New Technologies to Aid in Evaluation of Alternative Feedstuffs

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Take Home Message

High corn and soybean meal prices, and in some cases, reduced availability, are causing nutritionists to use more by-products and co-products than ever before in order to minimize diet costs. The three most common by-products being used in swine diets are DDGS, wheat midds, and bakery by-product. Managing nutrient variability among by-product sources is the primary challenge to obtaining accurate nutrient loading values for use in feed formulation. Significant research has been conducted recently regarding nutrient variability among DDGS sources and the use of various "nutritional tools" to estimate ME and digestible amino acid content among sources. Unfortunately, very little research has been conducted to develop similar "tools" for use with wheat midds and bakery by-product. Energy prediction equations for DDGS provide the capability for estimating actual energy value for specific sources but there are several concerns affecting their accuracy that must be considered when using them. Use of an *in vitro* digestible energy procedure resulted in accurate prediction of apparent total tract energy digestibility among single samples of 8 feedstuffs, but resulted in poor predictions within canola meal and corn DDGS sources. Use of NIR is becoming a popular method for assessing nutrient content of feed ingredients and calibrations have been developed for DDGS. There is considerable interest in using NIR to estimate ME and digestible amino acid content in by-products, but there are several challenges that must be overcome before this is a viable "tool". Several equations have been developed to estimate amino acid content from crude protein content in corn, soybean meal, DDGS, and wheat midds, but accuracy of lysine estimation is poor. Digestible lysine in DDGS can be estimated relatively accurately from total or reactive lysine content in DDGS. Use of *in vitro* "tools" such as IDEA® and AMINORED® do not appear to provide a high degree of accuracy in digestible amino acid estimates in DDGS for swine. Color of DDGS may be a general indicator of lysine digestibility among DDGS sources, but optical density and front face fluorescence may provide more accurate prediction of digestible amino acids in DDGS if some of their challenges can be overcome. In summary, several "nutritional tools" have been developed to estimate ME and digestible amino acid content in DDGS for swine, but more refinements and validation are needed. Efforts are needed to develop similar "tools" for other common by-product ingredients used in swine diets.

Introduction

The long history of our ability to utilize an abundant, low cost supply of corn and soybean meal as the primary sources of energy and amino acids in the U.S. livestock and poultry industries appears to have come to an end. Feed manufacturers and livestock and poultry producers are now competing with the biofuels industry for access to corn and soybeans, and their prices are the highest ever recorded. As a result, the demand for more economical, alternative energy and amino acid sources has increased in an attempt to minimize diet cost. Fortunately, corn distillers dried grains with solubles (DDGS), a co-product of the U.S. corn-based fuel ethanol industry, is being produced in large quantities (37 million metric tonnes), has high energy and moderate amino acid value, and is often priced at 75 to 85% of the value of corn, making it an attractive alternative ingredient. Lesser amounts of wheat midds (by-product of flour milling) and bakery by-product are also attractive, and are often lower cost alternative ingredients to corn and soybean meal, but their availability may vary by region and season.

However, there are several challenges to using these co-products or by-products in animal feeds. Variability in energy and digestible nutrient content among sources makes it difficult to establish accurate nutrient loading values for diet formulation, which are essential when using moderate to high dietary inclusion rates in order to avoid the negative economic consequences of over- or under-valuing their nutritional contributions to diets. Furthermore, these co-products and by-products are marketed using minimum or maximum specifications for moisture, crude fat, crude fiber, and crude protein, which have minimal value in estimating actual nutritional value in swine diets. Because there is no “grading system” or other means of differentiating feeding value among sources of these by-products or co-products, new nutritional “tools” are being developed and implemented to help nutritionists manage nutrient variability by estimating energy and digestible amino acid content and assessing relative feeding value among sources. The purpose of this paper is to define variation in energy and digestible amino acid content among sources of the most frequently used by-products in swine diets, and identify various “nutritional tools” that are being developed and implemented to assess their nutrient content and feeding value.

Nutrient Variability Among By-Product Sources

Perhaps the greatest challenge for nutritionists using by-products in feed formulation is managing variation in nutrient content and digestibility among sources. Historically, some nutritionists have attempted to manage nutrient content variability of feed ingredients by adjusting average nutrient values by one-half of a standard deviation for use in feed formulation (Combs 1970). While this approach has some benefit, it does not provide the degree of confidence required by most nutritionists when formulating more complex diets containing a wider variety of ingredients today.

We often use corn and soybean meal as our reference points for comparison, and assume that nutrient content variability is minimal among sources of these ingredients (Tables 1 and 2). In general, nutrient content is more variable among corn sources than among soybean meal sources. We need to remember that even though nutrient variability may be relatively low for corn and soybean meal, because these ingredients historically have comprised 97% of ingredients in swine diets, the combined effect of variation in both ingredients can affect the accuracy of diet formulation depending on the nutrient loading values assumed. Furthermore, although we are often more concerned about high nutrient content variability in by-products, we need to put this in context based on their dietary inclusion rates, which are typically much lower than the levels of corn and soybean meal used.

Table 1. Average and range in values (air-dry basis) of selected nutrients, and coefficients of variation (CV) among 45 samples of corn over a 3-year sampling period (Cromwell et al., 1999).

	Average	CV	Range
Dry matter, %	87.8	0.83	86.6 - 89.0
Crude protein, %	8.3	7.4	7.31 - 9.06
Ca, %	0.02	47.8	0.01 - 0.04
P, %	0.26	8.1	0.22 - 0.29
Lysine, %	0.26	5.6	0.25 - 0.30
Methionine, %	0.17	7.3	0.16 - 0.20
Threonine, %	0.31	6.2	0.27 - 0.34
Tryptophan, %	0.06	8.2	0.06 - 0.07

Table 2. Average and range in values (air-dry basis) of selected nutrients, and coefficients of variation (CV) among 31 samples of soybean meal over a 2-year sampling period (Cromwell et al., 1999).

	Average	CV	Range
Dry matter, %	89.9	0.81	89.0 - 91.2
Crude protein, %	43.8	1.9	42.8 - 44.6
Ca, %	0.32	13.0	0.28 - 0.37
P, %	0.62	4.1	0.59 - 0.65
Lysine, %	2.83	2.5	2.76 - 2.89
Methionine, %	0.61	1.0	0.60 - 0.63
Threonine, %	1.73	3.3	1.68 - 1.78
Tryptophan, %	0.61	1.7	0.59 - 0.63

DDGS

It is widely accepted that the nutrient content of DDGS varies among sources, and this variability can be attributed to many factors (Olentine, 1986). Data reported by Spiehs et al. (2002) serve as a good reference point for typical ranges and variation in DDGS content among sources (Table 3). Of the key nutritional components, crude fiber, ADF, and NDF, ash, phosphorus, and lysine are the most variable. However, with the exception of lysine and perhaps methionine, the coefficients of variation are similar among the nutrients shown in Table 1 and 3 for corn and DDGS, respectively.

Currently, approximately 30% of U.S. ethanol plants are removing a portion of the corn oil before producing DDGS, and some industry experts predict that 50% of ethanol plants will be extracting a portion of the oil during the DDGS production process by the year 2013. With increasing use of “back-end” oil extraction, the variability in crude fat content, and consequently ME value, is becoming more variable among DDGS sources. The calculated ME values for DDGS in Table 3 were derived from equations published by Noblet and Perez (1993) using chemical composition of complete feeds, and were not specific for DDGS. Therefore, although these appeared to be the best equations available at that time, they were not accurate enough to assess actual ME value among DDGS sources.

Table 3. Average and range in values (DM basis) of selected nutrients, and coefficients of variation (CV) among 10 sources of DDGS (Spiehs et al., 2002).

	Average	CV	Range
Dry matter, %	88.9	1.7	87.2 – 90.2
Crude protein, %	30.2	6.4	28.7 – 31.6
Crude fat, %	10.9	7.8	10.2 – 11.7
Crude fiber, %	8.8	8.7	8.3 – 9.7
ADF, %	16.2	28.4	13.8 – 18.5
NDF, %	42.1	14.3	36.7 – 49.1
Calculated ME, kcal/kg[a]	3,749	3.3	3,639 – 3,838
Ash, %	5.8	14.7	5.2 – 6.7
Ca, %	0.06	57.2	0.03 – 0.13
P, %	0.89	11.7	0.70 – 0.99
Lysine, %	0.85	17.3	0.72 – 1.02
Methionine, %	0.55	13.6	0.49 – 0.69
Threonine, %	1.13	6.4	1.07 – 1.21
Tryptophan, %	0.25	6.7	0.21 – 0.27

[a]DE = 4151 – (122 x % Ash) + (23 x % CP) + (38 x % EE) – (64 x % crude fiber); ME = DE x [1.003 – (0.0021 x % CP)]; Noblet and Perez (1993).

Distillers dried grains with solubles is primarily an energy source, but also supplies significant amounts of digestible amino acids and available phosphorus to swine diets. Recent studies have been conducted to determine DE and ME content of various sources of DDGS and develop prediction equations using chemical analysis measures to estimate actual energy content (Stein et al., 2006; Pedersen et al. 2007; Anderson et al. 2011; Stein et al., 2009; Mendoza et al., 2010). The average and ranges of GE, DE, and ME content of DDGS sources evaluated in these studies are shown in Table 4, and are compared to the energy values for corn obtained in these studies.

Average GE of DDGS samples was relatively consistent across the five studies (5,311 to 5,593 kcal/kg DM), but the overall range in GE was more variable (5,177 to 5,691 kcal/kg DM). Average DE estimates among the five studies was 3,950 kcal DE/kg DM, but ranged from 3,382 to 4,593 kcal/kg DM. Average ME of DDGS samples from 4 of the 5 studies reporting ME values was 3,784 kcal ME/kg DM, but like DE values, ranged from 3,381 to 4,336 kcal ME/kg DM. This range of 955 kcal/kg DM among DDGS sources is problematic when attempting to manage dietary energy values with high inclusion rates of DDGS. For comparison purposes, corn ME averaged 3,928 kcal/kg DM (range was from 3,805 to 4,103 kcal/kg DM) among the 4 studies that reported ME values (Table 4), and was higher than the value published (3,843 kcal/kg DM) in NRC (1998). Therefore, the average ME value of DDGS is approximately 96% of the value of corn, but can range from 88.9 to 105.7% of the value of corn.

Crude protein levels of DDGS sources used in these studies were relatively consistent, but the range in crude fat and NDF content (two primary contributing factors to DE and ME content) among sources within studies, and among studies, was highly variable (Table 4). Although, the variation in

DE and ME estimates among DDGS sources can largely be attributed to nutrient composition differences among sources, it is also likely that different methodologies used for conducting metabolism studies, different laboratory procedures used to measure nutrients, and lab to lab variation among studies had significant contributions to this variability. For example, the average and range in NDF values in the Pedersen et al. (2007) study were much lower than those reported in the other 4 studies. It is unclear if NDF composition was actually lower in these samples evaluated by Pedersen et al. (2007), or if a different analytical method was used compared to NDF procedures in other studies. Urriola et al. (2010) reported that apparent total tract digestibility (ATTD) of NDF among 8 corn DDGS sources averaged 59.3%, but ranged from 51.6 to 65.8%, and ATTD of total dietary fiber ranged from 39.4 to 56.4%. These results indicate that considerable variability in fiber digestibility exists among DDGS sources, which is likely a significant contributing factor to the variability in DE and ME content among DDGS sources. Recent unpublished data from our group (Pomerenke et al., 2011) showed that fecal digestibility values of fatty acids are higher than ileal fatty acid digestibility values, but MUFA and SFA digestibilities are higher when growing pigs are fed DDGS compared to a corn-soybean meal diet, but PUFA digestibility was lower (66.5% vs. 77.3% for a 30% DDGS diet compared to corn-soybean meal diet). Because corn oil in DDGS is predominantly PUFA, and because the crude fat content of DDGS can vary substantially, these factors also contribute to differences in ME variability among DDGS sources. Finally, several researchers have shown that apparent fat digestibility is significantly reduced when dietary fiber increases (Dierick et al., 1989; Noblet and Shi, 1993; Shi and Noblet, 1993). Just (1982a,b) showed that apparent fat digestibility decreases by 1.3 to 1.5 percentage units for each additional 1 percentage unit of crude fiber in the diet, and the depressive influence of crude fiber depends to some degree on the source of a feedstuff. Noblet and Shi (1993) demonstrated that apparent digestibility of fat decreased linearly with increasing dietary NDF content, and at the same time, the fat digestibility increased with increasing dietary fat level. These research results indicate that there are many factors that contribute to our ability to obtain accurate estimates of ME in various sources of DDGS. Because of the need to obtain source specific ME estimates among DDGS sources, we need to develop, validate, and implement rapid, accurate, and inexpensive “nutritional tools” to estimate actual energy values among DDGS sources.

Amino acid digestibility also varies considerably among sources. Urriola et al. (2009) determined amino acid digestibility of 8 corn DDGS sources and showed that standardized ileal lysine digestibility ranged from 55.7 to 68.7%, and tryptophan digestibility ranged from 56.2 to 72.0%, but standardized ileal digestibility of other amino acids was less variable among sources (Table 5). Additional studies have also shown considerable variation in amino acid digestibility among sources (Stein et al., 2005, 2006; Fastinger and Mahan, 2006; Pahm et al., 2008), and results from these studies were summarized by Stein and Shurson (2009). As a result, we need rapid, accurate, and inexpensive “nutritional tools” to estimate total and SID amino acid values among DDGS sources in order to assess relative value and obtain accurate nutrient loading values.

Table 4. Comparison of GE, DE, and ME estimates among DDGS sources and corn, and CP, NDF, and crude fat levels from 5 studies.

	Stein et al. (2006)	Pedersen et al. (2007)	Anderson et al. (2011)	Stein et al. (2009)	Mendoza et al. (2010b)
No. samples	10	10	6	4	17
GE, kcal/kg					
Average	5,426	5,434	5,420	5,593	5,311
Range	5,372 - 5,500	5,272 - 5,592	5,314 - 5,550	5,483 - 5,691	5,177 - 5,421
DE, kcal/kg					
Average	3,556	4,140	4,072	4,029	3,954
Range	3,382 - 3,811	3,947 - 4,593	3,705 - 4,332	3,920 - 4,252	3,663 - 4,107
ME, kcal/kg					
Average	ND[a]	3,897	3,750	3,790	3,700
Range	ND	3,674 - 4,336	3,414 - 4,141	3,575 - 3,976	3,381 - 3,876
ME/DE, %	ND	94.1	92.1	94.1	93.6
CP, %					
Average	30.9	32.2	31.3	31.8	30.3
Range	28.2 - 32.7	29.8 - 36.1	29.5 - 34.1	30.5 - 33.1	27.3 - 33.3
NDF, %					
Average	45.2	27.6	40.4	40.1	34.6
Range	41.8 - 49.1	23.1 - 29.7	33.4 - 49.1	35.1 - 45.2	25.3 - 43.1
Crude fat, %					
Average	ND	11.7	11.4	13.2	11.7
Range	ND	9.6 - 14.3	10.2 - 12.1	10.9 - 14.1	8.7 - 14.6
Corn					
DE, kcal/kg	3,845	4,088	3,885	4,181	3,893
ME, kcal/kg	ND	3,989	3,805	4,103	3,813

[a]ND = not determined,

Table 5. Averages and ranges in total amino content and standardized ileal digestibility among 8 corn DDGS sources (DM basis; Urriola et al., 2009).

Amino acid	Total Avg.	Total Range	Standardized Ileal Digestibility Avg.	Standardized Ileal Digestibility Range
Arg, %	1.37	1.28 - 1.60	81.5	75.7 - 86.2
His, %	0.82	0.78 - 0.93	79.3	75.5 - 83.6
Ile, %	1.14	1.08 - 1.37	76.0	71.1 - 81.0
Leu, %	3.53	3.21 - 3.94	86.0	82.9 - 89.4
Lys, %	0.93	0.81 - 1.12	61.6	55.7 - 68.7
Met, %	0.57	0.52 - 0.64	82.8	78.9 - 87.1
Phe, %	1.48	1.36 - 1.70	83.4	78.1 - 86.1
Thr, %	1.15	1.07 - 1.26	70.2	63.6 - 75.9
Trp, %	0.26	0.24 - 0.31	64.9	56.2 - 72.0
Val, %	1.51	1.42 - 1.74	75.9	70.9 - 81.3

Wheat Middlings

The most recent comprehensive study regarding variability in nutrient content of wheat midds was reported by Cromwell et al. (2000). Fourteen samples of wheat midds were collected at various Midwest universities during the fall of 1992 and analyzed to determine nutrient variability among sources and labs (Table 6). Results from this study suggest that compared to DDGS, wheat midds are less variable in nutrient content. However, Dale (1996) reported much greater variability in crude protein, crude fat, ash, crude fiber, NDF, and TME_n values among 15 sources of wheat midds for poultry (Table 7) than those reported by Cromwell et al. (2000). Furthermore, Dale (1996) developed TME_n prediction equations with r^2 values of 0.77 when NDF is included in the regression model, and indicated that NDF was a better measure than crude fiber for predicting TME_n. However, no equations have been developed to predict ME content of wheat midds sources for swine.

Pals and Ewan (1978) determined that the DE, ME, and NE content of wheat midds to be 3.47, 3.34, and 0.91 kcal/g DM for a single source of wheat midds. Recently, Nortey et al. (2008) showed that the total tract DE for wheat midds was 2.95 Mcal/kg DM, which is significantly lower than that reported by Pals and Ewan (1978). Digestible, metabolizable, and net energy values for wheat midds published in NRC (1998) are 3,455, 3,399, and 1,753 kcal/kg DM, respectively. These results indicate a wide range of estimates for energy content of wheat midds among publications. No studies have been conducted to compare DE and ME values for swine among various sources of wheat midds. Because of the apparent high variability in ME content among wheat midds sources for swine, we need to develop “nutritional tools”, including ME prediction equations to estimate ME content among wheat midds sources.

Unlike studies conducted for DDGS, no studies have been conducted to evaluate variability in amino acid digestibility among sources of wheat midds. Nortey (2008) reported apparent amino acid digestibility values for a single source of wheat midds, and NRC (1998) lists estimates for apparent and true amino acid digestibility of wheat midds, which can be used as a reference point, but does not account for variability among sources.

Table 6. Average and range in values of selected nutrients, and coefficients of variation (CV) of 14 sources of wheat middlings (Cromwell et al., 2000).

	Average	CV	Range
Dry matter, %	89.6	0.65	88.4 - 90.3
Crude protein, %	16.2	6.52	14.6 - 17.8
NDF, %	36.9	9.64	29.9 - 43.9
Ca, %	0.12	46.19	0.08 - 0.30
P, %	0.97	14.20	0.70 - 1.19
Lysine, %	0.66	4.68	0.62 - 0.72
Methionine, %	0.25	4.97	0.23 - 0.27
Cystine, %	0.34	5.69	0.31 - 0.37
Threonine, %	0.54	5.14	0.50 - 0.58
Tryptophan, %	0.19	5.61	0.17 - 0.21

Table 7. Average and range in values (87% dry matter) of selected nutrients of 17 samples of wheat middlings (Dale, 1996).

	Average	Range
Crude protein, %	15.3	12.4 - 23.8
Crude fat, %	3.3	2.1 - 6.9
Ash, %	4.1	1.5 - 7.5
Crude fiber, %	6.4	0.9 - 13.2
NDF, %	27.5	6.8 - 41.2
TME_n, kcal/kg	2422	1663 - 3178

Bakery By-product

Very little data have been published related to nutrient composition and variability among sources of bakery by-product, and most of the data collected decades ago may not accurately represent nutrient composition of sources of bakery by-product currently available to the feed industry. However, measures of variation may be useful in establishing “safety margins” when formulating diets containing this ingredient. Harms et al. (1966) reported that the processing and blending procedures over an 8 week production period resulted in a fairly uniform by-product at that time, with an average of 6.89% moisture, 13.74% crude fat, 8.25% crude protein, and 3.10% salt. Waldroup et al. (1982) collected 66 composite sample of bakery by-product over a 198 day period from one processing plant and analyzed the samples for moisture, crude fat, crude protein, and salt content (Table 8). The results from Waldroup et al. (1982) indicate substantially lower crude fat and salt, but higher crude protein content than values reported by Harms et al. (1966), but similar to the values of 8.5% crude fat and 10.4% crude protein reported by Champe and Church (1980). Waldroup et al. (1982) concluded that the nutrient composition of dried bakery by-product is more of a characteristic of a specific geographic region and is based on the supply of by-product gathered for blending by the manufacturer. To emphasize this point, Kwak and Kang (2006) collected bakery and bread by-products from several oriental restaurants in South Korea and reported that the crude fat and crude protein content was similar, 9.3 and 9.5%, respectively. The values (as-fed basis) reported by NRC (1998) for dried bakery by-product are 3,700 kcal/kg ME, 2,415 kcal/kg NE (calculated), 10.8% crude protein, 11.3% crude fat, 2.62% salt, 0.27% lysine, 0.41% met + cys, 0.33% threonine, and 0.10 tryptophan with apparent amino acid digestibility coefficients ranging from 62% for lysine to 86% for met + cys. These results indicate that dried bakery by-product must be continuously monitored by end-users to obtain accurate nutrient values for use in feed formulation because blends of a wide variety of by-products and the use of published nutrient composition tables will not be reflective of actual nutrient composition.

Table 8. Variation in nutrient composition of samples of dried bakery by-product (DM basis; Waldroup et al., 1982).

	Moisture, %	Crude fat, %	Crude protein, %	Salt, %
Mean	6.1	9.8	11.9	2.5
Standard deviation	0.7	1.8	1.0	0.3
Standard error	0.1	0.2	0.1	0.1
Lowest value	4.4	5.3	9.3	1.8
Highest value	7.8	14.4	15.3	3.4
CV[a], %	10.6	18.5	8.2	13.4

[a]CV = coefficient of variation.

Because of the variability in nutrient content of bakery by-product and the lack of published ME and digestible amino acid data, obtaining reliable ME and amino acid digestibility have been a problem for nutritionists. Fortunately, recent data from Almeida and Stein (2011) provide some estimates of amino acid digestibility of a current source of bakery by-product (Table 9). However, "nutritional tools" need to be developed to estimate ME content and amino acid digestibility among bakery by-product sources.

Table 9. Comparison of nutrient and amino acid content, and standardized ileal digestibility[a] of amino acids in corn and bakery meal (Almeida and Stein, 2011).

	Corn	Bakery meal
CP, %	6.68	11.30
CP digestibility, %	89.1	72.5
DM, %	84.11	86.99
ADF, %	2.00	6.28
NDF, %	8.53	17.52
Starch, %	67.29	40.50
Ca, %	0.02	0.14
P, %	0.22	0.34
Arg, %	0.33 (100.1)	0.46 (91.5)
His, %	0.19 (83.7)	0.27 (72.5)
Ile, %	0.23 (80.9)	0.39 (71.0)
Leu, %	0.76 (88.0)	1.10 (78.2)
Lys, %	0.22 (69.2)	0.27 (48.4)
Met, %	0.14 (86.2)	0.18 (76.5)
Phe, %	0.31 (85.9)	0.52 (77.7)
Thr, %	0.24 (74.9)	0.36 (62.1)
Trp, %	0.04 (83.9)	0.10 (83.1)
Val, %	0.32 (80.1)	0.52 (69.8)

[a]Numbers in parentheses indicate standardized ileal digestibility of amino acids.

"Nutritional Tools"

Because energy and digestible amino acids are the most expensive nutritional components in swine diets, and by-product ingredients are highly variable in nutrient content, researchers have been attempting to develop fast, inexpensive, and accurate "nutritional tools" to assess nutritional composition and value. Feed ingredients are generally sold on a crude protein, crude fat, crude fiber, and moisture basis, but marketing specifications are not very useful in determining ME, SID amino acid, and available phosphorus content needed by nutritionists to assess actual value among sources and determine nutrient loading values.

Near infrared spectroscopy is a technology that has been used for many years for estimating nutrient and chemical composition of a variety of foods and feed ingredients, and is becoming a popular method for assessing nutrient content in DDGS. We recently developed NIR calibrations for proximate analysis components, minerals, and amino acids among DDGS sources using a common Perten NIR instrument model. Calibration and validation statistics for the prediction of nutrient content of DDGS samples are shown in Table 10 and indicate that NIR can be a valuable tool for estimating nutrient content of DDGS sources.

Table 10. Calibration and validation statistics for predicting nutrient content of DDGS.

Nutrient, %	SEC[a]	R[b]	Bias[c]	SEP[d]
Moisture	0.65	0.97	0.01	0.69
Protein	0.76	0.98	-0.13	0.81
Fat	0.45	0.91	-0.08	0.51
Crude fiber	0.58	0.86	0.12	0.87
Ash	0.39	0.86	-0.01	0.46
ADF	0.90	0.80	-0.08	1.06
NDF	1.45	0.87	-0.73	1.67
Starch	0.69	0.95	-0.06	0.85
Sulfur	0.09	0.88	-0.02	0.11
Phosphorus	0.05	0.87	0.01	0.06
Calcium	0.01	0.57	0.00	0.01
Arginine	0.11	0.87	-0.04	0.14
Cysteine	0.23	0.83	-0.09	0.29
Histidine	0.06	0.82	-0.01	0.08
Isoleucine	0.07	0.73	0.05	0.08
Leucine	0.20	0.82	0.05	0.23
Lysine	0.55	0.81	-0.07	0.65
Methionine	0.09	0.84	0.00	0.11
Phenylalanine	0.10	0.80	0.07	0.11
Threonine	0.06	0.80	0.00	0.07
Tryptophan	0.18	0.80	-0.03	0.23
Valine	0.16	0.90	-0.01	0.22

[a]SEC = standard error of the calibration.
[b]R = correlation coefficient.
[c]Bias = mean of differences between reference and predicted values.
[d]SEP = standard error of prediction.

Methods to Assess Energy Content Among DDGS Sources

No DE or ME prediction equations have been developed for wheat midds or bakery by-product for swine. In contrast, DE and ME prediction equations have been developed for DDGS by Pedersen et al. (2007), Anderson et al. (2011), and Mendoza et al. (2010a). Pedersen et al. (2007) developed the following equations (based on 10 sources of DDGS) that were highly predictive (r^2 = 0.94 to 0.99) of DE and ME content (DM basis), based primarily on ash, gross energy (GE), ether extract (EE) and ADF content of samples.

DE

$$Y = -12{,}766 - (76.90 \times \text{ash}) + (34.92 \times \text{CP}) - (10.88 \times \text{starch}) - (123.69 \times \text{EE}) - (164.36 \times \text{ADF}) + (9.78 \times \text{NDF}) + (3.540 \times \text{GE}) \qquad r^2 = 0.99$$

$$Y = -12{,}220 - (111.21 \times \text{ash}) + (26.52 \times \text{CP}) - (10.35 \times \text{starch}) - (127.05 \times \text{EE}) - (154.95 \times \text{ADF}) + (3.550 \times \text{GE}) \qquad r^2 = 0.99$$

$$Y = -12{,}637 - (128.27 \times ash) + (25.38 \times CP) - (115.72 \times EE) - (138.02 \times ADF) + (3.569 \times GE) \quad r^2 = 0.99$$

$$Y = -9{,}929 - (180.38 \times ash) - (106.82 \times EE) - (120.44 \times ADF) + (3.202 \times GE) \quad r^2 = 0.96$$

ME

$$Y = -10{,}866 - (108.12 \times ash) + (37.55 \times CP) - (8.04 \times starch) - (71.78 \times EE) - (164.99 \times ADF) + (15.91 \times NDF) + (3.007 \times GE) \quad r^2 = 0.99$$

$$Y = -11{,}128 - (124.99 \times ash) + (35.76 \times CP) - (63.40 \times EE) - (150.92 \times ADF) + (14.85 \times NDF) + (3.023 \times GE) \quad r^2 = 0.99$$

$$Y = -10{,}267 - (175.78 \times ash) + (23.09 \times CP) - (71.22 \times EE) - (137.93 \times ADF) + (3.036 \times GE) \quad r^2 = 0.99$$

$$Y = -7{,}803 - (223.19 \times ash) - (61.30 \times EE) - (121.94 \times ADF) + (2.702 \times GE) \quad r^2 = 0.97$$

$$Y = -4{,}212 - (266.38 \times ash) - (108.35 \times ADF) + (1.911 \times GE) \quad r^2 = 0.94$$

The best fit equations developed from Anderson et al. (2011) evaluating 20 nutritionally diverse corn co-products from both dry-grind and wet mill ethanol production processes were:

$$DE, kcal/kg\ DM = -7{,}471 + (1.94 \times GE) - (50.91 \times EE) + (15.20 \times total\ starch) + (18.04 \times organic\ matter\ digestibility) \quad r^2 = 0.90$$

$$ME, kcal/kg\ DM = (0.90 \times GE) - (29.95 \times TDF) \quad r^2 = 0.72$$

Additional equations for DE and ME were developed to include NDF in the event that (total dietary fiber (TDF) data are not available.

Mendoza et al. (2010a) developed ME prediction equations based on 17 sources of DDGS ground a particle size within the range 265 to 403 microns. They observed that the correlations between chemical composition components and the DE and ME content of DDGS were relatively poor and differed between two laboratories. Acid detergent fiber had the highest correlation with DE and ME (-0.51 and -0.50, respectively) for Lab 1, but crude fat (0.60 and 0.67) and crude fiber (-0.56 and -0.52) had the highest correlations with DE and ME, respectively for Lab 2. The simplest, most accurate equation to predict ME content of DDGS was:

$$ME, kcal/kg\ DM = 2{,}815 + (94.5 \times \%\ crude\ fat) + (96.2 \times \%\ crude\ fiber) - (33.2 \times \%\ NDF) - (66.2 \times \%\ ash) + (25.9 \times \%\ starch) \quad r^2 = 0.90$$

Theoretically, we know that starch, fat, and protein have a positive influence on energy of a feed ingredient, while fiber and ash have negative effects. However, ingredients like DDGS and wheat midds have low amounts of starch and little is known whether the remaining starch is resistant or soluble starch. Urriola et al. (2010) reported that total starch in DDGS ranges from 3.8 to 11.4%, but the range in insoluble starch was from 2.0 to 7.6% suggesting that a high proportion of residual starch is indigestible in pigs. There are several methods that can be used to measure fiber including crude fiber, ADF, NDF, NSP, and total dietary fiber. Urriola et al. (2010) reported that apparent total tract digestibility of total dietary fiber in DDGS averaged 43.7% but ranged from 23.4 to 55.0% in DDGS. However, each of these methods has limitations for characterizing the fermentable vs. the non-fermentable complex carbohydrate fractions of feed ingredients used in swine diets. It is likely that the methods currently used to characterize fiber, lab to lab variation in measuring chemical components of feedstuffs, along with our relatively poor understanding of fiber utilization in pigs, are significant factors affecting the accuracy of ME prediction equations.

Therefore, estimating ME content of DDGS using existing chemical analysis measures is not as simple as choosing the highest fat and lowest fiber source. Although energy prediction equations offer the advantage of predicting ME from chemical analysis components, there are several questions that need to be considered when using these equations.

1. Have these equations been validated? Often times, prediction equations can be fairly accurate for predicting ME within the data set and samples from which they were derived, but may not be as accurate when applied to unknown samples outside of the data set.

2. How robust or diverse were the samples and data from which these equations were derived? Diversity of samples is usually preferred because equations can be applied across a broader range of sample nutrient content and still predict energy content relatively accurately. However, depending on the size of the data set, the r^2 of the equations is usually lower than equations derived from samples with less variable nutrient composition.

3. Are we using the most predictive components of equations? Some of the chemical analysis measures required for accurate ME prediction (e.g. gross energy, total dietary fiber) are not routinely measured in commercial labs or are expensive and time consuming. Because of this, some nutritionists choose less accurate equations that contain variables that they can more conveniently measure if they can find an equation that contains the variables they want to use.

4. What laboratory and laboratory methods are used to determine the nutritional components needed in prediction equations? As Mendoza et al. (2010) observed, lab to lab variation in routine proximate analysis can give different results and emphasize different chemical components in equations. There are many AOAC or AOCS approved procedures for measuring specific nutritional components, which sometimes are not specified “in the fine print” when prediction equations are published. The chemical method chosen along with normal lab to lab variation when following the same analysis protocol can greatly influence the inputs of prediction equations, and ultimately the accuracy of energy prediction. For example, some measures, such as NDF can be highly variable among labs, and because it is found in high concentrations in DDGS, can dramatically impact ME estimates.

5. Does the magnitude of the coefficients and their direction (positive or negative) make sense in the equation? Some adjustments for fiber and fat in some equations seem counterintuitive.

6. What methods were used to determine DE and ME values of the test sources? Length of adaptation to experimental diets, composition of basal diet, use of indigestible markers vs. total collection, age of pig, etc. all influence the accuracy of the original *in vivo* DE and ME estimates from which equations are derived.

7. How was the regression analysis conducted to develop the equations? Assumptions regarding the intercept, and how variables were included or eliminated from the model, influences the accuracy of results.

8. How does particle size of DDGS affect DE and ME content? Recent studies by Mendoza et al. (2010b) and Liu et al. (2011) indicate that for each 100 micron reduction in average DDGS particle size, DE increases by approximately 40 to 52 kcal/kg DM.

Because of these challenges, some nutritionists have evaluated the use of a 3-step *in vitro* energy digestibility technique involving pepsin, pancreatin, and Viscozyme (Wang et al., 2010). Use of this technique resulted in accurate prediction (r^2 = 0.97) of apparent total tract energy digestibility among single samples of 8 feedstuffs. Although within feedstuffs variability was predicted well for grains, it was poorly predicted for canola meal and corn DDGS.

Other nutritionists are trying to develop ME predictions using near infrared spectroscopy (NIR) as an alternative approach. However, the use of NIR, while it may initially appear to be simpler, less expensive, and provide results in minutes, it also has its challenges. First, accurate NIR calibrations require a minimum of 200 samples for many nutritional analytes, and may require more samples to accurately determine ME content because it is affected by many variables. To obtain *in vivo* estimates from this number of samples would require significant investment in time and money to conduct numerous metabolism trials and chemical analysis of samples to generate the number of *in vivo* ME values necessary to develop accurate NIR calibrations. Second, calibrations need to be updated on a regular basis as nutrient composition of the sources of the ingredients change. Third, calibrations generally cannot be universally applied to different types of NIR equipment. Therefore, separate calibrations would be needed for Perten vs. FOSS vs. Bruker instruments. Finally, use of data from multiple labs can often result in “clustering” of data in the spectrum, resulting in potentially inaccurate calibrations and predictions.

The use of neural networks may be a possible tool to identify complex patterns in large databases involved DE and ME estimates, from which more predictive equations may be derived. However, no research has been conducted to explore this possibility.

Methods to Estimate Amino Acid Content in Corn, Soybean Meal, DDGS, and Wheat Midds

Several regression coefficients have been proposed to estimate amino acid content from crude protein in feedstuffs (Fickler et al., 1995). Cromwell et al. (1999) reported that although crude protein was positively correlated to most amino acids, r^2 values ranged from 0.25 (methionine) to 0.87 (leucine), the relationship between crude protein and lysine was poor (r^2 = 0.49). Similarly, the relationship between crude protein and lysine in soybean meal with hulls and dehulled soybean meal was poor (r^2 = 0.44 and 0.36, respectively).

Fiene et al. (2006) published equations for predicting the amino acid content of DDGS from crude protein, crude fat, and crude fiber (Table 11). Although the equations for estimating methionine and threonine content were reasonable (r^2 = 0.78 and 0.87, respectively), equations poorly predicted lysine and tryptophan (r^2 = 0.45 and 0.31, respectively).

Table 11. Equations to predict amino acid content of DDGS from crude protein (CP), fat, and fiber (Fiene et al., 2006).

Amino acid	Equation	r^2
Arg	Y = 0.07926 + 0.0398 x CP	.48
Ile	Y = -0.23961 + 0.04084 x CP + 0.01227 x fat	.86
Leu	Y = -1.15573 + 0.13082 x CP + 0.06983 x fat	.86
Lys	Y = -0.41534 + 0.04177 x CP + 0.00913 x fiber	.45
Met	Y = -0.17997 + 0.02167 x CP + 0.01299 x fat	.78
Cys	Y = 0.11159 + 0.01610 x CP + 9.00244 x fat	.52
TSAA	Y = -0.12987 + 0.03499 x CP + 0.05344 x fat – 0.00229 x fat^2	.76
Thr	Y = -0.05630 + 0.03343 x CP + 0.02989 x fat – 0.00141 x fat^2	.87
Trp	Y = 0.01676 + 0.0073 x CP	.31
Val	Y = 0.01237 + 0.04731 x CP + 0.00054185 x fat^2	.81

In contrast, Cromwell et al. (2000) showed that most amino acids, except for lysine and tryptophan, can be predicted with a reasonable degree of accuracy in wheat midds because the r^2 values were > 0.80 (Table 12). However, lysine content could be better predicted by using the equation (Y = .2664 + .00528 × NDF + .0014 × CP; r^2 = .82).

Table 12. Relationship[a] between crude protein and amino acid concentrations in wheat middlings (Cromwell et al., 2000).

Amino acid	a	b	r^2
Arg	-.376	.0929	.84
His	.023	.0249	.86
Ile	.079	.0261	.94
Leu	.262	.0466	.90
Lys	.281	.0235	.61
Met	.069	.0108	.80
Cys	.043	.0183	.81
Met+cys	.112	.0291	.85
Phe	.059	.0353	.89
Thr	.123	.0254	.88
Trp	.074	.0071	.39
Val	.082	.0397	.90

[a]Y = a + bX; Y = predicted amino acid (%); X = crude protein (%); based on 14 samples of wheat middlings analyzed by 20 labs for crude protein and 7 to 9 labs for amino acids.

Estimation of Digestible Amino Acids in DDGS

Color measurement with Minolta or Hunter lab spectrophotometers has been used as a quality indicator related to lysine digestibility in DDGS for swine. Results from initial studies showed that L* (lightness or darkness of color) and b* (yellowness of color) measurements with Minolta or Hunter lab spectrophotometers may be useful general indicators of relative lysine digestibility among DDGS sources (Cromwell et al., 1993; Fastinger and Mahan, 2006). In general, dark colored DDGS (L* less than 50) has lower lysine digestibility than light colored DDGS samples, but this relationship is poor when considering a large, diverse set of DDGS samples (Urriola et al., 2007a,b; Figure 1). As a result, predicting lysine and amino acid digestibility by using color measurements may not be very accurate.

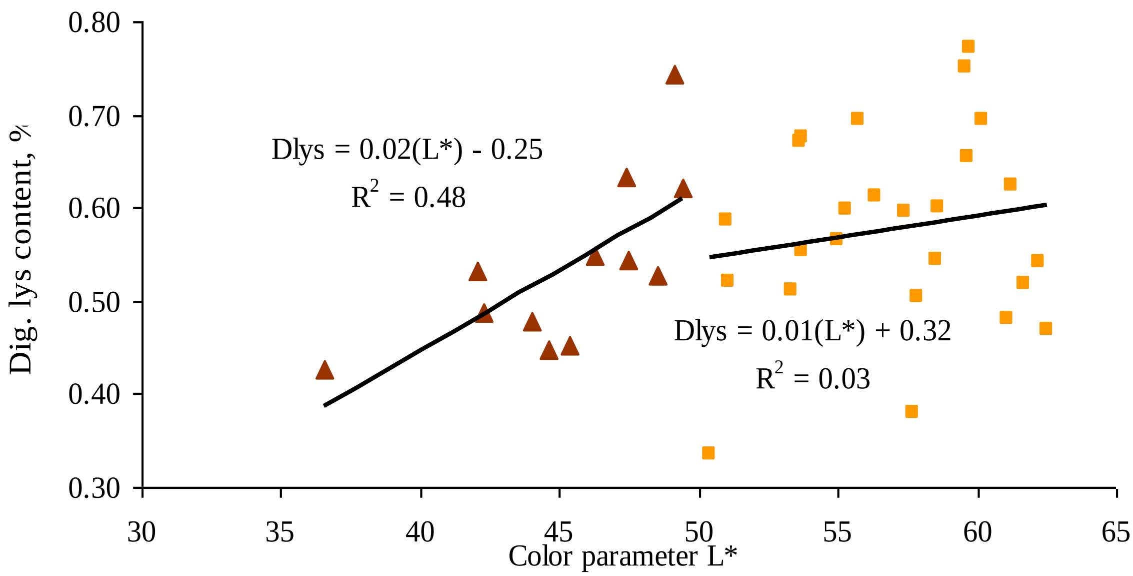

Figure 1. Relationship between lightness of color (L*) and digestible lysine content of corn DDGS (Urriola 2007a, b).

Cromwell et al. (1993) showed that increasing levels of ADIN (acid detergent insoluble nitrogen) as an indicator of amino acid digestibility in DDGS has a high negative correlation with broiler growth rate and feed conversion when fed DDGS, but it has not been evaluated as an indicator of amino acid digestibility in DDGS sources for swine. The lysine to crude protein ratio in DDGS can be used as a general predictor of relative lysine digestibility among DDGS sources, but not for precise estimations (Stein, 2007). If the lysine to crude protein ratio is > 2.80 for a DDGS source, it is considered to be highly digestible and suitable for use in swine and poultry diets. However, crude protein content is a poor predictor of standardized ileal digestible (SID) lysine in DDGS, but total lysine and reactive lysine content of DDGS are good predictors (Kim et al., 2010) using the following equations: SID Lys% = - 0.482 + (1.148 × analyzed Lys, %) or SID Lys% = - 0.016 + (0.716 × reactive Lys, %).

Several *in vitro* methods for estimating amino acid digestibility among DDGS have been evaluated for swine. Pedersen et al. (2005) evaluated the use of an *in vitro* pepsin-pancreatin procedure and found that it is a poor predictor of crude protein and amino acid digestibility (r^2 = 0.55) in DDGS. Similarly, Schasteen et al. (2005) evaluated the use of the IDEA® assay by Novus International and reported that it is a good predictor of digestible lysine in DDGS sources for poultry, but not other amino acids, or for predicting amino acid digestibility of DDGS sources for swine. IDEA® (Immobilized Digestive Enzyme Assay) is an analytical method marketed by NOVUS International and is used to estimate digestible amino acid content of various sources of DDGS, soybean meal, and other high protein ingredients for poultry and swine. Zhang et al. (2010) evaluated 20 DDGS samples using IDEA® and correlated these values with the furosine to lysine ratio and observed no relationship (Figure 2). Furosine, a lysine derivative, is produced during DDGS acid hydrolysis, and is used in the food industry as a quantitative indicator for unreactive lysine (unreactive lysine = 1.25 furosine). Unreactive lysine is not bioavailable for pigs, and cannot be detected by the usual testing method for total lysine, which involves acid hydrolysis of DDGS.

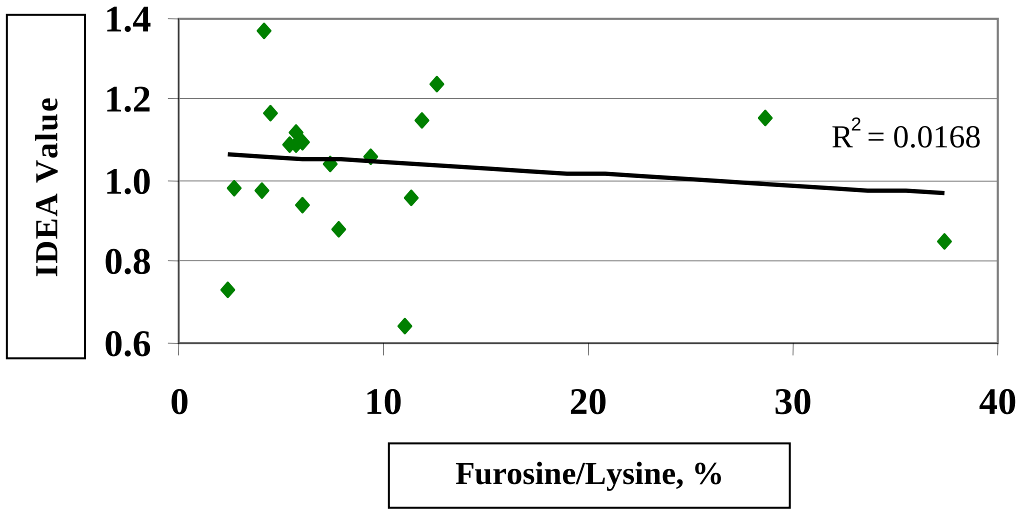

Figure 2. Relationship between IDEA® values and furosine:lysine in 20 DDGS samples (Zhang et al., 2010).

AMINORED® is a tool developed by Evonik to identify and rank heat damage of soybean meal and DDGS using an *in vitro* procedure called a Heat Damage Indicator (HDI). The HDI is used to adjust amino acid digestibility depending on the amount of heat damage using a “tool” called AMINORED®. Our preliminary results involving 40 DDGS samples with *in vivo* SID amino acid values indicate that AMINORED® is a poor indicator ($r < 0.22$) of SID amino acid digestibility for swine. The correlation between SID lysine and Aminored® in swine is shown in Figure 3.

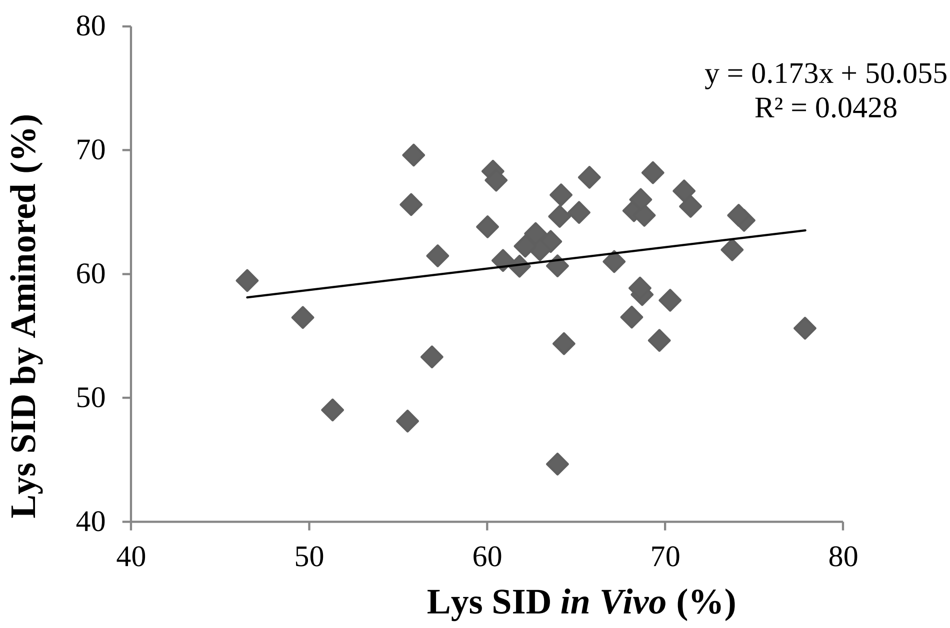

Figure 3. Correlation between SID lysine (*in vivo*) and predicted SID lysine by Aminored®.

However, results from initial studies using front face fluorescence with principle components analysis have shown that this “tool” has the potential to accurately predict (r^2 = 0.99, RMSE = 0.0009, principle components = 30) digestible lysine and other amino acids in DDGS (Urriola et al., 2007a, b), but more refinements are needed before it can be effectively implemented (Figure 4).

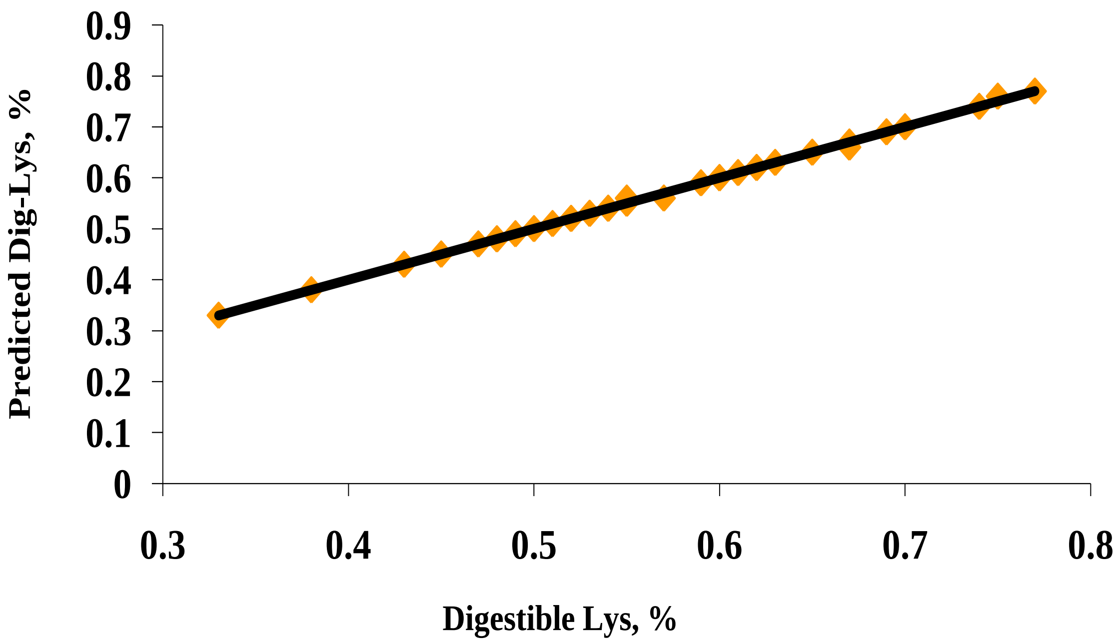

Figure 4. Prediction of SID lysine from front face fluorescence in DDGS (Urriola et al., 2007b).

Commercially Available “Tools” for DDGS

Several of the “nutritional tools” described have been incorporated into commercially available services by a few companies. Illuminate® is a commercially available “tool” developed by Value Added Science and Technology (http://vast.com/services.htm) specifically designed to estimate ME content, SID amino acids, and available phosphorus in specific DDGS sources, and provide relative value comparisons among sources for swine. Optimum Value Supplier® database has been developed by Cargill. It is based on NIR technology and is being used to estimate nutrient composition of a wide variety of feed ingredients around the world. Similarly, Adisseo provides a service in Asian countries to estimate nutrient content of several ingredients including corn, soybean meal, and DDGS for swine and poultry using NIRS (Near Infrared Reflectance Spectroscopy). Calibrations have been developed for determining proximate analysis components and predicting total and digestible amino acids, as well as AME in corn, soybean meal and DDGS for poultry.

DDGS Value “Calculator Tools”

Several DDGS value calculator tools have been developed to determine DDGS feeding value for livestock and poultry. These tools are extremely useful for determining the actual economic value of DDGS in specific livestock and poultry diets and should be used when evaluating whether the current price for DDGS is economical relative to its nutrient contributions and price relative to other competing feed ingredients. The most recent and comprehensive DDGS value calculator tool was developed by researchers at Iowa State University (Dahlke and Lawrence, 2008) and is useful for a wide variety of diets and food animal species (http://www.matric.iastate.edu/DGCalculator). SESAME, (www.sesamesoft.com) developed by researchers (Drs. Normand St-Pierre, Branislav Cobanov and Dragan Glamocic, 2007) at Ohio State University, is a comprehensive tool to help livestock and poultry producers make better feed purchasing choices. In addition, three DDGS evaluation tools have been developed specifically for swine and are available at www.ddgs.umn.edu:

- University of Illinois DDGS Calculator - developed by Drs. Beob G. Kim and Hans H. Stein (Dec. 2007).

- DDGS Cost Calculator for Swine - developed by Dr. Bob Thaler, South Dakota State University Extension Swine Specialist (Sep. 2002).

- DDGS Value Calculator - developed by Dr. Dean Koehler, Vita Plus Corporation, Madison, WI (Sep. 2002).

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