, "Black Magic" and "Shiny Crow". Black Magic is an opaque black bean with average canning quality but poor color retention following processing. Shiny Crow is a shiny black bean with superior canning quality and color retention. This RIL population exhibits variability for color leaching and appearance in thermally processed beans (Wright and Kelly 2008). In addition, 17 black bean cultivars and breeding lines were included for the analysis, which, together with the recombined inbred lines, allowed for a wide range of physical and sensorial quality attributes of processed beans. After harvest, dry seeds were stored at room temperature until the time of test.

Beans were canned following the small-scale operation protocol that approximates industrial canning on limited sample sizes as described in Hosfield et al. (1984). For each bean type, one dry bean solid sample was soaked in boiling distilled water containing 0.005 % calcium chloride for 10 min. The soaked beans were then canned in 300×407 (i.e., overall diameter and overall height in millimeters with 198- to 227-g capacity) tinplate cans. During the can filling, boiling brine composed of 1.5 % of sucrose, 1.2 % sodium chloride, and 0.005 % calcium chloride in distilled water was added leaving approximately 0.5-cm headspace. Cans were sealed and cooked in a retort for 45 min at 116 °C and 10.4×10^4 Pa (15 psi). After cooking, cans were cooled under cold running tap water and stored for at least 2 weeks at room temperature prior to opening for further evaluations.

Quality Evaluation

Figure 1 depicts the experimental procedure for quality evaluation of black beans in 2010, 2011, and 2012 seasons. Evaluations were made on the contents of all processed cans. Samples were evaluated for instrumental, physical, and sensorial traits at dry, soaked, and canned stages as follows:

Visible and Near-Infrared Reflectance (Vis/NIR) Spectroscopy Scans

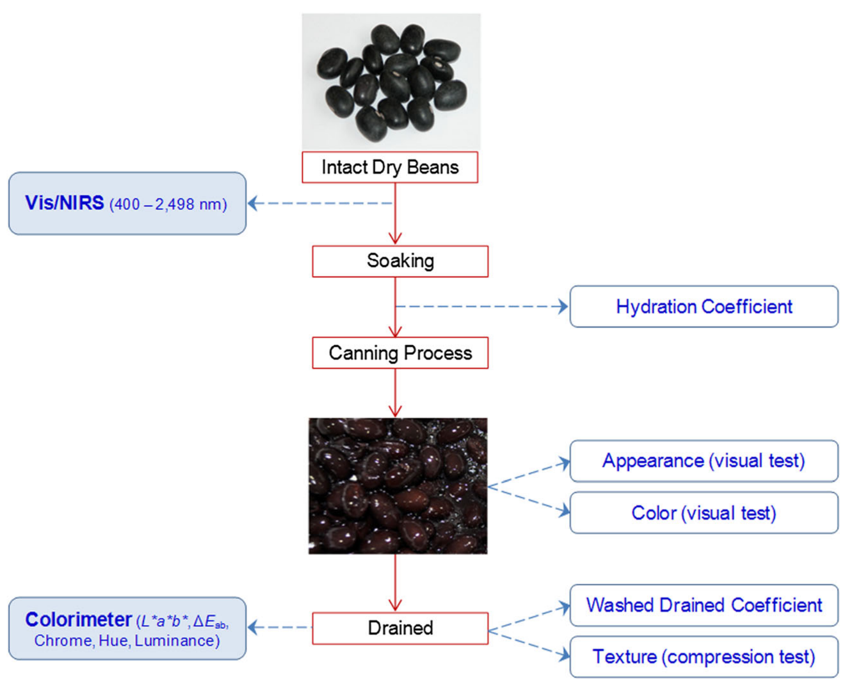
A laboratory Vis/NIR spectrophotometer (model 6500, Foss NIRSystems Inc., Silver Springs, MD, USA) was used to acquire spectral reflectance from intact dry beans in the range of 400 to 2,498 nm collected at increments of 2 nm, yielding each spectrum of 1,050 wavelengths. The model 6500 is a predispersive grating NIR instrument with a dual silicon and PbS detector system which allows full-range measurement of visible and near-infrared from 400–2,500 nm. For scanning, the sample cell (Model Natural Product Sample Cell, Foss NIRSystems Inc., Silver Springs, MD, USA) was filled and smoothly compacted/leveled to provide a stable measurement against sample orientation.

Hydration Coefficient (HC)

Hydration coefficient is the ratio of the weight (g) of the sample after soaking to the weight (g) of the intact dry seed. HC was calculated following the procedure recommended by Hosfield and Uebersax (1980). HC is a measure of the degree of hydration or water uptake after soaking.

Sensory Analysis Upon opening, canned beans were subjectively evaluated for overall appearance (i.e., seed shape, splits, clumps, color uniformity, and visual aspect such as surface texture) and black color retention (or discoloration) by a sensory panel of 13 to 15 consumers or panelists on a 7-point Hedonic scale or categories as follows: 1=very undesirable, 2=moderately undesirable, 3=slightly undesirable, 4=neither desirable nor undesirable, 5=slightly desirable, 6=moderately desirable, and 7=very desirable. The consumer panel consisted of students, technicians, researchers, and professors at Michigan State University. The resultant appearance (APP) and color (COL) scores were then averaged across

Fig. 1 Experimental procedure for quality evaluation of black beans in 2010, 2011, and 2012



judges for each sample and used in further prediction and grading analyses.

In addition, the Free-marginal Multirater Kappa (multirater K_{free}) method was used for the estimation of agreement between the raters or bean panelists. Multirater K_{free} is a statistical measure of inter-rater agreement for qualitative items, and it is recommended when raters are not restricted in the number of cases that can be assigned to each category, which is often the case in the typical agreement study (Randolph 2005). The method is independent on their marginal distributions of frequency rates, such that it allows for analysis of distributions of cases into categories with high degree of asymmetry. Values of Kappa can range from −1.0 to 1.0, with −1.0 indicating perfect disagreement below chance, 0.0 indicating agreement equal to chance, and 1.0 indicating perfect agreement above chance. A rule of thumb is that a Kappa of 0.70 or above indicates adequate inter-rater agreement. One possible interpretation of Kappa suggested by Altman (1991) is as follows: (i) poor agreement=less than 0.20, (ii) fair agreement=0.20 to 0.40, (iii) moderate agreement=0.40 to 0.60, (iv) good agreement=0.60 to 0.80, and (v) very good agreement=0.80 to 1.00. The analysis was carried out using the interactive Online Kappa Calculator freely available from Randolph (2008).

Washed Drained Coefficient (WDC) The washed drained coefficient was calculated by dividing the washed drained weight (g) of cooked beans by the soaked bean weight (g) (Hosfield and Uebersax 1980). WDC is a measure of the degree of hydration during cooking and thermal processing.

Texture Analysis (TXT) Bean firmness was estimated on 100 g of each rinsed and drained canned sample using a standard shear-compression cell of a Kramer Shear Press (Food Technology Corp., Rockville, MD, USA). The Kramer Shear press uses a dynamic hydraulic system to determine the peak force needed for the loss of total bean integrity. Values are reported as kilograms per 100 g.

Color Analysis A colorimeter, HunterLab's LabScan XE (Hunter Associates Laboratory, Inc., Reston, VA, USA), was used for extracting color parameters from washed drained canned beans. This instrument readout can be set to any CIE units. Its technical characteristics are 0/45 geometry, 10° for the normal observer, and D_{65} as the standard illuminant. For analysis, seven measurements of color were extracted: $L^*a^*b^*$ or CIELAB color channels, color difference ΔE^*_{ab}, hue (h^*_{ab}), chrome (C^*_{ab}) or saturation, and luminance (Y). The color difference ΔE^*_{ab} was calculated as the Euclidean distance between two points in the $L^*a^*b^*$ space, also called the CIE 1976 ($L^*a^*b^*$) color difference formula which is computed using the actual L^*, a^*, and b^* values from beans against the white plate standard (*std*) having an L^*_{std}=93.5, a^*_{std}=−1.4, and b^*_{std}=3.2. While the color difference ΔE^*_{ab} is widely used, its chrome scale is known to be fairly nonlinear. The luminance intensity or brightness of beans was computed from the *RGB* signals by forming a weighted sum of the red, green, and blue components.

$$Y = 0.2162 \times R_{linear} + 0.7152 \times G_{linear} + 0.0722 \times B_{linear} \quad (1)$$

The explanation of these weights is that for equal amounts of color, the eye is more sensitive to green, then red, and then blue. Thus, the weighted sum is perceptually more uniform.

Model Development for Prediction and Classification

Quantitative calibration models for predicting quality traits of dry beans from 2010, 2011, 2012, and their combination were developed using PLSR. PLSR provides a set of orthogonal factors that have the best predictive power from the combinations of different number of variables or features. The optimum numbers of latent variables were selected on the basis of minimizing the standard error of cross validation (SECV), which was calculated with the leave-one-out method. PLSR calibration models were developed in MATLAB 7.5.0 (The MathWorks, Inc., Natick, MA, USA) with the PLS Toolbox (Eigenvector Research, Inc., Wenatchee, WA, USA). Once the calibration models for the five canning quality traits of beans (i.e., HC, APP, COL, WDC, and TXT) were established, they were used to predict the test or validation set of samples.

For calibration and prediction, the extracted Vis/NIRS spectral data covering the spectral range of 400 to 2,498 nm at increments of 2 nm were preprocessed by performing first derivatives (1Der) as well as the multiresolution continuous wavelet transform (CWT) method based on continuous one-dimensional decomposition using the *symlet* wavelet at 64 scales. The resultant vector of spectral features after applying CWT represents the root mean square of the transformed data at each single wavelet. The details of calculating these spectral features can be found in Mendoza et al. (2011, 2012). For the extracted data from the HunterLab XE colorimeter, the seven color parameters L^*, a^*, b^*, ΔE_{ab}, chrome, hue, and luminance were first autoscaled by subtracting the mean and dividing by the standard deviation and then used for model building.

Prior to the model development, each set of beans were first sorted for their quality traits; the sorted samples were then divided into two groups: 75 % of the samples were used for calibration and the remaining 25 % samples were used for prediction. For a given analysis, the calibration and prediction results may vary depending on how the calibration and prediction samples are actually selected. To better evaluate the performance, we ran calibrations and predictions four times.

After calibration and prediction had been done for the first time, a second set of 25 % samples was taken out from the original calibration set of samples, and it was used for prediction in the second run. The procedure was repeated until all samples had been taken out for prediction once. Mean values for number of latent variables or factors, correlation coefficient, and standard error for the calibration and validation data sets (i.e., R_{cal} and R_{pred}, and SEC and SEP, respectively) were calculated to test the performance of Vis/NIR and conventional colorimeter techniques.

In addition to the regression analysis for sensory traits using the 7-point Hedonic scale, a classification analysis was carried out for sorting the appearance and color data of cooked beans into two quality groups: "acceptable" or "unacceptable" categories using linear discriminant analysis (LDA). These two categories were assigned as follows: First, the frequency probabilities of each category (from 1 to 7) for both APP and COL canning traits were obtained from the scores assigned by the panelists for each canned bean sample. Then, the frequency probabilities of the first two scores (1=very undesirable and 2=moderately undesirable) were combined and considered as a single "undesirable" quality group, representing the bean samples with the lowest preference in APP and COL by the panelists. The remaining categories, that is, the frequency probabilities of successes for scores higher than 3 (slightly undesirable) were also combined together, representing the group of beans which panelists would consider acceptable in APP and COL. Finally, since the available number of bean samples for the undesirable group in both traits was not sufficient for classification tests (lower than 100 samples combining 2010, 2011, and 2012 seasons), the new acceptable or unacceptable categories were assigned considering four thresholds of probability for selecting beans with acceptable quality: 0.7, 0.75, 0.8, and 0.9. These selected thresholds prevent an imbalance in the number of samples for each quality group and also improve the assessment of the robustness of the model.

LDA was performed using the codes from Balu Matlab Toolbox (Mery 2011) run in MATLAB 7.5.0 (The MathWorks, Inc., Natick, MA, USA). The best subset of Vis/NIR features after preprocessing (that leads to the smallest classification error) was found using the sequential forward selection (SFS) algorithm. Similar to the PLSR analysis, the performance of the classifier is tested for an independent set of samples. In our experiments, this procedure was repeated four times through rotating the training and test data; each time, 75 % of the data was used for training and the rest (25 %) for testing. Additionally, to avoid bias in the model development, the same number of samples for acceptable and unacceptable categories was used for sorting analysis. This sampling procedure was repeated in random six times; for each of the six sampling data sets, the same calibration and testing procedure, as described above, was followed. The average values for latent variables for the models and their overall performance (i.e., standard error and correlation coefficient for testing) were reported for comparisons.

Results and Discussion

Quality Measurements of Test Beans

Figure 2 presents the distribution of the data sets for APP, COL, HC, WDC, and TXT of canned black beans for the 2010, 2011, and 2012 harvest seasons. The bulk of the black bean samples evaluated were RILs that share the same parents. The parental genotypes Black Magic and Shiny Crow have different canned bean appearance and color. Overall measurements showed nonuniform distributions for all years with the distributions for 2012 being the most heterogeneous due to the low-density distribution of the quality traits and smaller number of samples tested for this season (70 samples), as compared with the number tested for 2010 (259 samples) and 2011 (142 samples) harvest seasons. The nonuniform, bimodal distributions for HC and WDC in 2010 and 2011 are likely to reflect the genetic variability of these traits in the RILs. A genetic study of the canning quality in the Black Magic× Shiny Crow RIL population indicated that WDC and HC were controlled by a single genomic region (Cichy et al. 2012).

The coefficient of variability, or CV (%), of the measured quality traits for the three harvest seasons ranged from 10.4 to16.7 % for HC, from 14.1 to 19.8 % for APP ratings, from 19.6 to 21.0 % for COL ratings, from 10.6 to 13.4 % for WDC, and between 16.0 and 31.9 % for TXT. The number of samples for COL, HC, and WDC in 2010 and 2011 were larger than that in the 2012 season, but the data sets from 2012 showed the largest range of variability for these traits (CV=21.0, 16.7, and 13.4 %, respectively). It should also be noted that the Hedonic rate 6 (moderately desirable) was scarcely assigned, and the rate 7 (very desirable) was never assigned by panelists of cooked beans for both APP and COL traits. However, scoring peaks were found mostly in between categories 3 and 4. The shape of the data distribution and its range of variation could affect, to some extent, the robustness and reproducibility of the prediction and classification models, and hence, they should be considered for suitable comparisons among seasons. Additionally, combining the data from 2010, 2011, and 2012 correlation analysis between pairs of quality traits showed the highest correlation for HC/WDC (R=0.930), followed by HC/TXT (R=0.547), and COL/APP (R=0.534). For the rest of the pairs, however, R values were lower than 0.354.

PLS Predictions of Bean Canning Quality Traits

In this research, the prediction performance of Vis/NIRS measurements on "intact dry beans" (before processing) and

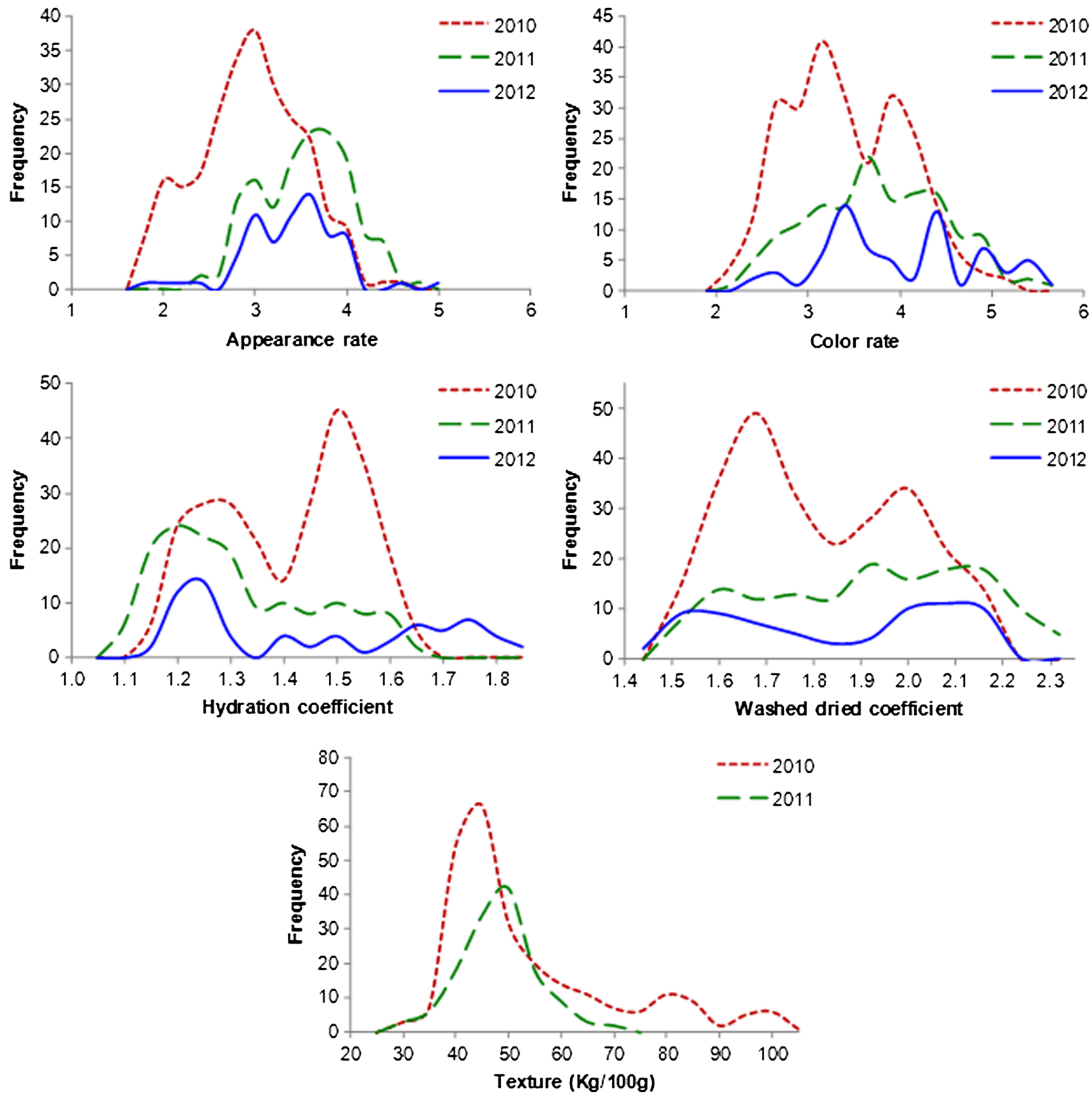


Fig. 2 Distributions of visual appearance and color rates, hydration coefficient, washed dried coefficient, and texture measurements of canned beans in 2010, 2011, and 2012

the performance of extracted color measurements using a conventional colorimeter on "drained canned beans" (after processing) for the five quality traits routinely assessed along the canning process were tested and compared. Tables 1–5 summarize the PLS prediction performance for HC, APP, COL, WDC, and TXT, respectively, using Vis/NIRS and the colorimetric measurement data for 2010, 2011, 2012, and for their combination.

Preliminary analysis for the Vis/NIRS data showed that better prediction results were found after performing CWT and 1Der on the relative reflectance data in comparison with the smoothed relative reflectance and second derivative preprocessing methods (results are not shown here). Hence, these two best preprocessing methods were implemented in the current study, and only their results are reported in Tables 1–5. Overall, using CWT was advantageous for HC, COL, and WDC predictions, as indicated by lower numbers of variables (Avg. Fact.) for building PLSR models, higher R_{cal} and R_{pred}, and lower *SEC* and *SEP,* compared with those using the 1Der preprocessing method. Furthermore, in spite of the inherent variability of the quality traits among the bean cultivars from different seasons, PLSR models for the combined seasons (i.e., 2010, 2011, and 2012) showed relatively consistent prediction results for COL, HC, and WDC traits, although, in general, more variables were needed for the model building. Predictions of HC and WDC for the combined seasons showed the largest number of latent variables ranging from 18 to 25 (Tables 1 and 4). It should be noted, however, that the best prediction results were obtained for COL using the extracted data from a colorimeter, and for HC and WDC using Vis/NIR data.

Table 1 Calibration and prediction results of hydration coefficient (after soaking) using Vis/NIR spectroscopy on intact dry beans and colorimeter on drained canned beans for 3 processing years and their combination

Hydration coefficient		2010					2011					2012					Combined seasons				
		Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$	Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$	Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$	Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$
Vis/NIRS	1Der	21	0.890	0.06	0.791	0.09	7	0.692	0.10	0.517	0.13	8	0.893	0.10	0.771	0.15	25	0.820	0.09	0.733	0.11
	CWT	18	0.913	0.06	0.810	0.08	9	0.791	0.09	0.569	0.13	13	0.950	0.06	0.760	0.16	22	0.868	0.08	0.758	0.11
Colorimeter		4	0.695	0.10	0.692	0.10	3	0.527	0.12	0.509	0.12	3	0.721	0.16	0.667	0.17	6	0.654	0.12	0.644	0.13

Vis/NIR is in the wavelength range of 400 to 2,498 nm in steps of 2 nm; colorimeter: $L^*a^*b^*$, ΔE_{ab}, chrome, hue, and luminance

1Der and *CWT* first derivatives and continuous wavelet transform decomposition for NIR data*; Avg. Fact.* average number of features required for the partial least square model after optimization; $\overline{R}_{cal}$ and $\overline{R}_{pred}$ average correlation coefficients of calibration and prediction, respectively, over four calculations; $\overline{SEC}$ and $\overline{SEP}$ average standard error for calibration and prediction, respectively, over four calculations

Table 2 Calibration and prediction results of visual appearance (after canning) using Vis/NIR spectroscopy on intact dry beans and colorimeter on drained canned beans for 3 processing years and their combination

Appearance		2010					2011					2012					Combined seasons				
		Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$	Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$	Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$	Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$
Vis/NIRS	1Der	8	0.518	0.48	0.308	0.56	18	0.838	0.26	0.493	0.48	2	0.522	0.44	0.342	0.54	15	0.677	0.44	0.566	0.50
	CWT	4	0.478	0.49	0.275	0.57	9	0.767	0.30	0.474	0.46	2	0.544	0.43	0.362	0.53	11	0.689	0.43	0.534	0.52
Colorimeter		3	0.300	0.54	0.185	0.57	2	0.523	0.41	0.493	0.43	1	0.431	0.48	0.436	0.48	5	0.547	0.51	0.520	0.52

Vis/NIR is in the wavelength range of 400 to 2,498 nm in steps of 2 nm; colorimeter: $L^*a^*b^*$, ΔE_{ab}, chrome, hue, and luminance

1Der and *CWT* first derivatives and continuous wavelet transform decomposition for NIR data; *Avg. Fact.* Average number of features required for the partial least square model after optimization; $\overline{R}_{cal}$ and $\overline{R}_{pred}$ average correlation coefficients of calibration and prediction, respectively, over four calculations; $\overline{SEC}$ and $\overline{SEP}$ average standard error for calibration and prediction, respectively, over four calculations

Table 3 Calibration and prediction results of visual color (after canning) using Vis/NIR spectroscopy on intact dry beans and colorimeter on drained canned beans for 3 processing years and their combination

Color		2010					2011					2012					Combined seasons				
		Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$	Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$	Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$	Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$
Vis/NIRS	1Der	17	0.780	0.40	0.578	0.56	14	0.837	0.39	0.533	0.69	10	0.832	0.40	0.682	0.64	18	0.755	0.48	0.658	0.56
	CWT	13	0.805	0.38	0.577	0.56	13	0.896	0.32	0.648	0.57	19	0.990	0.10	0.758	0.59	16	0.817	0.42	0.715	0.52
Colorimeter		4	0.831	0.36	0.827	0.36	3	0.910	0.30	0.907	0.31	4	0.903	0.35	0.878	0.41	7	0.802	0.44	0.796	0.44

Vis/NIR is in the wavelength range of 400 to 2,498 nm in steps of 2 nm; colorimeter: $L^*a^*b^*$, ΔE_{ab}, chrome, hue, and luminance

1Der and *CWT* first derivatives and continuous wavelet transform decomposition for NIR data; *Avg. Fact.* Average number of features required for the partial least square model after optimization; $\overline{R}_{cal}$ and $\overline{R}_{pred}$ average correlation coefficients of calibration and prediction, respectively, over four calculations; $\overline{SEC}$ and $\overline{SEP}$ average standard error for calibration and prediction, respectively, over four calculations

Table 4 Calibration and prediction results of washed drained coefficient (after canning) using Vis/NIR spectroscopy on intact dry beans and colorimeter on drained canned beans for 3 processing years and their combination

Washed drained coefficient		2010					2011					2012					Combined seasons				
		Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$	Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$	Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$	Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$
Vis/NIRS	1Der	21	0.876	0.09	0.796	0.12	9	0.709	0.16	0.420	0.23	10	0.912	0.10	0.733	0.19	25	0.781	0.13	0.674	0.16
	CWT	17	0.905	0.08	0.786	0.12	10	0.795	0.14	0.470	0.23	11	0.951	0.07	0.735	0.18	18	0.815	0.12	0.697	0.16
Colorimeter		4	0.675	0.13	0.662	0.14	3	0.481	0.20	0.431	0.21	3	0.686	0.17	0.669	0.18	4	0.607	0.17	0.597	0.17

Vis/NIR is in the wavelength range of 400 to 2,498 nm in steps of 2 nm; colorimeter: $L^*a^*b^*$, ΔE_{ab}, chrome, hue, and luminance

1Der and *CWT* first derivatives and continuous wavelet transform decomposition for NIR data; *Avg. Fact.* average number of features required for the partial least square model after optimization; $\overline{R}_{cal}$ and $\overline{R}_{pred}$ average correlation coefficients of calibration and prediction, respectively, over four calculations; $\overline{SEC}$ and $\overline{SEP}$ average standard error for calibration and prediction, respectively, over four calculations

Table 5 Calibration and prediction results of texture (kg/100 g) (after canning and drained) using Vis/NIR spectroscopy on intact dry beans and colorimeter on drained canned beans for 3 processing years and their combination

Texture		2010					2011					2012					Combined seasons				
		Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$	Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$	Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$	Avg Fact	$\overline{R}_{cal}$	$\overline{SEC}$	$\overline{R}_{pred}$	$\overline{SEP}$
Vis/NIRS	1Der	17	0.845	8.73	0.683	12.52	6	0.613	5.70	0.337	7.50	-	-	-	-	-	16	0.759	9.25	0.668	10.77
	CWT	11	0.836	9.00	0.681	12.74	3	0.502	6.20	0.270	7.69	-	-	-	-	-	10	0.752	9.36	0.634	11.35
Colorimeter		4	0.608	13.11	0.585	13.43	1	0.054	7.34	0.169	7.46	-	-	-	-	-	4	0.494	12.42	0.484	12.53

Vis/NIRS is in the wavelength range of 400 to 2,498 nm in steps of 2 nm; colorimeter: $L^*a^*b^*$, ΔE_{ab}, chrome, hue, and luminance

1Der and *CWT* first derivatives and continuous wavelet transform decomposition for Vis/NIR data; *Avg. Fact.* average number of features required for the partial least square model after optimization; $\overline{R}_{cal}$ and $\overline{R}_{pred}$ average correlation coefficients of calibration and prediction, respectively, over four calculations; $\overline{SEC}$ and $\overline{SEP}$ average standard error for calibration and prediction, respectively, over four calculations

Predictions of sensory analysis showed low accuracy and inconsistent results for APP rates (R_{pred}<0.566, SEP=0.52) among the harvest seasons and their combination using either Vis/NIR or colorimeter (Table 2). Moderate predictions were found for COL using Vis/NIR (R_{pred}<0.758, SEP=0.59) (Table 3). Low/moderate correlation coefficients can be explained by the high variation of the panelist responses. A multirater K_{free} analysis showed average measures for the 2010, 2011, and 2012 seasons of 0.20 (where raters agreed on 32 % of cases) for APP and of 0.18 (where raters agreed on 30 % of cases) for COL, which means a fair to poor agreement among the raters for these visual traits (Altman 1991). These results suggest that there is a need to adjust the current quality categories (i.e., a fewer categories) or/and redefine the factors perceived as different by the panelists to allow for better discrimination in canning quality within the black bean samples.

The best predictions were found for COL using the data from the colorimeter and with a small number of latent variables (ranging from 3 to 7). These were consistent among seasons and significantly better (p<0.05) than using Vis/NIRS for all seasons and combination (Table 3) with R_{pred} values ranging from 0.796 to 0.907 and SEP from 0.44 to 0.31, respectively. The improvement in prediction with this method is expected since the measurements with the colorimeter were carried out on the canned bean samples. With the exception of 2011, the prediction results for WDC were consistent for 2010, 2012, and their combination (including the 2011 data set) using both Vis/NIR and colorimetric techniques. However, significantly better results for WDC (p<0.05) were found using the CWT decomposition method (Table 4).

Although decent calibration results based on the Vis/NIR data were obtained for TXT measurements from 2010 and for its combination with 2011 season (Table 5), their prediction results for the test data set were, in general, low and inconsistent between seasons. The color data from colorimeter, as it would have been expected, did not show reasonable predictions for TXT. It was observed in linear correlation analysis that correlations between TXT and color parameters from colorimeter (L^*, a^*, b^*, ΔE_{ab}, chrome, and hue) were low, ranging from −0.320 to 0.011, which are not in agreement with a positive correlation between appearance and texture reported in a previous study on white beans (Walters et al. 1997). In this study, however, correlations between appearance and texture were 0.147 and 0.216 for 2010 and 2011 harvest seasons, respectively.

As beans are being cooked, two phenomena are expected to occur simultaneously—beans absorb and adsorb water, and this water-holding capacity is associated with physical entrainment and the hydrophilic properties of macromolecules. In the meantime, beans also lose solids during cooking, and solid loss is accompanied by structural changes that reduce physical entrainment. Thus, a bean sample with an excessive loss of solids or vice versa, which is with large swelling capacity, may have an atypically low or high WDC (Wassimi et al. 1990). These natural property modifications and structural changes, which are specific for different genotypes, production environment, and harvest seasons, not only affect the external and internal physicochemical and organoleptic properties of beans but also make it more difficult to predict some quality traits from intact seeds. In addition, it should be expected that these complex transport phenomena of water and solids from beans as well as the physicochemical quality changes vary for different bean genotypes during the canning process. This may explain the low-prediction accuracy for APP and TXT traits.

In addition to the complex internal and external changes of beans during process, nonuniform and/or tight range distributions of the quality traits were also the factors limiting the overall performance of the Vis/NIR technique. Prediction and classification models are typically built using multivariate regression analysis, whose performance in most cases depends on the characteristics of the data. Kuang and Mouazen (2011) showed that the number of samples and its distribution tended to affect the robustness and accuracy of the calibration models developed. These factors require careful consideration and need to be addressed in future research in order to achieve better performance of the models. The calculated ratios of sample standard deviation to standard error of prediction (or RPD) were, in general, low/moderate, ranging from 1.1 to 2.2 for Vis/NIR and 1.0 to 2.4 for colorimeter. Nonetheless, the canning quality models for the combined data were generally more robust, in terms of RPD values.

For better visualization of the performance of these PLSR models for COL, HC, and WDC, Fig. 3 shows the prediction results by the Vis/NIR and conventional colorimetric data for the combined data from 2010, 2011, and 2012 seasons. The fitted regression lines for the calibration and prediction data sets overlap well in all the ranges. From these plots, we can visually confirm that better correlations for COL predictions (R_{pred}=0.796, SEP=0.44) are obtained using the data from colorimeter, and for HC (R_{pred}=0.758, SEP=0.11) and WDC (R_{pred}=0.697, SEP=0.16) using the Vis/NIR data. Considering the fact that whole dry seeds were used to predict the canning quality of processed beans, overall results revealed promising opportunities for evaluating bean quality traits using Vis/NIR technique.

Recent studies have been reported on determining individual seed composition in raw dry beans. Hacisalihoglu et al. (2010) demonstrated the potential of NIR technique to predict protein, starch, and seed weight in intact seeds of common beans collected from 267 individual bean seeds representing 91 diverse genotypes. Plans et al. (2012) showed that NIR can help in breeding research and quality evaluation to estimate parameters such as dietary fiber, uronic acids, ashes, calcium, and magnesium from intact beans and ground seed coat samples. They also concluded that NIR can also help in monitoring the sensory properties of marketable seeds.

Grading of Beans into Two Visual Quality Groups

To improve the capability of Vis/NIR technique for modeling the bean preferences of appearance and color of a group of consumers (or panelists), the sensory rates for APP and COL were split to acceptable and unacceptable categories and classified applying the LDA method. Figure 4 depicts the performance of classification using different threshold probabilities (0.7, 0.75, 0.8, and 0.9) to be selected into the acceptable category. These thresholds are essential for classifying beans into distinct market quality classes, since they impact, to some degree, the expected canning quality of a market class.

Considering the two categories for analysis, a higher frequency of breeding lines with acceptable APP and COL traits was observed for all harvest seasons. Also, the multirater K_{free} for the 2010, 2011, and 2012 seasons in average significantly improved to 0.41 (where raters agreed on 70 % of cases) for APP and of 0.50 (where raters agreed on 75 % of cases) for COL, which mean a "moderate" agreement among the raters for both visual traits, respectively. Figure 4 shows the classification performance of different probabilities of success to be selected into the acceptable category of canned beans. Overall classification performances and number of latent variables for model building with probabilities of success of 0.7, 0.75, 0.8, and 0.9 were for APP 71.9 % (16 variables), 75.5 % (14 variables), 71.4 % (15 variables), and 73.0 % (13 variables), respectively, and for COL 73.1 % (18 variables), 75.2 % (18 variables), 71.0 % (17 variables), and 71.0 % (17 variables), respectively. Although low-prediction accuracies were found for APP rates using PLSR models, these classification results revealed that the APP variability can be better explained using a LDA model (with an overall performance of 73.0 % and peak at the probability of 0.75) when only two quality categories or grades of beans are considered. Similar results, in the same range of probabilities of success, were also observed for COL rates which in this case showed an average performance of 72.6 % and peak at the probability of 0.75 (Fig. 4).

The LDA models promisingly predicted two categories of quality preferences for appearance and color of canned beans, even when the panelists' agreement was only moderate. Hence, the current approach using Vis/NIR technique has potential as an objective method for the APP and COL prediction of canned beans from intact dry seeds. Moreover, inclusion of color data and surface textural features from digital color or grayscale images of intact seeds would likely improve the prediction and grading of beans by quality before processing. Color and textural image features have been successfully used in various applications for the characterization and evaluation of surface appearance of agricultural foods,

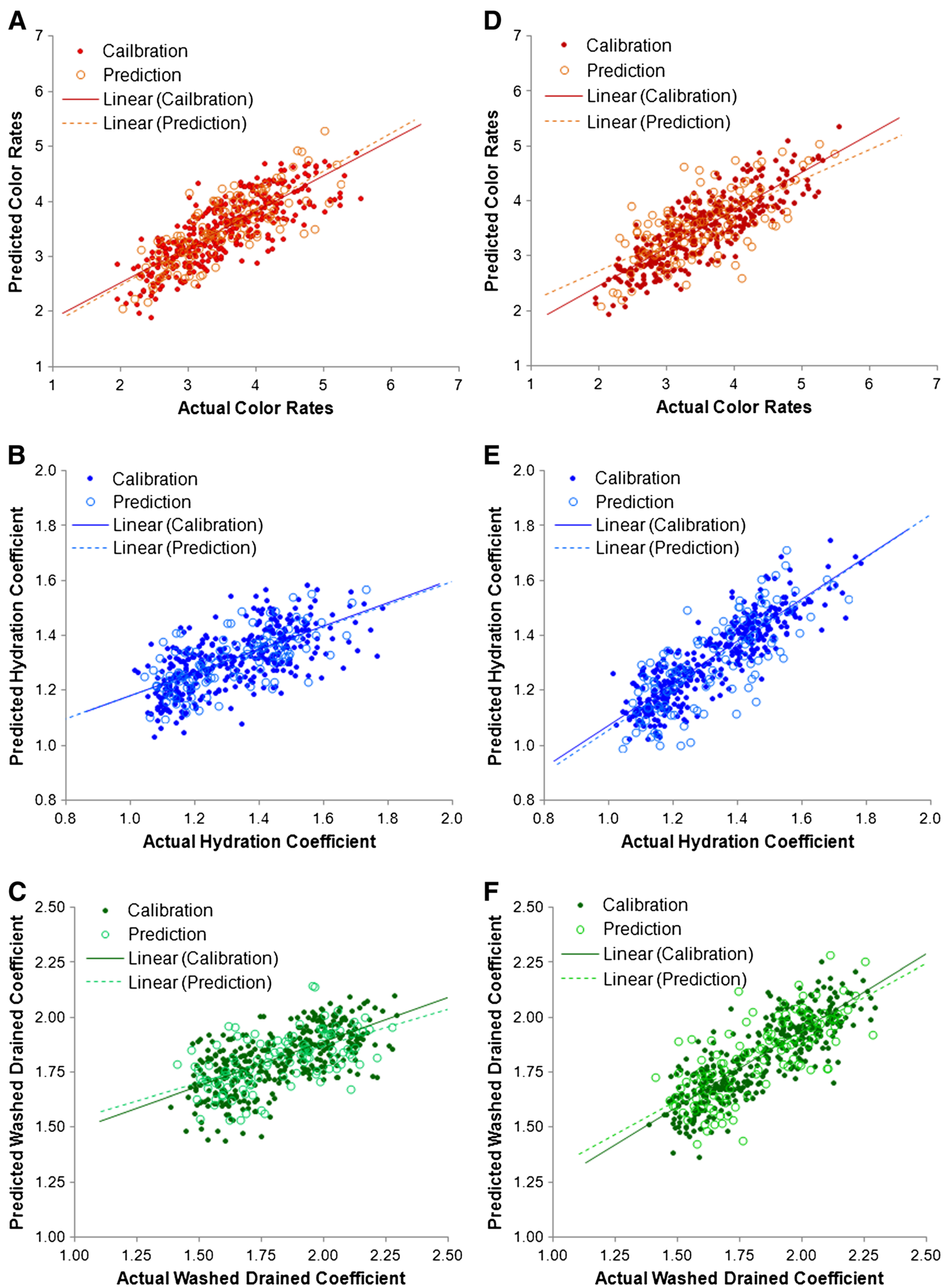


Fig. 3 Predictions for visual color rates, hydration coefficient, and washed drained coefficient of cooked beans using visible and near-infrared (Vis/NIR) spectroscopy (**a**, **b**, **c**, respectively) and conventional colorimeter (**d**, **e**, **f**, respectively) for the combined data of 2010, 2011, and 2012 seasons

such as in lentils (Shahin and Symons 2003), classification of ripening bananas and potato chips (Mendoza 2005), and recognition of grains, fruits, and flowers (Savakar and Anami 2009).

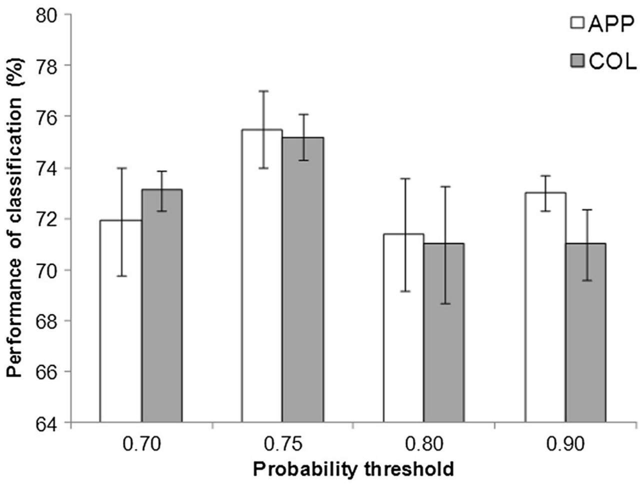


Fig. 4 Classification of dry beans into two quality categories, i.e., acceptable and unacceptable, using Vis/NIR data for appearance (APP) and color (COL) traits based on different probabilities of acceptance

In general, predictions of these five quality traits need to be further improved for practical application of Vis/NIR technology in the canning industry. To improve canning quality assessment from intact dry beans, it would be desirable to consider additional spectral imaging techniques (i.e., multispectral or hyperspectral) and image processing methods. Research in this area is still in its infancy, and there are opportunities for further exploring various techniques for evaluations of canning quality traits of black bean and/or other classes of bean.

Another critical quality trait related to the canning quality and color retention is the coat gloss or luster of the dry seeds. Recent studies by Cichy et al. (2012) showed a moderate negative relationship (R=−0.77) between visual color rating by a sensory panel and the lightness component, L^*, from CIELAB color space. Hence, seed coat luster did not appear to have advantage in canned bean color retention. This is in contrast to earlier studies which suggested that lines with shiny seed coats have superior color retention due primarily to the seed coat shine (Wright and Kelly 2008). It is worth mentioning that preliminary tests for the current study confirmed that LDA classification models of canning quality based on bean gloss of intact seeds for the 2010, 2011, and 2012 seasons showed low performances, ranging from 52.6 to 66.74 %. Hence, the bean coat gloss trait was not included in the current study.

The consumption of black bean has increased recently in the USA (USDA-ERS 2011). Hence, there is an increasing need for cultivars with superior canning quality and color retention. Bean breeders must include canning quality, along with seed yield, disease resistance, and plant architecture, in their selection. However, the standard method of processing quality evaluation has limited the number of lines that can be evaluated. The use of NIRS and color imaging techniques offers great potential for selection in early generations when seed quantities are limited. Furthermore, identifying the differences in canning quality among diverse bean breeding lines and their relationships with consumer quality preferences continues to be challenging in those bean breeding programs where canning facilities are not available.

Black bean is a nutritionally rich seed legume. Hence, improved consumer acceptance of its processed products (e.g., canned beans) will contribute to the health and nutrition and further increase black bean production opportunities for farmers and processors. The present study evaluated the feasibility of Vis/NIR spectroscopy for predicting from intact dry bean canning quality traits or attributes (i.e., HC, APP, COL, WDC, and TXT), which are routinely used by bean breeders and processors. A prior knowledge of these quality traits before canning would allow better decisions by bean breeders and processors.

Conclusion

This study explored the feasibility of Vis/NIRS technique for predicting canning quality traits from intact dry beans (i.e., before canning). The technique gave better prediction of HC, WDC, and visual COL ratings, in comparison with poor prediction accuracies for visual APP and TXT of canned beans. Hence, further improvements in Vis/NIR measurement, along with additional spectral imaging technique (e.g., multispectral and hyperspectral) and image processing methods, should be considered.

In spite of the high genetic variability of bean samples as well as the relatively low sensory agreement among the panelists' ratings for the appearance and color attributes (multirater Kappa analysis, K_{free}, of 0.20 for APP and 0.18 for COL), linear discriminant models using different preference probabilities of success (0.7, 0.75, 0.8, and 0.9) were able to grade the bean samples into two sensory quality categories (i.e., acceptable and unacceptable) with average classification accuracies of 72.6 % or higher. This shows that statistical modeling of sensorial preferences for APP and COL using Vis/NIR data has the potential to predict consumer preferences of canned black beans.

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