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EVALUATION OF MEASUREMENT PROCEDURES USED TO DETERMINE THE BULK DENSITY OF DISTILLERS DRIED GRAINS WITH SOLUBLES (DDGS)

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ABSTRACT. *The production of corn-based ethanol in the U.S. has been dramatically increasing in recent years, and consequently so has the quantity of co-products, especially distillers dried grains with solubles (DDGS), generated from this industrial sector. DDGS is sold as a commodity for animal feed, and like corn, its bulk physical and chemical properties are quality attributes that can be used in trading by merchandisers. Consistency in product quality has been a cause for concern in the industry, and the lack of standard methods for physical and chemical property determination potentially confounds the issue, especially when results of attributes measured by different methods have not been evaluated for method parity. Toward that end, this research examined the sources of DDGS bulk density variability using samples from six commercial ethanol plants (three from Indiana, and three from South Dakota) and conducted in two different laboratories. Variations due to sample handling, container filling method, filling height, and container size were also examined. It was ascertained that DDGS source accounted for most of the bulk density variability observed. It was also determined that filling height and measuring container size resulted in significant differences in the resulting bulk density values.*

Keywords. Bulk density measurement, DDGS, Physical property.

Distillers dried grains with solubles (DDGS) is a co-product of dry grind fuel ethanol manufacturing using corn. The marketability of DDGS has significant implications for the success of the ethanol industry. However, this product cannot always be fairly traded because of inconsistencies in its chemical and physical properties, especially bulk density. Bulk density is a measure of the weight of a material per unit volume (kg m^{-3}). As such, it is used to determine the weight of the bulk product stored in a given volume. Rosentrater (2006) showed that the bulk density of DDGS produced at six ethanol plants in South Dakota ranged from 391 to 496 kg m^{-3} . Bhadra et al. (2009) found ranges of 490 to 590 kg m^{-3} from five plants in South Dakota. In another study of DDGS from 69 sources in 2004 and 2005, it was found that the bulk density ranged from 365 to 561 kg m^{-3} (U.S. Grains Council, 2008). These wide ranges in bulk density present economic challenges with regard to shipping the product (Ileleji and Rosentrater, 2008). Some variation could be caused by differences in manufacturing process conditions, as pointed out by Kingsly et al.

(2010). For example, they showed that by increasing the addition rate of condensed distillers solubles (CDS) mixed (from 0 to 212 L min^{-1}) with wet distillers grains (WDG), the combination of which was then dried in a rotary drum dryer, the bulk density increased from 420.47 to 458.05 kg m^{-3} .

While the bulk density of DDGS can inherently vary due to varying processing conditions, particle segregation during handling of DDGS can also cause bulk density variations within the same bulk (Clementson and Ileleji, 2010). This is because, on a particle level, DDGS consists of a heterogeneous mixture of granular particles that vary in morphology and size (Ileleji et al., 2007). Thus, sample handling and physical property testing must be done with care to avoid inducing errors due to inappropriate sampling methods for these bulk solids. Hence, it is critical to have an established procedure for sample handling and determination of basic physical properties such as bulk density. Manley et al. (2009) investigated a similar question for determining bulk density of wheat samples using various equipment and procedures from six wheat producing and exporting countries. They found that there were significant differences in the bulk density values measured using these devices, which they attributed to different operating procedures, including the drop height and the volume of the measuring container. They also pointed out that there was high correlation between the bulk density values determined by these devices, and they suggested the use of correction factors to convert bulk density values between devices.

Standard bulk density procedures exist for several materials, including aggregates (ASTM C29; ASTM, 2007b), particles (ASTM F1877; ASTM, 2005), granular materials (ASTM C357; ASTM, 2007a), and grains and oilseeds (ASAE D241.4; ASABE Standards, 2008), among others. However, there is currently no standard procedure for the

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bulk density measurement of DDGS. ASTM C357 (ASTM, 2007a) has been proposed for granular materials; however, this method specifically applies to materials in the sieve size range of U.S. No. 4 (4.76 mm) to U.S. No. 12 (1.70 mm). DDGS has a wider particle size distribution (Rausch et al., 2005), with material retained on sieve sizes from U.S. No. 4 through U.S. No. 270 (Clementson et al., 2009). Thus, it is important to examine the current methods used for bulk density determination in other materials and to evaluate their applicability to DDGS, as well as potential causes of errors and variation in bulk density determination. Therefore, this study evaluated some current practices used for bulk density measurement of DDGS and identified possible sources of variability. Additionally, moisture content, true density, and particle size distribution were determined for these samples to more fully quantify the DDGS characteristics.

MATERIALS AND METHODS

BULK DENSITY MEASUREMENT

For this study, DDGS was obtained from six ethanol plants: three plants in South Dakota (samples denoted SD1, SD2, and SD3) and three plants in Indiana (samples denoted PU1, PU2, and PU3). The DDGS from each plant was collected in individual 18.9 L (5 gal) containers that were marked to clearly identify their sources. The bulk density of the DDGS samples was assessed using a Seedburo filling hopper and stand (Seedburo Equipment Co., Chicago, Ill.), which consisted of a brass hopper mounted on a tripod (fig. 1). DDGS was poured into the funnel-shaped hopper, the hopper was centered over the measuring cup, the hopper valve was opened quickly, and the DDGS was allowed to flow freely into the measuring cup. After the cup was filled, the excess material was leveled off with gentle zigzag strokes using the standard Seedburo striking stick. The filled measuring cup was then weighed, and the mass of DDGS in the cup was determined by subtracting the mass of the measuring cup itself. The bulk density (ρ) of DDGS was then calculated using the following expression:

$$\rho = \frac{\text{mass of DDGS in measuring cup (g)}}{\text{volume of measuring cup (cm}^3\text{)}} \quad (1)$$

For comparative analysis, the bulk density was measured at two laboratories: the Department of Agricultural and Biological Engineering at Purdue University, West Lafayette, Indiana (denoted PU), and the USDA-ARS North Central

Agricultural Research Laboratory in Brookings, South Dakota (denoted SD). At each laboratory, three independent variables were systematically altered when assessing the bulk density: drop height, measuring cup size, and sampling method.

Drop height was defined as the distance between the hopper discharge valve and the base of the measuring cup. DDGS was dropped from the hopper into the measuring cup by gravity discharge. Studies by Ileleji et al. (2007) and Clementson et al. (2009) showed that particle segregation can occur during the handling of DDGS, especially during gravity-driven discharge, which can lead to bulk density variation (Clementson and Ileleji, 2010). Additionally, Tanaka (1971) proposed the push-away model when filling hoppers where particles falling on or flowing down a heap push against the heap. This is analogous to the filling of the measuring container for bulk density determination. From their analysis, particles possess different potential energies at different drop heights, which could cause varying compaction and particle penetration, which would thus affect the measured bulk density of the material. The drop height was varied from an upper level (highest point at which the hopper could be mounted on the tripod, 17.2 cm) to a lower level (lowest point at which the hopper could be mounted, 13.9 cm).

Measuring cup size was the physical size of the measurement container. From studies by Shinohara et al. (1972) and Standish (1985), the size of the hopper and container can influence the extent of particle segregation that occurs during discharge from the hopper, and thus the bulk density as pointed out by Manley et al. (2009). For this study, standard Seedburo density measuring cups (Seedburo Equipment Co., Chicago, Ill.) with volumes of 0.5 L and 1.0 L were used.

Sampling method (or sample reduction method) was the procedure used to reduce the bulk supply of DDGS in the storage containers to an appropriate quantity for testing. Ileleji et al. (2007) showed that DDGS became segregated under different handling scenarios, while Clementson et al. (2009) showed that proper and consistent sampling procedures must be used to obtain a representative sample of DDGS. During this study, two methods were used to obtain samples for testing: (1) obtaining a sample directly from the holding bucket (which was a non-random approach), and (2) using a Boerner divider to split the DDGS into equal, random proportions.

These variables provided a 2^3 factorial experiment (table 1); each treatment combination was replicated three times in each participating laboratory (that is, eight treatment combinations in triplicate) for the DDGS samples from each

Figure 1. Bulk density measurement assembly.

Table 1. Experimental design used in the study (each sample was replicated three times at each laboratory for each treatment) and resulting bulk density measurements.^[a]

Run	Sample	Sampling Method	Cup Size	Drop Height	Laboratory			
					Purdue		South Dakota	
					Mean (kg m ⁻³)	Std. Dev. (kg m ⁻³)	Mean (kg m ⁻³)	Std. Dev. (kg m ⁻³)
1	PU1	Scooped	1/2 L	Lower	576.36	0.42	551.05	6.87
2				Upper	570.59	11.23	557.62	0.63
3		Divided	1 L	Lower	564.73	1.08	555.68	1.03
4				Upper	572.48	4.82	554.77	4.74
5			1/2 L	Lower	571.83	7.35	557.94	7.48
6				Upper	575.74	3.45	567.67	2.93
7			1 L	Lower	556.07	2.50	561.36	5.26
8				Upper	577.78	1.25	561.29	3.05
9	PU2	Scooped	1/2 L	Lower	443.95	0.10	438.66	0.51
10				Upper	443.40	0.81	443.30	4.61
11			1 L	Lower	436.18	0.28	433.11	1.39
12				Upper	441.27	2.03	435.73	1.92
13		Divided	1/2 L	Lower	443.39	4.16	441.71	3.23
14				Upper	445.11	4.62	444.45	2.82
15			1 L	Lower	430.43	3.16	435.21	2.06
16				Upper	436.33	2.14	439.47	1.79
17	PU3	Scooped	1/2 L	Lower	425.79	0.99	418.67	0.50
18				Upper	421.87	1.25	421.35	0.97
19			1 L	Lower	414.85	1.78	419.43	2.27
20				Upper	422.16	1.15	420.89	1.30
21		Divided	1/2 L	Lower	424.39	2.21	420.23	3.33
22				Upper	423.59	5.30	423.38	4.27
23			1 L	Lower	414.37	1.79	417.31	2.15
24				Upper	420.08	2.52	418.60	2.73
25	SD1	Scooped	1/2 L	Lower	433.41	0.60	428.97	0.25
26				Upper	431.64	2.39	431.97	0.90
27			1 L	Lower	425.27	3.79	426.20	1.81
28				Upper	432.89	1.63	428.30	1.16
29		Divided	1/2 L	Lower	430.03	1.61	429.29	2.64
30				Upper	432.17	3.89	435.13	5.64
31			1 L	Lower	427.84	3.80	422.87	1.35
32				Upper	425.88	2.20	428.90	4.02
33	SD2	Scooped	1/2 L	Lower	444.11	0.82	442.97	1.04
34				Upper	442.39	1.54	443.46	1.00
35			1 L	Lower	440.00	2.02	440.25	1.05
36				Upper	441.40	1.77	440.70	0.56
37		Divided	1/2 L	Lower	438.97	0.38	441.37	1.04
38				Upper	442.43	1.08	445.28	1.21
39			1 L	Lower	437.12	1.89	438.91	1.71
40				Upper	439.33	0.49	440.73	1.20
41	SD3	Scooped	1/2 L	Lower	481.05	1.38	476.31	1.96
42				Upper	476.13	3.10	484.97	1.96
43			1 L	Lower	466.74	2.94	472.20	0.69
44				Upper	475.51	3.69	475.52	1.77
45		Divided	1/2 L	Lower	479.41	3.19	474.33	4.07
46				Upper	477.36	3.66	476.32	5.43
47			1 L	Lower	467.01	2.84	471.69	2.25
48				Upper	471.65	2.79	472.78	3.15

^[a] $n = 3$ for each treatment combination (i.e., run), PU = Purdue, SD = South Dakota, and the lower and upper drop heights are the lowest point at which the hopper could be mounted on the tripod (13.9 cm) and the highest point at which it could be mounted (17.2 cm), respectively.

plant. With DDGS from six ethanol plants used, a total of 144 tests in each laboratory (or 288 measurements in all) were conducted. Statistical analyses were conducted on the

collected data with SAS (ver. 9.1, SAS Institute, Inc., Cary, N.C.) using the PROC GLM analysis of variance (ANOVA) procedure, using a Type I error rate of 0.05. ANOVA was used

to determine whether there were significant differences in the bulk density values due to the three main effects (i.e., drop height, measuring cup size, and sampling method), whether there were any interactions among these effects, and to partition the observed variation associated with the laboratories, cup size, and drop height.

PHYSICAL PROPERTIES AND MOISTURE CONTENT

In addition to bulk density, other properties were determined for the DDGS samples; these included true density, particle size distribution, and moisture content. For all of these tests, a Boerner divider was used to obtain representative DDGS samples from each bulk container (i.e., each plant). A gas multipycnometer (Quantachrome Corp., Boynton Beach, Fla.) was used to determine the true density. The true density, also known as the absolute density, is a measure of only the solid density, excluding all pores within the particle. The measurement procedure followed the standard protocol as outlined by the equipment manufacturer using the micro cell (1.0772 cm³).

Particle size analysis was conducted using the standard procedure described in ANSI/ASAE S319.3 (*ASABE Standards*, 2005). A stack of sieves, arranged from U.S. No. 4 (4.75 mm nominal opening size) through U.S. No. 270 (0.053 mm nominal opening size), was mounted on a Ro-tap shaker (model RX-29, W.S. Tyler, Inc., Mentor, Ohio). A charge of approximately 100 g was placed on the top sieve, and the shaker was operated for 10 min. As outlined by the standard, the resulting mass on each sieve was weighed and then used to calculate the geometric mean diameter (d_{gw}) and the geometric standard deviation (S_{gw}).

The moisture content (% d.b.) of DDGS from each plant was assessed using NFTA Method 2.1.4 (NFTA, 2006), as recommended by Thiex (2009) and Ileleji et al. (2010). This involved weighing a sample of 2 g, drying it in an air-oven for 3 h at 105°C, and then determining the percentage of mass lost due to drying.

For each bulk DDGS sample, true density, particle size distribution, and moisture content were all measured in triplicate. Statistical analyses was conducted on the resulting data with SAS (ver. 9.1, SAS Institute, Inc., Cary, N.C.) using the PROC GLM analysis of variance (ANOVA) procedure to determine whether significant differences existed among the six DDGS bulk samples, using a Type I error rate of 0.05.

RESULTS AND DISCUSSION

There were significant differences in the geometric mean diameter among the six samples used. The PU1 sample had the largest particle size (1861.75 μ m) and greatest particle

Figure 2. Particle size (d , μ m) distribution of the DDGS samples used in the study.

size distribution (fig. 2), while the PU2 sample had the smallest particle size (679.81 μ m). The range of particle sizes for the samples in this study was wider than the range reported by the U.S. Grains Council (2008), which included data from 16 ethanol plants in 2001, 35 plants in 2004, and 35 plants in 2005. The range of values in this study was also broader than that reported by Kingsly et al. (2010) but less than the range of particle sizes found by Clementson et al. (2009). True density also showed significant differences among the samples (table 2). The true densities were within the range of values obtained by Ileleji et al. (2007) but greater than those obtained by Kingsly et al. (2010); they ranged from 1307.63 kg m⁻³ (PU1) to 1291.91 kg m⁻³ (PU2). Moisture content also showed significant differences among the samples (table 2); moisture values ranged from 11.82% (PU1) to 7.75% (SD3) and were generally within the moisture content range at which DDGS is normally produced (except for the SD3 sample, which was very low).

The data show that the sample (plant source) accounted for most of the bulk density variation (table 3) compared to the method of measurement. This confirms previous studies (Bhadra et al., 2009; U.S. Grains Council, 2008) that quantified the variability of DDGS bulk density from different plants, and it reiterates the influence that operating conditions have on the resulting DDGS bulk density, as pointed out by Kingsly et al. (2010). There were significant differences in bulk density values between laboratories (table 3). This would not be expected, since both laboratories used the same procedure; however, because of the heterogeneous nature of DDGS, the feasibility of having the same particle distribution for each test is limited, which would affect the measured bulk density. This is evident by the variability of the laboratories being significant. There were also significant differences in

Table 2. Particle size, true density, and moisture content of DDGS samples.^[a]

Sample	Particle Size (μ m)		True Density (kg m ⁻³)		Moisture (% d.b.)	
	d_{gw}	S_{gw}	Mean	Std. Dev.	Mean	Std. Dev.
PU1	1861.75 a	1494.42	1307.63 a	1.57	11.82 a	0.55
PU2	679.81 d	418.28	1291.91 c	2.21	9.28 bc	0.11
PU3	1043.31 b	456.67	1285.23 d	1.15	10.03 b	0.56
SD1	830.24 c	430.19	1281.34 d	2.39	9.87 b	0.57
SD2	921.37 c	419.10	1301.22 b	1.26	10.69 ab	0.82
SD3	1053.04 b	619.83	1292.16 c	1.09	7.75 c	0.82

^[a] Means followed by the same letter are not significantly different at 0.05 probability level among samples for a given dependent variable; d_{gw} = geometric mean diameter, and S_{gw} = geometric standard deviation.

Table 3. Means and p-values of main effects.^[a]

Main Effect	Levels	Nested Variable	Mean (kg m ⁻³)	Std. Dev. (kg m ⁻³)	p-Value
Lab	PU		462.76	51.47	<0.0001
	SD		460.59	47.38	
Sample	PU1		564.56	9.48	<0.0001
	PU2		439.48 a	4.93	
	PU3		420.44	3.75	
	SD1		429.42	3.98	
	SD2		441.21 a	2.35	
	SD3		474.94	5.24	
		Labs			<0.0001
		Cup size			0.1025
		Drop height			0.4088
Sampling method	Scooped		461.80	48.83	0.6519
	Divided		461.55	50.12	
Cup size	1/2 L		463.99	49.26	<0.0001
	1 L		459.36	49.58	
Drop height	Lower		460.19	48.96	<0.0001
	Upper		463.16	49.94	

[a] Means followed by the same letter are not significantly different at 0.05 probability level among samples for a given main effect.

Table 4. P-values for interaction effects.

Variable Combinations					Probability (p-value)
Lab	Sample				<0.0001
Lab		Sampling method			0.0007
Lab			Cup size		0.0024
Lab				Drop height	0.5253
	Sample	Sampling method			0.0005
	Sample		Cup size		0.0016
	Sample			Drop height	0.0503
		Sampling method	Cup size		0.0462
		Sampling method		Drop height	0.0513
			Cup size	Drop height	0.0013
Lab	Sample	Sampling method			0.0013
Lab	Sample		Cup size		0.0557
Lab	Sample			Drop height	0.2563
Lab		Sampling method	Cup size		0.4937
Lab		Sampling method		Drop height	0.2361
Lab			Cup size	Drop height	<0.0001
	Sample	Sampling method	Cup size		0.6179
	Sample	Sampling method		Drop height	0.0083
	Sample		Cup size	Drop height	0.5850
		Sampling method	Cup size	Drop height	0.1917
Lab	Sample	Sampling method	Cup size		0.2731
Lab	Sample	Sampling method		Drop height	0.0595
Lab		Sampling method	Cup size	Drop height	0.0770
Lab	Sample	Sampling method	Cup size	Drop height	0.0027

bulk densities measured with different cup sizes, as well as the two drop heights. These results indicate that the apparatus assembly and measuring cup used could contribute to the resulting variability of the measured bulk density. However, further investigation to explain the specific causes of these differences is warranted.

There were no significant differences in bulk density due to sampling method. This was not expected, and it possibly occurred because the bulk samples used were small, compared to the large piles found at ethanol plants, and thus did not allow for sufficient segregation of DDGS as found by

Ileleji et al. (2007) and Clementson et al. (2009). However, with the scoop sampling method, it would be necessary to consider the prior handling history of the material, which may not always be clear and may encompass segregation of the bulk material. Hence, scooping samples out of a bag to produce subsamples for use in measurement is discouraged. Instead, using a sample splitter, such as a Boerner divider, is encouraged. Sampling DDGS from a pile must be done from several locations, including various depths and heights in the pile (Clementson et al., 2009). Samples collected in bags from these locations should be thoroughly mixed prior to

pouring into the Boerner divider for splitting into subsamples.

It should also be noted that there were some interactions among the independent variables, which also resulted in significant differences in the bulk density (table 4), most notably the interactions between sample, sampling method, and drop height. Because of the heterogeneity of DDGS particles (i.e., size, shape, and true density), the hopper emptying mechanism may affect the filling of the measuring cup and may interact with the drop height. In other words, drop height variation could cause DDGS to consolidate in the cup differently.

CONCLUSIONS

It was determined that the plants from which material is sourced caused most of the measured variability in DDGS bulk density, although the method of bulk density measurement did not cause as much variability. The laboratories also contributed to bulk density variability, which indicates that consistent handling of samples is essential. Additionally, the drop height and measuring cup size each had significant effects on resulting bulk density values. These results emphasize that the variability of reported values could be minimized by the use of a standard protocol and the need to validly compare material property results among experiments.

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REFERENCES

- ASABE Standards. 2008. ASAE D241.4: Density, specific gravity, and mass-moisture relationships of grain for storage. St. Joseph, Mich.: ASABE.
- ASABE Standards. 2005. ASAE S319.3: Method of determining and expressing fineness of feed materials by sieving. St. Joseph, Mich.: ASABE.
- ASTM. 2005. ASTM F1877-05: Standard practice for characterization of particles. West Conshohocken, Pa.: ASTM International.
- ASTM. 2007a. ASTM C357-07: Standard test method for bulk density of granular refractory materials. West Conshohocken, Pa.: ASTM International.
- ASTM. 2007b. ASTM C29-07: Standard test method for bulk density ("unit weight") and voids in aggregate. West Conshohocken, Pa.: ASTM International.
- Bhadra, R., K. Muthukumarappan, and K. A. Rosentrater. 2009. Flowability properties of commercial distillers dried grains with solubles (DDGS). *Cereal Chem.* 86(2): 170-180.
- Clementson, C. L., and K. E. Ileleji. 2010. Variability of bulk density of distillers dried grains with solubles (DDGS) during gravity-driven discharge. *Bioresource Tech.* doi:10.1016/j.biortech.2010.02.066.
- Clementson, C. L., K. E. Ileleji, and R. L. Strohshine. 2009. Particle segregation within a pile of bulk distillers dried grains with soluble (DDGS) and variability of nutrient content. *Cereal Chem.* 86(3): 267-273.
- Ileleji, K. E., and K. A. Rosentrater. 2008. On the physical properties of dried distillers grains with solubles (DDGS). ASABE Paper No. 084576. St. Joseph, Mich.: ASABE.
- Ileleji, K. E., K. S. Prakash, R. L. Strohshine, and C. L. Clementson. 2007. An investigation of particle segregation in corn processed dried distillers grains with solubles (DDGS) induced by three handling scenarios. *Bulk Solids and Powder Sci. and Tech.* 2(2): 84-94.
- Ileleji, K. E., A. A. Garcia, A. R. P. Kingsly, and C. L. Clementson . 2010. A comparison of standard moisture loss-on-drying methods for the determination of moisture content of corn distillers dried grains with solubles (DDGS). *J. AOAC Intl.* (accepted).
- Kingsly, A. R. P., K. E. Ileleji, C. L. Clementson, A. Garcia, D. E. Maier, R. L. Strohshine, and S. Radcliff. 2010. The effect of process variables on the physical and chemical characteristics of corn distillers dried grains with solubles (DDGS): Part II. Plant-scale experiments. *Bioresource Tech.* 101(1): 193-199.
- Manley, M., M. L. Engelbrecht, P. C. Williams, and M. Kidd. 2009. Assessment of variance in the measurement of hectolitre mass of wheat, using equipment from different grain producing and exporting countries. *Biosystems Eng.* 103(2): 176-186.
- NFTA. 2006. Method 2.1.4: Dry matter by oven drying for 3 hr at 105 °C. Omaha, Neb.: National Forage Testing Association.
- Rausch, K. D., R. L. Belyea, M. R. Ellersieck, V. Singh, D. B. Johnston, and M. E. Tumbleson. 2005. Particle size distributions of ground corn and DDGS from dry grind processing. *Trans. ASABE* 48(1): 273-277.
- Rosentrater, K. A. 2006. Some physical properties of distillers dried grains with solubles (DDGS). *Applied Eng. in Agric.* 22(4): 589-595.
- Shinohara, K., K. Shoji, and T. Tanaka. 1972. Mechanism of size segregation of particles in filling a hopper. *Ind. Eng. Chem. Proc. Des. Dev.* 11(3): 369-376.
- Standish, N. 1985. Studies of size segregation in filling and emptying a hopper. *Powder Tech.* 45(1): 43-56.
- Tanaka, T. 1971. Segregation models of solid mixtures composed of different densities and particle sizes. *Ind. Eng. Chem. Proc. Des. Dev.* 10(3): 332-340.
- Thiex, N. 2009. Evaluation of analytical methods for the determination of moisture, crude protein, crude fat, and crude fiber in distillers dried grains with solubles. *J. AOAC Intl.* 92(1): 61-73.
- U.S. Grains Council. 2008. Physical and chemical characteristics of DDGS. In *DDGS User Handbook*. Washington, D.C.: U.S. Grains Council. Available at: www.grains.org/images/stories/DDGS_user_handbook/08%20-%20Physical%20and%20Chemical%20Characteristics%20of%20DDGS.ERE%20revisions.pdf. Accessed 7 May 2008.