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Some Physical Properties of Distillers Dried Grains With Solubles (DDGS)

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ABSTRACT. *With the rapid growth in the fuel ethanol industry in recent years, considerable research is being devoted to determining distillers dried grains with solubles (DDGS) nutritional properties and to optimizing their inclusion in livestock diets; physical properties of these materials, however, have been largely ignored. Using standard laboratory methods, several physical properties for typical DDGS streams were determined, including moisture content, water activity, thermal properties (conductivity, resistivity, and diffusivity), bulk density, angle of repose, and color. The DDGS samples in this study were golden-brown in color and exhibited physical properties similar to other dry feed ingredients, such as hominy feed, corn gluten feed, and other corn-based materials. As a first step, the numerical data generated during this study will help fill a current void in design information for the ethanol and livestock industries.*

Keywords. *Characterization, Coproducts, Corn, Distillers grains, Distillers dried grains with solubles, DDGS, Ethanol, Evaluation, Physical properties.*

Currently corn grain is the primary biological material that can be economically converted into bioethanol on an industrial scale. The number of corn ethanol plants, and their processing capacities, has been markedly increasing in recent years. For example, in 2005 97 manufacturing plants in the United States had an aggregate production capacity of nearly 15.8 billion L/y (4.2 billion gal/y), which represents a growth of 156% over the previous five years. More information on the historical growth of this industry can be found in Lyons (2003), BBI (2006), and RFA (2006). The corn-based fuel ethanol industry is poised to produce substantial quantities of biofuel during the coming century as it continues its rapid expansion.

Ethanol manufacturing from corn grain results in three main products: bioethanol, the primary end product; residual nonfermentable corn kernel components, which are typically marketed as the coproduct known as distillers dried grains with solubles (DDGS), and carbon dioxide. A rule of thumb commonly used in industry states that for each 1 kg of corn processed, approximately 1/3 kg of each of these constituent product streams will be produced. The production process consists of several steps, including grinding, cooking, liquefying, saccharifying, fermenting, and distilling the corn grain. In-depth information on this process can be found in Tibelius (1996), Weigel et al. (1997), Dien et al. (2003), and Jaques et al. (2003).

The nonfermentable residual materials following fermentation are removed from the process stream during the distillation stage in the form of stillage. After removing excess water via centrifugation, these wet grains are combined with condensed distillers solubles, dried to ensure a substantial shelf life, and then sold as DDGS to local livestock producers, or shipped via truck or rail for use by distant customers for inclusion in feed rations. The sale of DDGS contributes substantially to the economic viability of ethanol manufacturing itself and is thus a vital component to each plant's operations. Hence the nutritional content and quality of DDGS is important to ethanol processors. Several studies have examined chemical and nutritional properties of these byproduct feeds, including Belyea et al. (1998), Spiehs et al. (2002), Belyea et al. (2004), and Shurson et al. (2004). Rosentrater et al. (2005) comprehensively reviewed much of the chemical and nutritional research to date.

There is, however, a scarcity of information on the physical properties of DDGS. These data are not only essential for livestock diet formulation, but also for the design of equipment and processing facilities, and the optimization of unit operations, storage, and material handling systems. As this industry continues its rapid growth, it is imperative to establish baseline data. Thus the objective of this research was to examine some of the physical properties of DDGS including moisture content, water activity, thermal properties (conductivity, resistivity, and diffusivity), bulk density, angle of repose, and color.

MATERIALS AND METHODS

Samples of DDGS were collected from six dry grind corn ethanol processing facilities in eastern South Dakota. Eighteen 18.9-L (5-gal) convenience samples were collected during the fall of 2004 (i.e., four unique samples per plant from four plants, and one unique sample per plant from two plants) and were stored at room temperature (24 ± 1°C) in sealed plastic buckets. All physical property determinations,

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except moisture content, were conducted at room temperature. Each property was studied using a completely randomized design.

Moisture content was determined following *ASAE Standards* (2004), using a forced-convection laboratory oven (Thelco Precision, Jovan Inc., Wincester, Va.) at 103°C for 72 h. Water activity was measured using a calibrated water activity meter (AW Sprint TH 500, Novasina, Talstrasse, Switzerland). Thermal conductivity, resistivity, and diffusivity were determined with a thermal properties meter (KD2, Decagon Devices, Pullman, Wash.) that utilized the line heat-source probe technique (Baghe-Khandan et al., 1981). Bulk density was measured using a standard bushel tester (Seedburo Equipment Co., Chicago, Ill.) following the method prescribed by USDA (1999). Angle of repose was determined by allowing DDGS to fall onto a 44 mm diameter circular plate following the method described by Mohsenin (1980). Color was measured using a spectrocolorimeter (LabScan XE, Hunter Associates Laboratory, Reston, Va.) using the L-a-b opposable color scales (Hunter Associates Laboratory, 2002).

For each physical property studied, four replicates from each of the 18 samples were measured; this resulted in a total of 72 observations for each property. Formal statistical analyses on all collected data were performed via Microsoft Excel v. 2003 (Microsoft Corp., Redmond, Wash.), Minitab v. 14.11 (Minitab Inc., State College, Pa.), and SAS (SAS Institute, Cary, N.C.) software, using a Type I error rate (α) of 0.05, and included summary statistics, ANOVA (to test for differences between processing plants), correlation analysis, and principal components analysis.

RESULTS AND DISCUSSION

Physical property results are shown in table 1, which provides minimum, maximum, and mean values, as well as standard deviation for each property, in aggregate, as well as for each processing plant. As shown in the table, all physical properties exhibited statistically significant differences between processing plants. This behavior was anticipated *a priori*. Belyea et al. (2004) and Spiehs et al. (2002) investigated chemical composition of DDGS from a variety of ethanol plants and found variation both between plants and within plants over time. The physical properties of the samples in the current study generally had relatively low standard deviations, except for bulk density, which exhibited substantial variability between sources.

The samples studied had moisture contents ranging from 13.2% to 21.2% (d.b. – dry basis). A maximum moisture content of ~12% is generally recommended for feed products because this level minimizes transportation costs and is microbiologically stable (Beauchat, 1981). Furthermore, water activity quantifies the amount of “free” (i.e., unbound) water available for use by microorganisms and chemical agents, and is therefore a measure of a material’s susceptibility to spoilage and deterioration. Products with no free water ($a_W = 0.0$) are not at risk for spoilage, while materials with free surface water ($a_W = 1.0$) are at high risk for rapid spoilage. Materials have a reduced chance of bacterial growth below water activities of approximately 0.9, mold growth below approximately 0.7 to 0.8, and yeast growth below approximately 0.7 (Barbosa-Canovas and Vega-Mercado, 1996). Even though the samples studied had low levels of water available for microorganism growth, with water activity values between 0.53 and 0.63, it appears that they may be prone to spoilage problems due to potential moisture migration (due to the moisture content levels) when they are stored in bulk. To be effectively utilized as feed materials, especially during rail shipping across the United States, it is crucial that DDGS be consistently dried to approximately 12% moisture content, or even slightly lower.

The DDGS in this study had low thermal conductivity, which varied between 0.06 and 0.08 W/m °C, high thermal resistivity, which ranged from 13.1 and 15.6 m°C/W, and low thermal diffusivity, which varied between 0.13 and 0.15 mm^2/s. Bulk density, which is a key parameter in the design and utilization of storage vessels, such as bins, tanks, trucks, and rail cars, varied between 389.3 and 501.5 kg/m^3. Angle of repose, which is also a key design parameter, varied between 26.5° and 34.2°. Color, which has been shown to be an indicator of nutritional value (Goihl, 1993; Ergul et al., 2003), did show some variation between samples: “L” varied between 40.0 and 49.8; “a” varied between 8.0 and 9.8; and “b” varied between 18.2 and 23.5. Overall, however, all samples appeared “golden brown.”

Relationships between all measured physical properties were then investigated using correlation analysis. The 55 resulting Pearson product-moment correlations (Speigel, 1994) are shown in table 2. Twenty-nine of these were significant ($p < 0.05$); the remainder of the correlations was not. The correlation coefficient (r) quantifies the strength of the linear relationship between two variables, and as shown, five of the variable combinations had resulting correlation coefficients greater than 0.80, while two had coefficients greater than 0.90, and thus exhibited fairly strong linear relationships. It appears that water activity was highly correlated with bulk density, and moderately correlated with thermal properties and color. These relationships are logical, as water in biological materials has substantial effects on resulting physical properties (Stroshine and Hamann, 1995). Bulk density was moderately correlated with thermal properties. These relationships were understandable because the ability to transmit heat energy is directly related to surface contact and the interstitial air spaces between particles (Incropera and DeWitt, 1990), which is a function of how compacted the particles are (i.e., bulk density). Additionally, color is moderately to highly correlated with most other physical properties in the study.

These relationships can be readily observed by examining a scatterplot matrix of all multivariate data (fig. 1). It appears that several of these correlations were, in fact, not due to linear relationships, but instead were caused by a specific grouping of four data points (these four points were actually replicates that belonged to a specific sample of DDGS). As shown, all correlations involving water activity were caused by this data cluster, as were most of the correlations involving color. The correlations between thermal properties and bulk density may or may not be due to this grouping. Not only were these four replicates “yellower” than the others, they also exhibited distinctive physical property values. The fact that they produced unique results vis-à-vis the other samples underscores the fact that variations can be seen between ethanol production plants, and over time within a single plant, which are, in large part, due to different production

Table 1. Physical properties of distillers dried grains with solubles (DDGS).[a]

Physical Property	Processing Plant	No. of Observations	Minimum	Maximum	Mean	Standard Deviation
Moisture content (%, d.b.)		72	13.2	21.2	14.7[b]	1.5
	1	16	13.9	14.8	14.5a	0.2
	2	4	13.2	13.4	13.3b	0.1
	3	4	14.3	14.7	14.5ae	0.1
	4	16	13.8	15.0	14.3ce	0.3
	5	16	13.6	21.2	16.0d	2.1
	6	16	14.2	14.9	14.6a	0.2
Water activity (–)		72	0.53	0.63	0.55[b]	0.02
	1	16	0.54	0.56	0.55a	0.01
	2	4	0.62	0.63	0.63b	0.01
	3	4	0.54	0.55	0.55a	0.01
	4	16	0.54	0.55	0.54c	0.00
	5	16	0.54	0.57	0.55d	0.01
	6	16	0.53	0.56	0.54c	0.01
Thermal conductivity (W/m°C)		72	0.06	0.08	0.07[b]	0.01
	1	16	0.07	0.08	0.07a	0.01
	2	4	0.06	0.07	0.07b	0.01
	3	4	0.07	0.08	0.07a	0.01
	4	16	0.07	0.08	0.07a	0.01
	5	16	0.07	0.07	0.07a	0.01
	6	16	0.07	0.08	0.07a	0.01
Thermal resistivity (m°C/W)		72	13.1	15.6	14.0[b]	0.5
	1	16	13.2	14.6	14.0a	0.4
	2	4	14.9	15.6	15.3b	0.3
	3	4	13.3	14.2	13.8ae	0.4
	4	16	13.3	14.6	13.9a	0.4
	5	16	13.8	14.8	14.2c	0.3
	6	16	13.1	14.3	13.6de	0.3
Thermal diffusivity (mm^2/s)		72	0.13	0.15	0.13[b]	0.01
	1	16	0.13	0.14	0.13af	0.01
	2	4	0.14	0.15	0.15b	0.01
	3	4	0.13	0.13	0.13ad	0.01
	4	16	0.13	0.14	0.13ae	0.01
	5	16	0.13	0.14	0.14cf	0.01
	6	16	0.13	0.14	0.13de	0.01
Bulk density (kg/m^3)		72	389.3	501.5	483.3[b]	24.1
	1	16	476.7	496.3	485.5a	8.2
	2	4	389.3	392.8	391.0b	1.5
	3	4	486.6	492.7	489.7c	3.2
	4	16	489.0	496.4	493.8d	2.0
	5	16	468.0	489.6	479.1e	8.0
	6	16	490.7	501.5	496.1f	3.7
Angle of repose (°)		72	26.5	34.2	31.5[b]	1.8
	1	16	26.5	33.3	30.9a	1.8
	2	4	30.5	34.2	33.1b	1.7
	3	4	29.5	31.5	30.5a	0.8
	4	16	28.6	34.2	31.3a	1.6
	5	16	28.6	34.2	31.0a	1.6
	6	16	28.6	34.2	32.5b	1.9
Color – Hunter L (–)	1	72	40.0	49.8	43.1[b]	1.6
	2	16	40.0	42.8	41.8a	0.8
	3	4	47.6	49.8	48.8b	0.9
	4	4	43.2	44.0	43.5c	0.4
	5	16	41.6	44.1	43.0d	0.8

Table 1. Physical properties of distillers dried grains with solubles (DDGS).[a] (con't)

Color – Hunter L (−)	6	16	42.0	44.1	43.2cd	0.6
		16	42.6	43.4	43.0d	0.2
Color – Hunter a (−)		72	8.0	9.8	8.7[b]	0.4
	1	16	8.0	9.2	8.8a	0.4
	2	4	9.6	9.8	9.7b	0.1
	3	4	8.1	8.5	8.3c	0.2
	4	16	8.3	8.9	8.6d	0.2
	5	16	8.0	9.0	8.6d	0.3
	6	16	8.4	8.8	8.6d	0.1
Color – Hunter b (−)		72	18.2	23.5	19.4[b]	0.9
	1	16	18.2	19.7	19.0a	0.3
	2	4	22.4	23.5	23.0b	0.5
	3	4	18.9	19.2	19.0ac	0.1
	4	16	19.0	19.4	19.2c	0.1
	5	16	18.7	19.6	19.2ac	0.2
	6	16	19.0	19.4	19.2c	0.1

[a] Values followed by the same letter within a given property are not significantly different ($p < 0.05$).

[b] Denotes that significant differences in a given property between processing plants are present ($p < 0.05$).

processes as well as raw materials. Thus, the examination of a larger pool of DDGS samples is warranted for further study.

Correlations involving the color (L-a-b) values are especially appealing for further study, because they hold potential for developing prediction relationships between product color and other variables with which they are correlated. A more thorough quantification could lead to low-cost visual sensing strategies for process quality control and property monitoring at production facilities.

To further examine the relationships and interactions between the various physical properties under investigation, a principal components analysis was conducted using all

Table 2. Correlation coefficients (r) between physical properties of distillers dried grains with solubles (DDGS) and (associated p values; significance level of 0.05).

	Moisture Content	Water Activity	Conductivity	Resistivity	Diffusivity	Bulk Density	Angle	L	a	b
Moisture content	1.000									

Water activity	−0.053	1.000								
	(0.661)	---								
Conductivity	0.064	−0.443	1.000							
	(0.590)	(0.000)	---							
Resistivity	−0.091	0.679	−0.643	1.000						
	(0.447)	(0.000)	(0.000)	---						
Diffusivity	0.025	0.634	−0.414	0.828	1.000					
	(0.835)	(0.000)	(0.000)	(0.000)	---					
Bulk density	0.074	−0.932	0.414	−0.709	−0.671	1.000				
	(0.538)	(0.000)	(0.000)	(0.000)	(0.000)	---				
Angle	−0.329	0.040	−0.097	0.049	−0.026	−0.097	1.000			
	(0.005)	(0.739)	(0.415)	(0.684)	(0.826)	(0.418)	---			
L	−0.253	0.729	−0.323	0.570	0.476	−0.784	0.198	1.000		
	(0.032)	(0.000)	(0.006)	(0.000)	(0.000)	(0.000)	(0.095)	---		
a	0.043	0.697	−0.243	0.393	0.473	−0.731	−0.075	0.435	1.000	
	(0.720)	(0.000)	(0.040)	(0.001)	(0.000)	(0.000)	(0.532)	(0.000)	---	
b	−0.247	0.832	−0.375	0.568	0.520	−0.886	0.236	0.917	0.640	1.000
	(0.036)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.046)	(0.000)	(0.000)	---

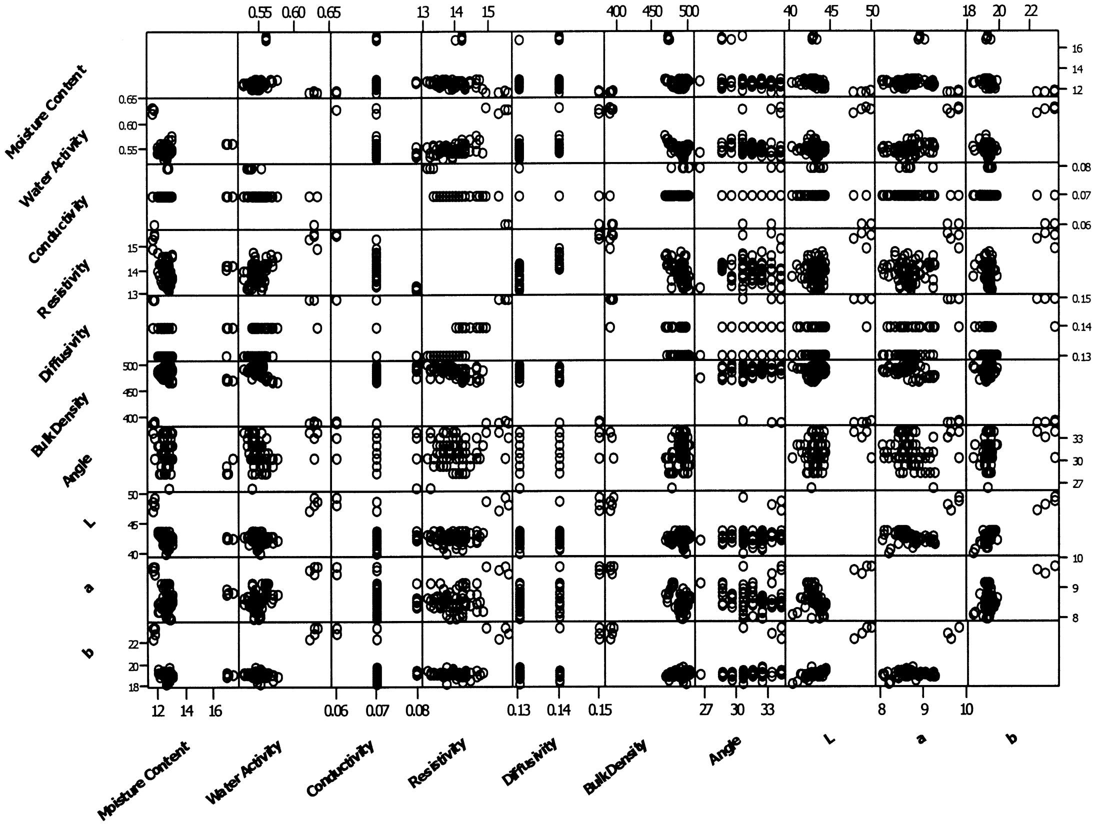

Figure 1. Scatterplot matrix of all physical property data.

variables in the study. This type of analysis is typically used to reduce the dimensionality of multivariate data by summarizing the observed variance and projecting it into a set of uncorrelated, orthogonal linear combinations (i.e., eigenvectors) based on the original variables, which have the form:

$$y_{P.C.} = a_1 X_1 + a_2 X_2 + \ldots + a_Z X_Z \qquad (1)$$

where $y_{P.C.}$ is a principal component value (or score), a_1 through a_Z are principal component coefficients (i.e., eigenvectors), and X_1 through X_Z are the original property variables in vector form (Marascuilo and Levin, 1983). A "scree" plot of the resulting principal component eigenvalues (fig. 2), and a plot of the error explained through the use of these principal components (fig. 3), indicated that the use of two principal components should be adequate to summarize the multivariate data in this study. These first two principal components (with eigenvalues of 5.374 and 1.477, respectively) together accounted for 68.5% of the total variability in the data and provide a relatively convenient summary of the information contained in all the original variables in the study, but utilize a reduced dimensionality of only two variables. It appears that the first principal component may be an indication of thermal, color, and bulk density properties, while the second principal component may be an indication of moisture content and angle of repose, although the interpretation of principal components can often be subjective (Everitt and Dunn, 1991). To be sure, the plane defined by the first two principal components is the best fit to the observed variance in the data set. Further data collection and analysis is warranted to clarify these interpretations.

A benefit to using principal components analysis to summarize multivariate data is the ability to identify curvature, outliers, and clustering through examination of low-dimensional scatterplots of the calculated principal component scores (fig. 4). Using this approach, no curvature was indicated in this data set, and most data points appeared to be randomly distributed, but it did appear that two outlying groups did exist. Investigation into the cause of these groupings revealed that they were due to two distinct samples of DDGS. These were collected from two specific processing

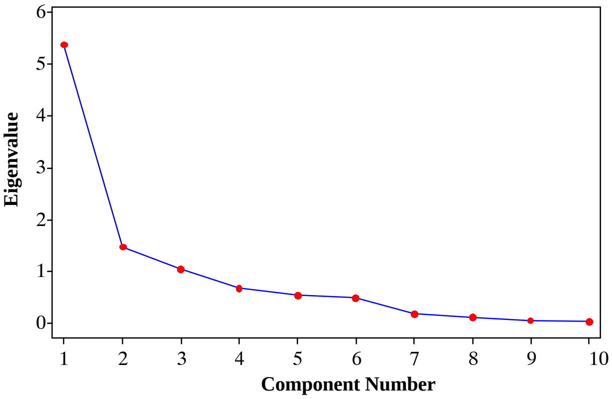

Figure 2. Scree plot used to determine the number of principal components required to summarize the entire multivariate data set.

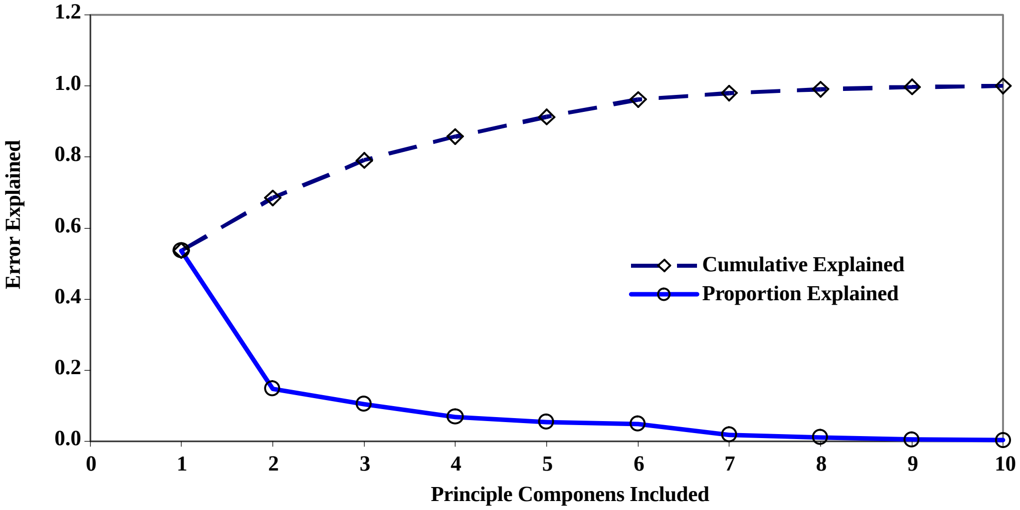

Figure 3. Error explained through use of additional principal components to summarize the entire multivariate data set.

plants. The left-most cluster consisted of one DDGS sample that had much lower bulk density (389.3 to 392.8 kg/m^3) and higher L-a-b color scores (Hunter L ranged from 47.6 to 49.8; Hunter a ranged from 9.6 to 9.8; Hunter b ranged from 22.4 to 23.5) compared to the other samples in the study. The top-most grouping had higher moisture content (17.0 to 17.5% d.b.) than the other samples. This clustering behavior reinforced the fact that samples of DDGS can vary substantially between collected lots. Specific reasons for the observed differences in these two samples remain elusive, however, and warrant further analysis, especially investigation into their chemical composition.

The DDGS samples utilized in this study were examined at room temperature and as-received moisture content. Physical properties will, however, be dependent upon both temperature and moisture levels and will also be affected by soluble content, and thus differences in chemical composition. Even though this study has examined physical properties of typical DDGS streams, there is a pressing need to quantify these additional effects. Understanding the behavior of DDGS when subjected to various levels of these factors will be essential for actual industrial applications.

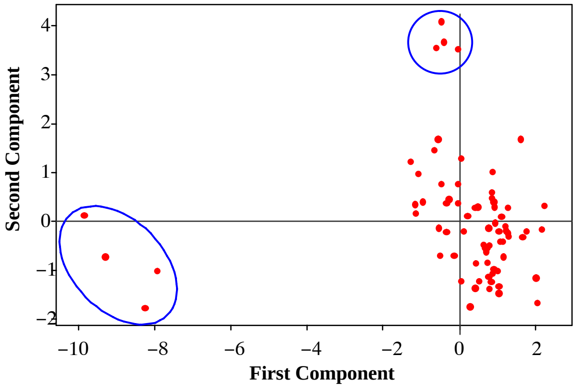

Figure 4. Calculated principal component scores for the first two principal components, based on all collected multivariate data.

CONCLUSIONS

The goal of this research was to provide baseline physical property data for typical DDGS that are produced in eastern South Dakota. The samples studied had a mean moisture content of 14.7% (d.b.), water activity of 0.55, thermal conductivity of 0.07 W/m°C, resistivity of 14.0 m°C/W, diffusivity of 0.13 mm^2/s, bulk density of 483.3 kg/m^3, angle of repose of 31.5°, Hunter L of 43.1, Hunter a of 8.7, and Hunter b of 19.4. Thus, DDGS exhibited properties similar to other dry feed ingredients, such as hominy feed, corn gluten feed, and other corn-based feed materials. This information, which to date has been nonexistent in the literature, is essential for the design of equipment, processes, and facilities to handle, store, as well as utilize these coproducts. This research represents a first step in an ongoing effort at the USDA-ARS to add value to DDGS and other dry mill residue streams. Future work will address additional physical and chemical parameters identified in this initial study.

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