Bioresource Technology 99 (2008) 8421–8428

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Particle size distribution of distillers dried grains with solubles (DDGS) and relationships to compositional and color properties

Keshun Liu *

Grain Chemistry and Utilization Laboratory, National Small Grains and Potato Germplasm Research Unit, USDA-ARS, 1691 S. 2700 West, Aberdeen, ID 83201, USA

ARTICLE INFO

Article history:
Received 2 January 2008
Received in revised form 25 February 2008
Accepted 25 February 2008
Available online 29 April 2008

Keywords:
Particle size distribution (PSD)
Distillers dried grains with solubles (DDGS)
Composition
Color
Nutrient distribution

ABSTRACT

Eleven distillers dried grains with solubles (DDGS), processed from yellow corn, were collected from different ethanol processing plants in the US Midwest area. Particle size distribution (PSD) by mass of each sample was determined using a series of six selected US standard sieves: Nos. 8, 12, 18, 35, 60, and 100, and a pan. The original sample and sieve sized fractions were measured for surface color and contents of moisture, protein, oil, ash, and starch. Total carbohydrate (CHO) and total non-starch CHO were also calculated. Results show that there was a great variation in composition and color among DDGS from different plants. Surprisingly, a few DDGS samples contained unusually high amounts of residual starch (11.1–17.6%, dry matter basis, vs. about 5% of the rest), presumably resulting from modified processing methods. Particle size of DDGS varied greatly within a sample and PSD varied greatly among samples. The 11 samples had a mean value of 0.660 mm for the geometric mean diameter (d_{gw}) of particles and a mean value of 0.440 mm for the geometric standard deviation (S_{gw}) of particle diameters by mass. The majority had a unimodal PSD, with a mode in the size class between 0.5 and 1.0 mm. Although PSD and color parameters had little correlation with composition of whole DDGS samples, distribution of nutrients as well as color attributes correlated well with PSD. In sieved fractions, protein content, *L* and a color values negatively while contents of oil and total CHO positively correlated with particle size. It is highly feasible to fractionate DDGS for compositional enrichment based on particle size, while the extent of PSD can serve as an index for potential of DDGS fractionation. The above information should be a vital addition to quality and baseline data of DDGS.

© 2008 Elsevier Ltd. All rights reserved.

1. Introduction

Increase in demand of ethanol as a fuel additive and decrease in dependency on fossil fuels have led to a dramatic increase in the amount of corn used for ethanol production. Ethanol can be produced from corn by either wet milling or dry grinding method. Wet milling requires extensive equipment and high capital investment, but generates a variety of co-products to defray production costs. Dry grind method, on the other hand, requires less equipment and lower capital investment, and thus is gaining popularity (Bothast and Schlicher, 2005).

There are only two co-products generated from the dry grind method, distillers dried grains with solubles (DDGS) and carbon dioxide. Marketing of DDGS is critical to sustainability of a dry grinding plant. At present, DDGS is sold primarily as a livestock feed at a varying market price (US$85–140/ton), but newer value-added uses are under exploration. Factors that affect quality of DDGS directly impact the price and end use of DDGS, and thus the economics of ethanol production. Several studies have examined such quality factors of DDGS as compositional (Belyea et al., 2004), nutritional (Spiehs et al., 2002) and physical properties (Rosentrater, 2006; Ganesan et al., 2007), as well as feeding performance in animals (Liu et al., 2000) and fishes (Cheng et al., 2003), and thus provided important information about quality and baseline data of DDGS.

DDGS is a mix of particulate materials. Thus, the relative amounts of particles present, sorted according to size, would be a characteristic of a particular DDGS sample. Such a feature, commonly known as particle size distribution (PSD), has been widely used to describe many other powder materials, since it is an important quality parameter that helps in understanding physical and chemical properties of a particular powder material (Barbosa-Canovas et al., 2005). Particle size has been shown to affect the volume and acceptability of baked products incorporated with DDGS (Abbott et al., 1991). It could also affect animal digestibility (Wondra et al., 1995; Amezcua and Parsons, 2007). Therefore, PSD data of DDGS are essential for many aspects, including formulation of animal feed, digestibility and nutrient availability, design of equipment and processing facilities, optimization of unit operation, storage, material handling systems, assessment of potential or flexibility for a particular nutrient enrichment by sizing, and of end product quality.

* Tel.: +44 208 397 4162; fax: +44 208 397 4165.
E-mail address: Keshun.Liu@ars.usda.gov

0960-8524/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.biortech.2008.02.060

Surprisingly, there is limited information in literature on the PSD of DDGS. Rausch et al. (2005) compared particle size distributions of ground corn and DDGS but no other properties of DDGS were measured. Rosentrater (2006) studied some physical properties of DDGS but did not include particle size. Sieving or screening DDGS were reported (Wu and Stringfellow, 1986; Srinivasan et al., 2005) but it was done only for protein enrichment and fiber removal. The objective of this study was to investigate PSD of DDGS and its relationships to composition of various nutrients and surface color in the original and sieve sized fractions. Such information would be a vital addition to quality and baseline data of DDGS. It would also help improving quality and consistency of DDGS, which has become necessary for market expansion of the co-product beyond cattle to swine, poultry, aquaculture, and other industries.

2. Methods

2.1. Materials

Eleven DDGS samples were supplied from 11 selected dry grind ethanol plants located in the three Midwest states of Iowa, South Dakota and Illinois, and labeled as Nos. 1, 2, 3, etc., according to plant Nos. that were assigned sequentially upon the order of sample arriving in the laboratory. These plants processed commodity yellow dent corn available locally. While the majority used a conventional processing method, a few apparently adopted modified methods that might include a pre-fractionation step to remove germ and/or fiber from the grain before milling (Singh et al., 2005).

2.2. Measurement and expression of particle size distribution

PSD was measured with a series of six selected US standard sieves (Nos. 8, 12, 18, 35, 60, and 100) and a pan, fitted into a sieve shaker (DuraTap, Model DT168, Advantech Mfg. Co. New Berlin, WS). The sieving procedure was according to a standard method (ASAE Standards, 2003). Basically, 100 g of DDGS sample, without any additional processing, was sieved with shaking for 10 min. In the standard method, no word was mentioned about tapping during shaking. In this study, in order to improve sieving efficiency, tapping option was used during shaking. The mass of material retained on each sieve as well as on the pan was determined and recorded. The test was duplicated. The mass frequency (%) for material retained on each sieve size was calculated and plotted against each particle size category. Geometric mean diameter (d_{gw}) and geometric standard deviation (S_{gw}) were also calculated for each sieving replicate based on the formula described in the ASAE Standards (2003).

2.3. Chemical analysis

The original DDGS samples and all sieve sized fractions were measured for contents of moisture, protein, oil, ash and starch. The original DDGS is termed as "whole" or "original" fraction, in contrast to sieved fractions. Moisture and ash contents were determined according to official methods (AOAC, 2002). The moisture content was used to convert concentrations of other components into a dry matter basis. The total nitrogen/protein content in samples was measured by a combustion method (AOAC, 2002), using a protein analyzer (Model FT528, Leco Corp. St. Joseph, MI). The protein content was calculated with a conversion factor of 5.75. The oil content was determined by an AOCS Official Procedure (AOCS, 2005), using a fat analyzer (Model XT 10, Ankom Technology, Macedon, NY). However, instead of using petroleum ether, hexane was used as the extracting solvent.

Starch was measured according to an enzymatic method using a starch test kit (R-Biopharm, Inc., Marshall, MI). Samples were treated with dimethylsulfoxide and HCl to solubilize starch, which was then hydrolyzed to D-glucose in the presence of amyloglucosidase. The resulting D-glucose reacted with hexokinase and glucose-6-phosphate dehydrogenase. The amount of NADPH (reduced nicotinamide–adenine dinucleotide phosphate) formed in the reaction was determined colorimetrically, which was stoichiometric to the amount of D-glucose. The total carbohydrate (CHO) was calculated based on contents of protein, oil and ash, dry matter basis, while total non-starch CHO was calculated based on the difference between the total carbohydrate and starch content, also dry matter basis.

2.4. Surface color measurement

A Minolta colorimeter (Model CR-300) was used to measure surface colors of whole and sized fractions of both DDGS and ground corn samples. The colors were expressed in $L^* a^* b$ color space, also known as CIELAB, in which L indicates lightness and a^* and b^* are the chromaticity coordinates. $+a^*$ is the red direction, $-a^*$ is a green direction, $+b^*$ is the yellow direction, and $-b^*$ is the blue direction.

2.5. Data treatments and statistical analysis

Data were treated with JMP software, version 5 (JMP, a business unit of SAS, Cary, NC, USA), for calculation of means and standard deviation of measured attributes, and correlation coefficients between attributes in whole samples and sieved fractions, and for analysis of variance in order to determine the effect of processing plant, sieve size, and their interaction. The Tukey's HSD (honestly significant difference) test was also conducted for pair comparisons when there was a significant effect at $p < 0.05$ based on analysis of variance.

3. Results and discussion

3.1. Particle size distribution

PSD of a powder or granular material is a list of values or a mathematical function that defines the relative amounts of particles present, sorted according to size. The way the PSD is expressed is usually defined by the method by which it is determined (Barbosa-Canovas et al., 2005). In this study, a sieve analysis, the easiest understood method for particle size determination, was used (ASAE Standards, 2003), where DDGS powder was separated on sieves of different sizes, and PSD was defined in terms of mass frequency over discrete size ranges. It was based on an assumption that the particles are spheres that will just pass through a square hole in a sieve. In reality particles in powder materials, including DDGS, are irregular in shape, often extremely so. However, it does not diminish the value of particle size analysis. Statistical treatment of duplicate data sets for sieved fractions of all samples gave an average standard deviation of 0.49 g for the method. In the context of 100 g bulk mass for each sample, the result indicates that the method used in this study was rather repeatable.

The geometric mean diameter (d_{gw}) of particles among the 11 DDGS samples varied greatly, with a range between 0.434 and 0.949 mm, and a mean of 0.660 mm (Table 1). There were significant differences among samples. The geometric standard deviation (S_{gw}) of particle diameter by mass also varied significantly among the samples, with a mean of 0.440 mm and a range between 0.313 and 0.556 mm. The S_{gw} value was lower than its corresponding d_{gw}. Rausch et al. (2005) reported a mean d_{gw} of 0.92 mm for nine DDGS

Table 1
Geometric mean diameter and geometric standard deviation of particle diameter by mass for 11 DDGS samples[a]

Plant No.	DDGS	
	d_{gw} (mm)	S_{gw} (mm)
1	0.543 ± 0.013 c	0.536 ± 0.016 a
2	0.949 ± 0.016 a	0.556 ± 0.016 a
3	0.434 ± 0.008 d	0.313 ± 0.002 f
4	0.474 ± 0.016 d	0.460 ± 0.021 bcd
5	0.907 ± 0.030 a	0.475 ± 0.013 bc
6	0.657 ± 0.016 b	0.431 ± 0.011 cde
7	0.709 ± 0.014 b	0.429 ± 0.005 de
8	0.691 ± 0.011 b	0.390 ± 0.001 e
9	0.483 ± 0.004 cd	0.337 ± 0.003 f
10	0.716 ± 0.025 b	0.481 ± 0.007 b
11	0.699 ± 0.013 b	0.432 ± 0.006 cde
Mean	0.660	0.440
Minimum	0.434	0.313
Maximum	0.949	0.556
Range	0.515	0.243
Standard deviation	0.168	0.074

[a] Mean value of duplicate measurements ± standard deviation. Column means with different letters differ significantly at $p < 0.05$.

samples. This value was much larger than that found in the current study. Change or improvement of processing methods over the last few years might explain the discrepancy between the studies.

Geometric mean diameter is an effective way of expressing and comparing PSD on a statistical basis (ASAE Standards, 2003) but expression in the proportion of material retained on (or pass through) each sieve size can be more easily understood by processors. When using the selected series of 6 sieves (US standard Sieve Nos. 8, 12, 18, 35, 60, and 100) and a pan, all 11 DDGS had a unimodal particle size distribution, except for DDGS 1 and 4 which had bimodal curves (Fig. 1). The mode is the center of the size class that contains most of the material. For the samples having a unimode the PSD had a mode in the center of the size class between 0.5 and 1.0 mm (the material retained in No. 35 sieve but passed through No. 18 sieve), but the height of the peaks varied among them. DDGS 2 had the narrowest peak, indicating that the particle size varied least for this sample. By comparing Fig. 1 with d_{gw} and S_{gw} values in Table 1, it appears that the higher the peak, the larger the d_{gw} value. The broader (wider) the peak, the larger the S_{gw} value. For the samples with a bimode (DDGS 1 and 4), the PSD had a major mode in the center of size class between 0.25 and 0.5 mm, that is, the largest proportion of material was retained on No. 60 mesh but passed through No. 35 mesh. The minor mode was in the center of the size class larger than 2.36 mm, that is, the material retained on No. 8 sieve. These two samples had the flattest curves and thus the largest variation in particle size distribution.

Analysis of variance showed that sieve size had a significant effect on mass frequency of DDGS. The interaction between plant (processor) and sieve size was also significant. For example, in the particle size category of 0.25 mm (60 mesh size), the amount of material retained was largest for DDGS 1 and 4, but relatively lower for other DDGS samples. Significant interactive effect between plant and sieve size was also observed by Rausch et al. (2005). Yet, unlike their report that the most variation was in the larger particle size categories among plants, this study showed that most variation was in the middle particle size category. A key explanation is that, as noted earlier, the particle size of DDGS was found much larger, in terms of mean d_{gw} values, in the Rausch et al. study than in the current study.

3.2. Protein, oil and ash contents in whole samples and sized fractions

The protein content in the whole DDGS sample varied greatly (Fig. 2A), ranging from 26.5% in DDGS 6, to 42.3% in DDGS 4. DDGS 2 and 4 apparently were high protein types, while the rest were in a normal range. As the particle size by sieving increased from 0.11 to 2.36 mm, protein in sized fractions of all the DDGS samples followed a general decreasing pattern. Thus, finer fractions had higher protein content than coarser fractions. It is interesting to note that protein concentrations in samples 4–11 decreased to a minimum level as the particle size increased to No. 18 mesh, and then increased with increasing particle size.

DDGS 2 was an exception; its protein content was high (41.1%) in the original sample and slightly increased in sized fractions with increasing particle size from 0.15 to 2.36 mm. Overall, the protein variation in sized fractions for this sample was much lower than other samples. Among all the samples, sizing by sieving was most

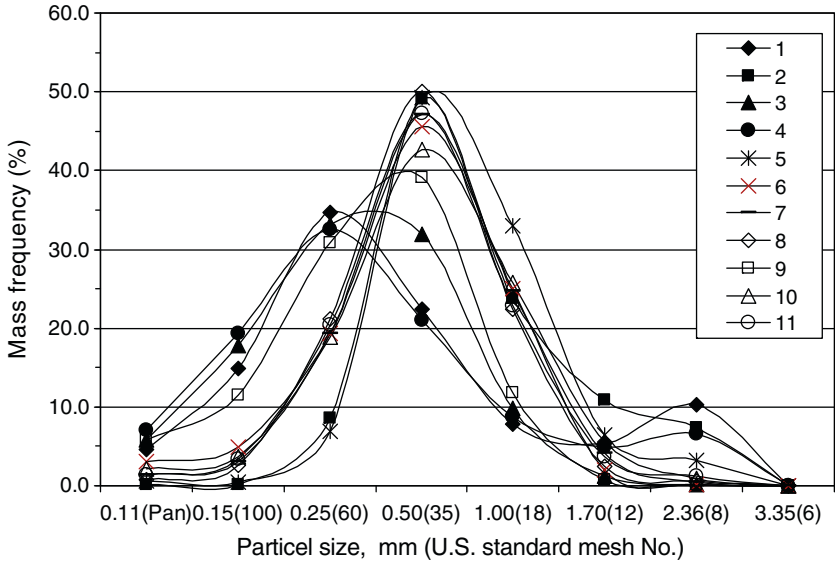

Fig. 1. Particle size distribution of 11 DDGS samples collected from the US Midwest region. Mass frequency was based on the proportion of material retained on each sieve size, by weight.

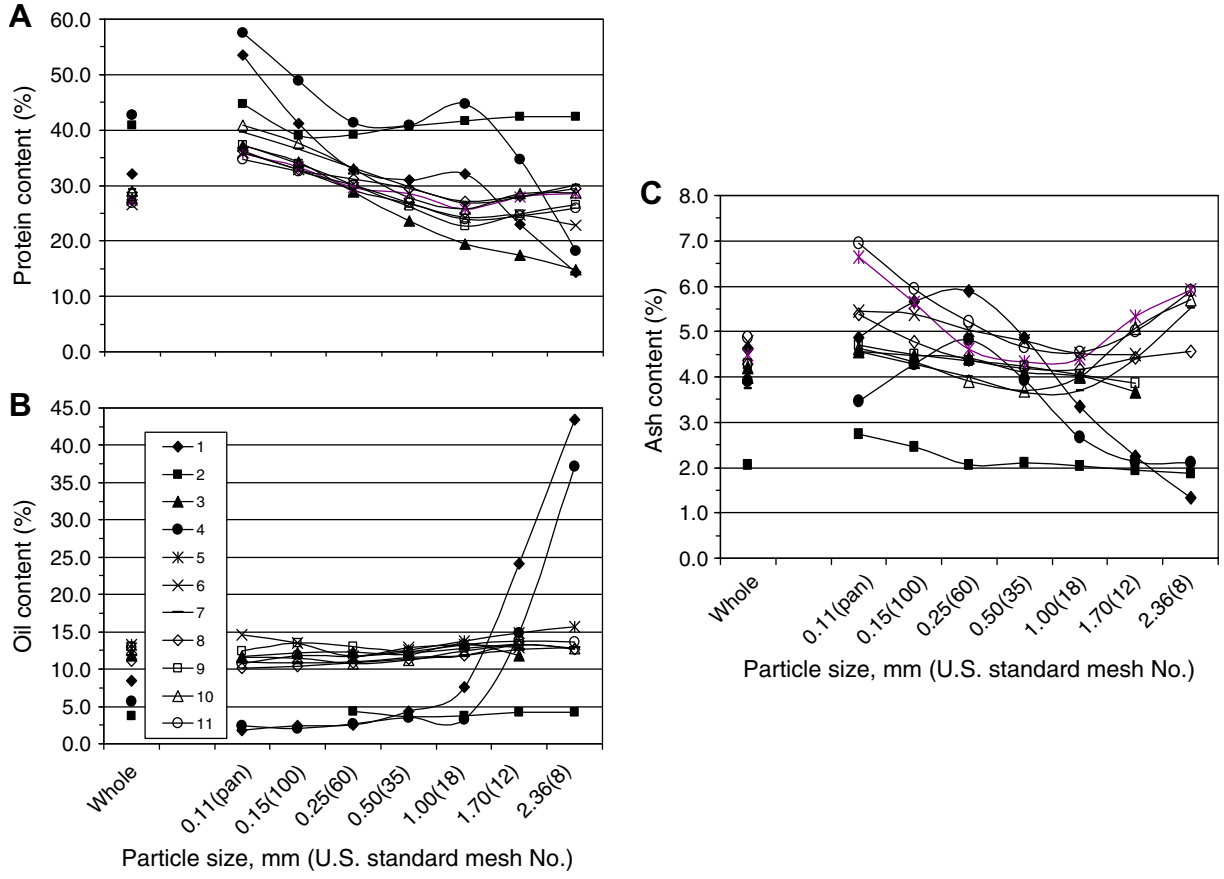

Fig. 2. Protein (A), oil (B) and ash (C) contents (%, dry matter basis) in the original (whole) and sieve sized fractions of the 11 DDGS samples.

effective for DDGS 1 and 4 and least effective for DDGS 2 in differentiating fractions for protein content. Although both DDGS 1 and 2 were high protein types, they exhibited opposite changes and different variation of protein content in sized fractions. Apparently, the extent of protein variation in sized fractions positively links to that of particle size variation (Fig. 1); the larger the variation in particle size, the larger the variation of protein in sized fractions. However, protein content in the original DDGS had little effect on the particle size distribution and on its own variation in sized fractions.

The oil content in most DDGS samples was in the range of 11.3–13.1% (Fig. 2B). Oil content in sized fractions for most DDGS samples had a slightly upper trend with increase in particle size. This was in contrast to the change of protein content in sized fractions, which had a decreasing trend. DDGS 1 and 4 were rather unique that their oil content in whole sample was 8.7% and 5.6%, respectively. In size fractions it increased dramatically when particle size increased from 1 to 2.36 mm. An explanation is that in these two samples, intact germ, which contained highest amount of oil, was visible and naturally it went to larger size fractions during sieving. In was possible that these two samples resulted from a modified method, in which germs were removed before liquefaction/saccharification (the steps convert starch to fermentable sugars) and added back in a later step. DDGS 2 was another exception since its oil content in the original sample was lowest (3.9%), and remained unchanged in sized fractions. Apparently, this sample resulted from another modified method, in which fiber and germ were removed prior to liquefaction and saccharification and the removed germs were not added back.

The ash content varied greatly among DDGS, ranged from 2.1% in Sample 2 to 4.9% in Sample 11 (Fig. 2C). However, most DDGS had ash content between 4 and 5%. Again, DDGS 2 was an exception apparently due to its unique process (fiber and germ removal prior to fermentation). In sized fractions, there were mixed trends among DDGS samples from different plants. As the particle size increased, some (Nos. 1 and 4) increased and then decreased in the ash content, others decreased and then increased. Still others had a slightly decreasing trend. For some samples, particularly Nos. 1 and 4, the variation of ash content among sized fractions were rather large.

3.3. Starch, total non-starch CHO and total CHO contents in whole samples and sized fractions

Starch is the main component for ethanol production. However, since complete conversion to ethanol during yeast fermentation is hard to achieve, there is still residual starch in DDGS. In the present study, residual starch in most DDGS samples was around 5% (Fig. 3A). This value matches that reported by Belyea et al. (2004). Yet, surprisingly, three DDGS samples had unusually high concentration of starch, ranging from 11.1% in Sample 2 to 15.6% in Sample 1, and further to 17.6% in Sample 4. As mentioned earlier, these samples were apparently processed unconventionally. DDGS 1 and 4 contained intact germs, while DDGS 2 was high in protein. This unique observation indicates that although some pre-fractionation procedures (such as fiber and/or germ removal) prior to ethanol fermentation can increase protein content in DDGS, they could harm fermentation and lead to higher residual starch in DDGS.

There were some changes in starch concentration in sized fractions of DDGS samples. For most samples, starch increased in fractions with increasing particle size, while for a few samples,

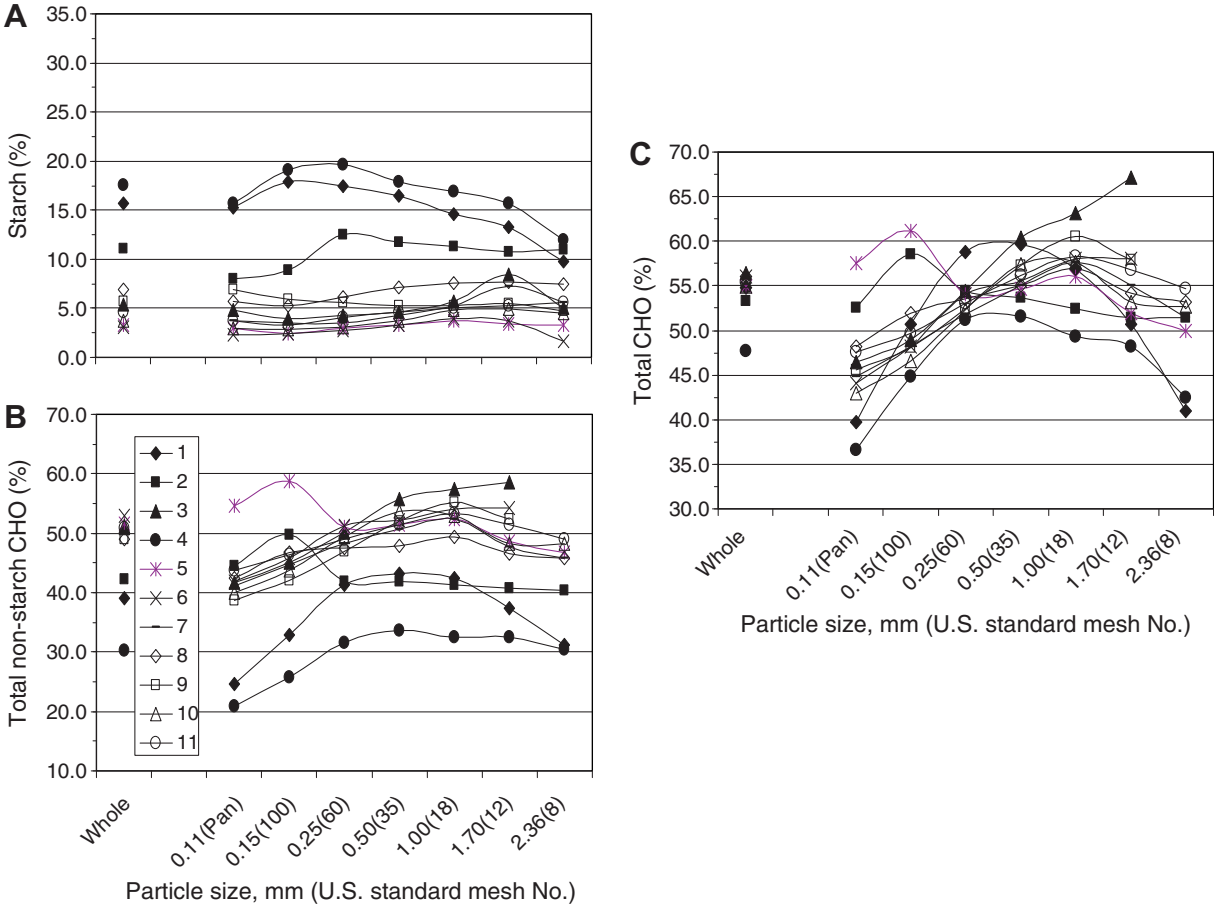

Fig. 3. Starch (A), total non-starch carbohydrate (B), and total carbohydrate (C) contents (%, dry matter basis) in the original (whole) and sieve sized fractions of the 11 DDGS samples.

particularly those with high starch content, the opposite trend was observed.

Total non-starch carbohydrate in corn co-products refers to all the carbohydrates excluding starch. This includes soluble sugars, cellulose, hemicellulose and lignin. The last three are also known as fiber. During ethanol fermentation soluble sugars are completely converted, and starch is mostly converted to ethanol, leaving non-fermentable fiber in DDGS. Most DDGS samples had non-starch CHO around 50% (Fig. 3B). However, Samples 1, 2 and 4 had much lower values, indicating that they were co-products of modified ethanol production methods. Total non-starch CHO in sieved fractions of most DDGS samples had an increasing trend with increasing particle size. This is due to visual observation that fibrous materials left in DDGS samples, such as seed coat, tended to be larger in particle size. DDGS 2 and 5 somehow showed exception.

Most DDGS samples had a content of total CHO around 55% (Fig. 3C). The only exception was Sample 4, which had a value of 47.8%. This sample was a low-fiber type since its fiber was most likely removed prior to fermentation by a pre-fractionation procedure. In sized fractions, as particle size increased, total CHO in most samples generally increased. Again, DDGS 2 and 5 were exception; their total CHO slightly decreased or showed no change. It is interesting that although starch and non-starch CHO varied greatly among DDGS samples, the total CHO varied much less. This is also true for sized fractions. The explanation is that DDGS samples or sized fractions with much lower levels of non-starch CHO (Fig. 3B) happened to have much higher levels of residual starch (Fig. 3A).

3.4. Surface color in whole samples and sized fractions

DDGS from different plants varied greatly in color, with *L* varying from 44.9 to 59.6, a value from 8.3 to 13.2, and *b* value from 31.0 to 46.3 (Fig. 4). These range values indicate that some DDGS were darker, yellower or redder than others. There were also some noticeable changes in surface color of sized fractions among DDGS samples. Most samples showed a slight decrease in *L* and *b* values and an increase in *a* value as the particle size increased. In other words, for DDGS samples, fractions of smaller particle size were relatively lighter and less red, but more yellow. The largest variation in color, particularly in *b* value, among DDGS samples was found in fractions of smaller particle size.

3.5. Correlations between attributes measured in whole DDGS samples

During conversion of corn to ethanol, although the principle is similar, there is a great variation in corn material and methods used among processing plants (Bothast and Schlicher, 2005; Singh et al., 2005). Some plants pre-fractionate corn material before fermentation, such as removing fiber and/or germ, others by-pass or modify certain steps. Still others use different parameters (pH, temperature, duration, sources of enzyme, type of equipment, size of screens used for grinding, etc.). It has been shown that composition of distillers solubles (thin stillage) (Belyea et al., 1998) and DDGS (Belyea et al., 2004) can vary significantly even from batch to batch within the same processing plant. Thus, the variations in

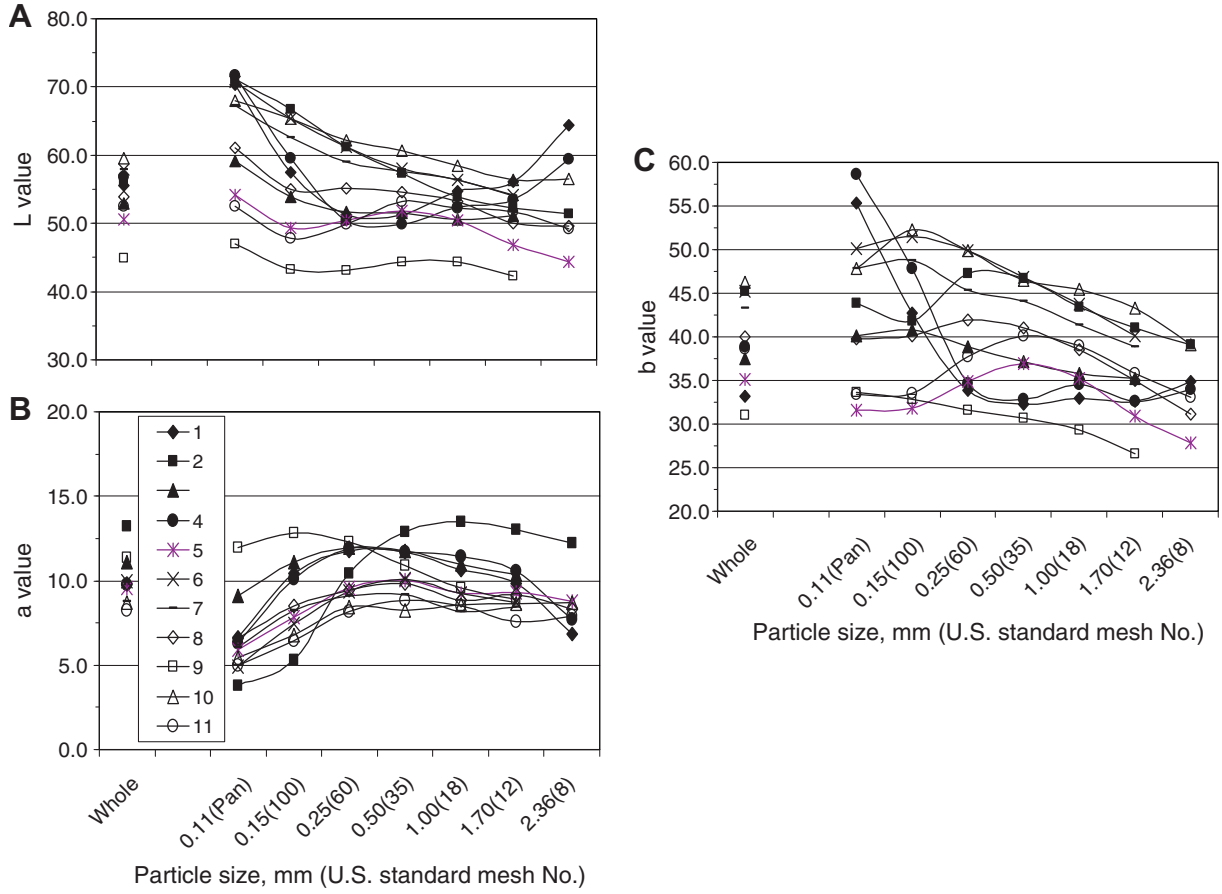

Fig. 4. Surface color, expressed in *L* (A), *a* (B), and *b* (C) color space, in the original (whole) and sieve sized fractions of the 11 DDGS samples.

corn and methods used among plants, plus complex interactions of many factors during the process within a plant, would lead to great variations in PSD, nutrient composition, and surface color in the original DDGS samples from different plants observed in this study. Regardless of these variations, with exception of DDGS 1, 2 and 4, the chemical compositions of several nutrients (protein, oil, starch, and ash) in the original DDGS samples observed in this study generally agree with previous reported ranges (Belyea et al., 2004).

For determining any correlation between attributes measured on the whole DDGS sample, correlation coefficients, *r* values, were calculated using data from the 11 samples. As discussed earlier, DDGS 1, 2 and 4 deviated greatly from the rest of the samples in physical and compositional properties as well as visual appearance, presumably resulting from use of modified processing methods, they are considered outlying. Correlation coefficients were also compiled without these outlying samples (Table 2). In both cases, protein correlated negatively with oil, ash, non-starch CHO and total CHO, and positively with starch; oil correlated negatively with starch and positively with ash. These correlations were consistent with the finding mentioned earlier that higher protein and lower oil samples tended to have higher starch content. This further supports a notion that although some pre-fractionation procedures (such as fiber and/or germ removal) prior to ethanol fermentation could increase protein content in DDGS, they could lead to incomplete fermentation and result in higher residual starch in DDGS.

Furthermore, the two major physical property indexes, geometric mean diameter (d_{gw}) of particles and color attributes (*L*, *a* and *b* values) did not show good correlations with any compositional traits, when both pools of DDGS samples (one with all samples and one without the outlying samples) are taken into consideration. Apparently, variation in particle size and coloration of corn material during ethanol production had little impact on composition of whole DDGS samples. Interestingly, among color attributes, *L* and *b* values had a very good positive correlation.

Variation in color of DDGS was not only visible but also measurable, as shown in this study as well as in the previous one (Rosentrater, 2006). It is also a major factor that determines the perceived value of DDGS by purchasers. Efforts have been made or suggested to develop relationships between DDGS color and other quality parameters (Goihl, 1993; Rosentrater, 2006; Rosentrater and Muthukumarappan, 2006), since establishment of such relationships could lead to development of low cost visual sensors for quality control during processing and quality characterization of the co-product. However, based on observation of this study, for whole DDGS samples, the relationship was not strong enough for color to be an indicator of nutritional quality.

3.6. Correlations between attributes measured in sieve sized fractions

Although for the whole DDGS samples, particle size distribution, expressed as d_{gw} (geometric mean diameter), had little correlation with chemical composition and color attributes, for sieved fractions with different particle sizes, protein, oil, ash, residual starch, total CHO, total non-starch CHO, and surface color were all found varying greatly (Figs. 2–4). Close examination of DDGS showed that the particles can be grouped into three classes, flakes, granules and aggregate granules (Fig. 5). The flakes came mostly from tip cap and broken seed coat of corn kernels. The granules were mostly non-fermentable materials which were left from

Table 2
Correlation coefficient (r) values between attributes measured in whole DDGS samples[a]

	d_{gw}	S_{gw}	Protein	Oil	Starch	Ash	T CHO	T NS CHO	L	a	b
All DDGS samples											
d_{gw}		0.589	0.057	−0.115	−0.295	−0.436	0.160	0.267	0.201	0.086	0.452
S_{gw}			0.532	−0.594	0.442	−0.406	−0.331	−0.431	0.512	0.034	0.310
Protien				−0.958	0.823	−0.696	−0.856	−0.884	0.312	0.438	0.166
Oil					−0.825	0.736	0.687	0.828	−0.355	−0.534	−0.196
Starch						−0.290	−0.747	−0.974	0.174	0.250	−0.228
Ash							0.333	0.322	−0.255	−0.672	−0.432
T CHO								0.877	−0.178	−0.101	0.010
T NS CHO									−0.185	−0.215	0.167
L										−0.261	0.811
a											−0.063
b											
Without the outlying samples (DDGS 1, 2 and 4)											
d_{gw}		0.897	0.029	0.199	−0.492	0.127	−0.307	0.322	0.293	−0.688	0.262
S_{gw}			0.067	0.224	−0.689	0.089	−0.447	0.493	0.526	−0.804	0.5323
Protien				−0.663	0.386	−0.931	−0.255	−0.528	0.295	−0.180	0.249
Oil					−0.585	0.579	−0.499	0.363	−0.467	0.038	−0.422
Starch						−0.289	0.262	−0.895	−0.391	0.368	−0.391
Ash							0.240	0.401	−0.259	0.019	−0.185
T CHO								0.195	0.252	0.275	0.228
T NS CHO									0.514	−0.247	0.502
L										0.594	0.984
a											−0.588
b											

[a] T CHO, total carbohydrate; T NS CHO, total non-starch carbohydrate.

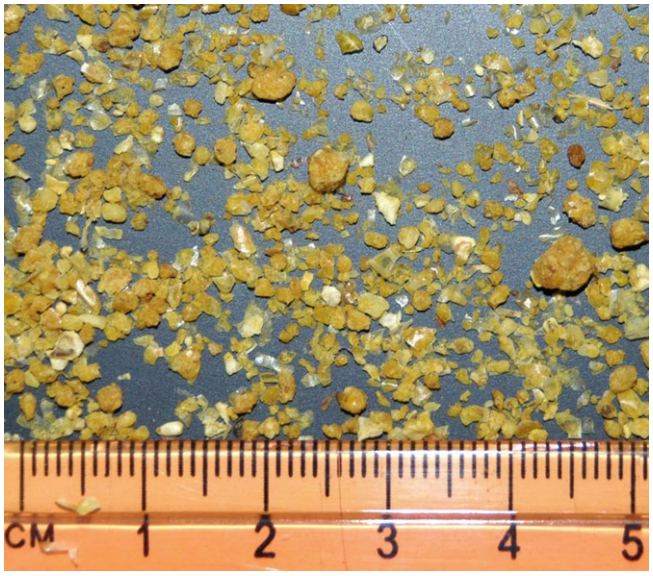

Fig. 5. Close-up photograph of a DDGS sample, showing different texture and shapes of particulate material.

ground endosperm and germ. The aggregate granules are mostly granules glued together, apparently by solubles added during the final stage of the process. Because all thee types of particulates varied in size and shape, sieving could cause changes of their proportions in sized fractions. Since the flakes were mostly fiber, while the granules and aggregate ones were mostly non-fiber components, shifts in their proportions led to change in composition in sieve sized fractions. This is the scientific basis for relationship between particle size and chemical composition of sieved DDGS fractions.

Although the extent of variations for these attributes in sieved fractions was governed by individual DDGS, a few had good correlation coefficients with particle size, expressed in mm diameter (Table 3). In other words, distribution of nutrients and color attributes correlated well with that of particle size in DDGS. For example, in sieved fractions, protein content, L and a values were negatively correlated with particle size, while contents of oil and total CHO positively correlated with particle size (Table 3). These correlations were enhanced when the 3 outlying samples were removed from the sample pool. These data further supported the idea of nutrient enrichment of DDGS through sieving reported previously (Wu and Stringfellow, 1986; Srinivasan et al., 2005). Sieved DDGS fractions with varying particle size has been shown to affect the volume and acceptability of baked products (Abbott et al., 1991), apparently due to differential changes in composition and physical properties among fractions by sieving, shown in this study and previous ones (Wu and Stringfellow, 1986; Srinivasan et al., 2005). It is worthy to note that there is a small discrepancy in the literature regarding the changing pattern of fat with particle size. Wu and Stringfellow (1986) reported that protein and ash contents increased, and lipid and neutral detergent fiber contents decreased as particle size decreased (higher screen number). However, Srinivasan et al. (2005) reported that fractions with smaller particle size had reduced fiber and increased protein and fat contents relative to the original DDGS. Data of this study agreed with the finding of Wu and Stringfellow (1986).

Furthermore, in sized fractions, some nutrients and color attributes had relatively high correlations between them. For example, protein correlated negatively with oil, total CHO, and total no-starch CHO, but positively with starch, L and b values. Again, most of these correlations were enhanced in the sample pool without the 3 outlying samples. This means that finer fractions were higher in protein concentration, but lower in oil and CHO, and lighter in color. It is also interesting to note that starch was very negatively correlated with total no-starch CHO. In other word, fractions with high starch tended to have much lower total non-starch CHO. As discussed earlier, this observation explained why total CHO changed much less among DDGS samples. Also, not surprisingly, total CHO and total non-starch CHO had a highly positive correlation, since fiber was the major component of the two attributes.

Finally, based on observation of this study, it appears that the extent of particle size distribution of DDGS can be considered as an index for potential of fractionation. For example, DDGS 2 had

Table 3
Correlation coefficient (r) values between attributes measured in sieve sized DDGS fractions[a]

	Particle size	Protein	Oil	Starch	Ash	T CHO	T NS CHO	*L*	*a*	*b*
All DDGS samples										
Particle size		−0.520	0.442	−0.033	−0.340	0.153	0.089	−0.294	0.106	−0.386
Protein			−0.712	0.515	−0.078	−0.572	−0.627	0.397	0.005	0.446
Oil				−0.408	−0.171	−0.077	0.165	−0.003	−0.372	−0.266
Starch					−0.347	−0.261	−0.774	0.125	0.277	−0.004
Ash						0.129	0.294	−0.187	−0.200	−0.087
T CHO							0.839	−0.435	0.126	−0.312
T NS CHO								−0.291	−0.162	−0.141
L									−0.560	0.831
a										−0.270
b										
Without the outlying samples (DDGS 1, 2 and 4)										
Particle size		−0.626	0.575	0.267	−0.044	0.386	0.278	−0.329	0.057	−0.342
Protein			−0.363	−0.256	0.439	−0.814	−0.616	0.437	−0.388	0.309
Oil				−0.267	0.401	0.088	0.093	−0.379	0.136	−0.383
Starch					−0.461	0.218	−0.114	−0.341	0.333	−0.324
Ash						−0.339	−0.190	0.145	−0.458	−0.038
T CHO							0.911	−0.320	0.115	−0.245
T NS CHO								−0.131	−0.111	−0.068
L									−0.551	0.921
a										−0.305
b										

[a] T CHO, total carbohydrate; T NS CHO, total non-starch carbohydrate.

a very narrower PSD peak and thus it had very limited variation in nutrients in sized fractions. For this sample, dry fractionation by sieving would not be very effective. In contrast, DDGS 1 and 4 had much flatter curves of PSD, a good candidate for dry fractionation to achieve fractions with large variation in attributes of interest. For this reason, even though PSD was shown to have little relationship to chemical composition of the whole DDGS sample, it is suggested that PSD be measured as a quality factor during evaluation of the co-product.

In conclusion, this study showed that there was great variation in composition and color among DDGS from different plants. Surprisingly, a few DDGS samples contained unusually high amounts of residual starch, presumably resulting from some unspecified pre-fractionation steps. More importantly, particle size of DDGS varied greatly within a sample and particle size distribution varied greatly among samples. Particle size distribution and color parameters had little correlations with composition of whole DDGS samples, but distribution of nutrients as well as color attributes was related to the distribution of particle size. In other words, there is highly heterogeneous distribution of nutrients in sized fractions. Thus, it is highly feasible to fractionate DDGS for compositional enrichment based on particle size. Since the extent of PSD can serve as an index for potential of DDGS fractionation, it is suggested that PSD of DDGS be a quality parameter for measurement.

Acknowledgements

The author expresses thanks to Michael Woolman of USDA, ARS at Aberdeen, ID, for his assistance in conducting the experiments and collecting data, and to those individuals from ethanol production plants who supported the ARS research by providing their DDGS samples.

References

Abbott, J., Opalka, J., McGuire, C.F., 1991. Dried distillers' grains with solubles: particle size effects on volume and acceptability of baked products. J. Food Sci. 56 (5), 1323–1326.

Amezcua, C.M., Parsons, C.M., 2007. Effect of increased heat processing and particle size on phosphorus bioavailability in corn distillers dried grains with solubles. Poultry Sci. 86, 331–337.

AOAC (Association of Official Analytical Chemists), 2002. AOAC Official Methods of Analysis. AOAC International.

AOCS (American Oil Chemists' Society) Official Method, 2005. Rapid determination of oil/fat utilizing high temperature solvent extraction. Method Am 5-04.

ASAE (American Society of Agricultural Engineers) Standards, 2003. Methods for determining and expressing fineness of feed materials by sieving. S319.3. St. Joseph, MI.

Barbosa-Canovas, G.V., Ortega-Rivas, E., Juliano, P., Yan, H. (Eds.), 2005. Food Powders, Physical Properties, Processing, and Functionality. Kluwer Academic/Plenum Publishers, New York, NY.

Belyea, R., Eckhollf, S., Wallig, M., Tumbleson, M., 1998. Variability in the nutritional quality of distillers solubles. Bioresour. Technol. 66, 207–212.

Belyea, R.L., Rausch, K.D., Tumbleson, M.E., 2004. Composition of corn and distillers dried grains with solubles from dry grind ethanol processing. Bioresour. Technol. 94, 93–298.

Bothast, R.J., Schlicher, M.A., 2005. Biotechnological processes for conversion of corn into ethanol. Appl. Microbiol. Biotechnol. 67, 19–25.

Cheng, Z.J., Hardy, R.W., Blair, M., 2003. Effects of supplementing methionine hydroxyl analogue in soybean meal and distiller's dried grain-based diets on the performance and nutrient retention of rainbow trount [Oncorhynchus mykiss (Walbaum)]. Aquacult. Res. 34, 1303–1310.

Ganesan, V., Muthukumarappan, K., Rosentrater, K.A., 2007. Flow properties of DDGS with varying soluble and moisture content using Jenike shear testing. Paper No. 076063. ASAE: St. Joseph, MI.

Goihl, J., 1993. Color, odor good indicators of DDGS nutritional value. Feedstuffs 65 (21), 11.

Liu, C., Schingoethe, D.J., Stegeman, G.A., 2000. Corn distillers grains versus a blend of protein supplements with or without ruminally protected amino acids for lactating cows. J. Dairy Sci. 83, 2075.

Rausch, K.D., Belyea, R.L., Ellersieck, M.R., Singh, V., Johnston, D.B., Tumbleson, M.E., 2005. Particle size distribution of ground corn and DDGS from dry grind processing. Trans. ASAE 48 (1), 273–277.

Rosentrater, K.A., 2006. Some physical properties of distillers dried grains with solubles (DDGS). Appl. Eng. Agric. 22 (4), 589–595.

Rosentrater, K.A., Muthukumarappan, K., 2006. Corn ethanol coproducts: generation, properties, and future prospects. Int. Sugar J. 108, 648–657.

Singh, V., Johnston, D.B., Naidu, K., Rausch, K.D., Belyea, R.L., Tumbleson, M.E., 2005. Comparison of modified dry-grind corn processes for fermentation characteristics and DDGS composition. Cereal Chem. 82 (2), 187–190.

Spiehs, M.J., Whitney, M.H., Shurson, G.C., 2002. Nutrient database for distiller's dried grains with solubles produced from new ethanol plants in Minnesota and South Dakota. J. Anim. Sci. 80, 2639–2645.

Srinivasan, R., Moreau, R.A., Rausch, K.D., Belyea, R.L., 2005. Separation of fiber from distillers dried grains with solubles (DDGS) using sieving and elutriation. Cereal Chem. 82 (5), 528–533.

Wondra, K.J., Hancock, J.D., Behnke, K.C., Hines, R.H., Stark, C.R., 1995. Effects of particle size and pelleting on growth performance, nutrient digestibility, and stomach morphology in finishing pigs. J. Anim. Sci. 73, 757–763.

Wu, Y.V., Stringfellow, A.C., 1986. Simple dry fractionation of corn distillers' dried grains and corn distillers dried grains with solubles. Cereal Chem. 63 (1), 60–61.