

JOURNAL OF ANIMAL SCIENCE

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J Anim Sci 2008.86:2377-2384.

doi: 10.2527/jas.2007-0811 originally published online Apr 25, 2008;

The online version of this article, along with updated information and services, is located on the World Wide Web at:

<http://jas.fass.org/cgi/content/full/86/9/2377>



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Comparative sulfur analysis using thermal combustion or inductively coupled plasma methodology and mineral composition of common livestock feedstuffs¹

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ABSTRACT: The objective of this study was to compare the use of thermal combustion (CNS) and inductively coupled plasma (ICP) to measure the total S content in plant-, animal-, and mineral-based feedstuffs, and to provide concentrations of other macro- and micro-minerals contained in these feedstuffs. Forty-five feedstuffs (464 total samples) were obtained from suppliers as well as swine feed and pet food manufacturers throughout the United States. Mineral data from IPC analysis were summarized on a DM basis using sample mean and SD, whereas the comparison of total S content between CNS and ICP was examined by bivariate plot and correspondence correlation. Analyses of a wide range of feedstuffs by CNS and ICP for total S were comparable for all but a few feedstuffs. For potassium iodide and tribasic copper chloride, ICP estimated total S to be lower than when analyzed by CNS (bias = 2.51 ± 0.15 SE, $P < 0.01$). In contrast, for defluorinated phosphate and limestone, ICP estimated total S to be greater than when analyzed by CNS

(bias = -1.46 ± 0.51 SE, $P < 0.01$). All other samples had similar estimates of total S, whether analyzed by CNS or ICP. As expected, S composition varied greatly among feedstuffs. For total S, plant-based feedstuffs generally had lower total S compared with animal-based feedstuffs, whereas minerals supplied in sulfate form had the greatest concentration of total S. In addition to total S, mineral composition data are provided for all feedstuffs as obtained by ICP analysis. Within specific feedstuffs, mineral composition was quite variable, potentially due to low concentrations in the feedstuff causing high mathematical variation or due to the source of feedstock obtained. In general, analyzed values of P were similar to previous tabular values. These data provide feed formulators a database from which modifications in dietary minerals can be accomplished and from which mineral requirements can be met more precisely to reduce losses of minerals into the environment.

Key words: analysis, dietary sulfur, feedstuff, inductively coupled plasma, thermal combustion

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J. Anim. Sci. 2008. 86:2377–2384
doi:10.2527/jas.2007-0811

INTRODUCTION

Literature pertaining to S chemistry and metabolism is both dated (Lewis, 1924; Du Vigneaud, 1952; Dziewiatkowski, 1962) and recent (Stipanuk, 2004; Shoveller et al., 2005; Baker, 2006), but little attention has been given to inorganic S (Baker, 1977). Gastrointestinal ecology is a growing area of science (Anderson,

2003), and it is well established that sulfate reduction does not occur in mammalian cells, but does in sulfate reducing bacteria (Gibson, 1990; Florin et al., 1991). Because evidence suggests organic and inorganic S in gastrointestinal tissues may be linked to chronic intestinal disease (Burrin and Stoll, 2007), excess dietary S reaching the intestinal tract is of great importance. In addition, high concentrations of total dissolved solids in drinking water are known to affect scour scores (Maenz et al., 1994), with sulfate being suggested as the major compound of concern (McLeese et al., 1991). Research studies specifically evaluating increased inorganic sulfate intake showed an increase in diarrhea, but did not show any adverse effect on pig BW gain or feed intake (Veenhuizen et al., 1992; Gomez et al., 1995). Limited research results have shown that reducing total dietary S reduces odor and hydrogen sulfide emissions (Apgar et al., 2002). With S known to affect gastroin-

¹Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the USDA or the University of Minnesota and does not imply approval to the exclusion of other products that may be suitable. The authors gratefully acknowledge the assistance of J. Cook (USDA-ARS, Ames, IA) for laboratory assistance and D. Meek (USDA-ARS, Ames, IA) for statistical assistance.

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Received December 18, 2007.

Accepted April 17, 2008.

testinal health, occurrence of diarrhea, nutrient utilization, and odor emission, data are needed to quantify the total concentration of S in feedstuffs commonly fed to livestock. Because standard manure values reported by the ASAE (2003) do not consider changes in dietary mineral concentrations, updated mineral content of ingredients are needed for nutritionists to modify dietary mineral intakes to ultimately reduce mineral excretion. Therefore, the objective of this research was to analyze common feed ingredients for mineral concentration and to determine the difference in total S of ingredients as measured by thermal combustion (CNS) and inductively coupled plasma (ICP).

MATERIALS AND METHODS

Animal Care and Use Committee approval was not obtained for this manuscript because no animals were used in the research.

Four hundred sixty-four samples of 45 different feedstuffs were obtained from ingredient suppliers as well as swine feed and pet food manufacturers throughout the United States for total mineral analysis. To protect the confidentiality of ingredient sourcing, however, suppliers or locations of each feedstuff are not provided in this manuscript. All samples were ground through a 1-mm screen before analysis. Dry matter was determined by drying 1-g samples at 70°C for 24 h. After drying, samples were either analyzed for minerals by ICP and for total S by CNS. For ICP, 10-g samples were shipped to the University of Minnesota and analyzed for mineral content by the University of Minnesota Soils Laboratory. Feedstuffs were digested following methods described by Miller (1998) and then analyzed in 10% HCl by ICP (model 3560, Applied Research Laboratory, Sunland, CA). For thermal combustion, total S was analyzed using a thermal combustion analyzer (VarioMAX, Elementar Analysensysteme GmbH, Hanau, Germany), which uses catalytic tube combustion to volatilize the sample. The target gas is converted to SO₂, separated from other gases using adsorption columns, and after heating, measured using a thermal conductivity detector. For S analysis by CNS, sulfadiazine was used as the S standard. Mineral data obtained from ICP analysis were summarized on a DM basis using sample mean and SD. Comparison of total S content between CNS and ICP was examined by bivariate plot and correspondence correlation where it is assumed that if CNS = ICP the slope would equal 1 and the intercept would equal, with deviation from the line (i.e., bias) indicating a difference between analytical methods (Lin, 1989; Meek, 2007). For the purposes of data reporting, the feedstuffs were classified into 1 of 3 groups: plant-based, animal-based, and mineral-based feedstuffs.

RESULTS AND DISCUSSION

Mineral analysis of plant-, animal-, and mineral-based feedstuffs are presented in Tables 1, 2, and 3,

respectively, whereas only a subset of the ingredients could be analyzed for Cl (Table 4). With the wide array of feedstuffs analyzed, it was fully expected that total S concentrations would vary greatly, ranging from less than 500 mg/kg for feedstuffs such as calcium iodide, tribasic copper chloride, defluorinated phosphate, and potassium iodide; to concentrations over 100,000 mg/kg for cobalt-, copper-, iron-, manganese-, and zinc-sulfate. Bivariate plot and correspondence correlation revealed a correspondence correlation coefficient ($r = 0.941$) for S analysis between CNS and ICP (Figure 1). Only 4 feedstuffs appeared to deviate from this relationship. For potassium iodide and tribasic copper chloride (group 1, Figure 1), S values determined by ICP were lower than S determined by CNS (bias = 2.51 ± 0.15 SE, $P < 0.01$) In contrast, S values for defluorinated phosphate and limestone (group 2, Figure 1) determined by ICP were greater than S determined by CNS (bias = -1.46 ± 0.51 SE, $P < 0.01$). Feedstuffs in group 3 representing the sulfate containing minerals (cobalt-, copper-, iron-, manganese-, and zinc-sulfate), were high in total S, but had similar S concentrations whether measured by CNS or ICP.

For plant-based feedstuffs (Table 1), concentrations of total S were relatively low compared with other feedstuffs, except for feedstuffs known to contain moderate concentrations of total sulfur amino acids (NRC, 1998) or by-products derived from corn or soybean processing. Although various nutrients typically increase 3-fold due to the removal of starch during dry-grinding and fermentation of corn to produce ethanol (Spiehs et al., 2002; Stein et al., 2006; Pedersen et al., 2007), the use of sulfuric acid in the dry grind process appears to increase the total S content of dried distillers grains with solubles by 5-fold compared with corn (Table 1). Slightly greater concentrations of S relative to corn were also noted for corn gluten feed and corn gluten meal, which are by-products of the wet-milling industry, where sulfuric acid is used in the steeping process. In contrast, this same magnitude of S increase was not noted when comparing values from the NRC (1998) for corn relative to its by-products, suggesting that either corn processing methods have changed by-product composition or the values reported in NRC (1998) may underestimate the true S content. Because whole soybeans were not analyzed, comparisons between soybean milling by-products relative to whole soybeans could not be made. However, S content would be expected to increase due to removal of the oil during soybean processing, but we are not aware of any S containing ingredients used during processing that would increase S content.

Animal-based feedstuffs contained greater concentrations of total S relative to most plant-based ingredients. Because sulfur amino acids are prevalent in various body components (chondroitin, glutathione, taurine, etc.) are high in S (21% in Met and 26% in Cys), this was expected. Two examples of animal-based feed ingredients with high S content are feather meal and plasma protein. Both of these ingredients are known

Table 1. Mineral composition of plant-based feedstuffs¹

Item	Distiller														
	Bakery product	Barley	Beet pulp	Corn	Corn gluten feed	Corn gluten meal	Corn dried grains with solubles	Flax seed meal	Oats	Rice	Sorghum concentrate	Soybean hulls	Soybean meal	Wheat flour	Wheat middlings
Samples	4	1	8	23	5	8	19	6	5	9	1	10	29	10	29
DM, %	90.69	89.45	90.45	86.07	87.66	90.18	87.96	93.40	88.84	87.34	89.51	89.84	88.86	88.67	88.2
SD	1.98	—	1.16	0.98	0.58	1.39	1.83	0.44	1.57	1.08	—	1.38	0.88	1.80	0.97
Inductively coupled plasma-mass spectrometry analysis															
Al	219	15.0	587	1.38	31.9	13.3	18.1	5.21	8.89	6.65	7.33	189	139	7.16	25.0
SD	105	—	216.5	1.67	1.89	7.27	31.54	1.18	3.78	4.41	—	81.2	192.2	6.88	33.02
B	62.1	52.7	102	45.0	51.7	43.6	48.4	66.1	56.9	61.1	59.0	35.3	51.2	55.1	47.8
SD	6.05	—	4.8	4.36	2.44	3.50	4.80	2.30	3.03	4.59	—	4.37	6.71	5.01	5.69
Ca	2,656	1,046	13,416	72.7	5,958	48.4	461	3,051	605	275	212	7,735	5,285	525	1,348
SD	458	—	12,732	56.16	616	17.48	250.2	243	34.0	281.5	—	190	1,586	76.7	529
Cd	ND	0.13	0.46	0.01	ND	0.05	ND	0.39	0.01	0.03	ND	0.27	0.04	0.01	0.04
SD	—	—	0.10	0.01	—	0.16	—	0.23	0.01	0.05	—	0.31	0.14	0.03	0.05
Cr	5.99	5.41	22.7	1.98	8.21	2.31	3.21	2.51	4.62	3.86	3.43	2.31	1.64	2.46	2.76
SD	0.79	—	8.34	0.99	1.18	1.38	2.97	0.11	1.15	1.28	—	0.74	2.35	0.19	0.76
Cu	5.10	5.90	7.74	0.93	4.73	10.9	4.06	9.98	5.08	3.29	3.10	7.54	16.7	3.91	11.8
SD	1.46	—	0.83	0.65	0.22	0.94	1.31	2.69	0.46	1.04	—	0.63	3.76	0.52	1.61
Fe	633	71.9	680	27.5	163	125	240	70.1	68.5	38.5	42.1	616	210	50.1	184
SD	577.2	—	266.5	7.60	7.9	13.5	468.0	10.15	6.81	47.08	—	81.4	152.5	9.13	40.6
K	4,952	5,959	5,417	3,760	16,873	2,242	10,538	8,790	4,725	2,358	3,958	14,650	19,355	4,652	12,717
SD	1,386	—	2,083	455	676	320	1,635	727	345	1,167	—	697	1,904	390	2,058
Mg	1,613	1,798	3,092	1,212	5,522	731	3,445	4,449	1,913	1,125	1,656	2,883	3,878	1,671	5,658
SD	503	—	157	166	203	95.1	598	197	151	670	—	153	349	123	802
Mn	41.0	20.4	60.5	3.59	33.6	2.78	16.8	30.2	61.1	41.5	15.3	26.5	42.2	51.7	167
SD	17.8	—	4.41	1.07	1.45	0.95	4.51	3.30	3.59	22.22	—	11.51	8.24	5.97	24.4
Na	5,017	208	855	12.23	7,240	99.1	1,383	424	30.4	24.1	0.52	24.0	52.7	18.0	53.4
SD	663	—	345.6	13.26	439	79.46	1,300	89.3	11.01	36.05	—	11.78	81.04	8.22	78.73
Ni	2.46	1.78	9.15	0.49	3.62	0.31	1.13	1.56	5.06	1.13	1.47	2.65	8.59	0.10	0.80
SD	0.58	—	3.44	0.73	0.63	0.88	1.72	0.37	0.79	0.85	—	0.66	3.29	0.09	0.55
P	4,088	5,171	892	3,040	12,148	6,290	8,922	6,948	5,276	3,114	3,320	1,522	7,966	4,464	14,037
SD	1,244	—	108.2	428	469	473	1,137	447	385	1,426	—	218	2,284	343	1,675
Pb	ND	0.72	0.90	ND	ND	ND	ND	ND	ND	0.19	0.26	ND	ND	ND	ND
SD	—	—	0.17	—	—	—	—	—	—	0.23	—	—	—	—	—
S	1,650	1,641	1,775	1,132	7,482	10,581	6,866	2,428	2,295	1,332	1,415	1,414	4,625	1,778	2,359
SD	329	—	644	106	476	1,146	2,263	132	113	163	—	129	1,132	222	164
Zn	65.8	37.4	22.4	22.7	72.6	25.1	114	51.8	42.0	29.6	31.3	49.1	60.5	38.9	115
SD	8.2	—	2.39	3.51	3.18	5.75	84.72	7.53	4.44	6.65	—	4.11	5.51	5.74	13.7
Thermal combustion analysis															
S	2,253	1,509	1,805	1,250	7,127	9,682	6,353	2,403	2,282	1,296	1,447	1,498	4,490	1,845	2,248
SD	527	—	540	67	499	938	2,062	146	113	215	—	113	1,089	222	149

¹All mineral data expressed as mg/kg, DM basis.

Table 2. Mineral composition of animal-based feedstuffs¹

Item	Blood cells	Blood meal	Chicken meal	Dried whey	Feather meal	Fish meal	Meat and bone meal	Casein	Skim milk	Whole milk	Plasma protein	Whey permeate	Yeast
Samples	10	9	16	16	3	18	57	1	1	1	8	3	3
DM, %	93.14	93.91	96.13	94.93	95.22	92.79	96.57	95.38	95.16	95.63	92.78	9,629	95.56
SD	1.02	1.65	2.26	1.35	0.50	1.30	1.64	—	—	—	0.63	0.48	0.58
Inductively coupled plasma-mass spectrometry analysis													
Al	1.08	5.71	77.6	3.73	18.0	1,136	220	32.7	0.98	1.40	13.2	26.0	4.88
SD	1.24	7.16	66.19	2.82	4.27	332	192.9	—	—	—	8.69	0.22	1.41
B	55.5	54.9	2.43	60.9	0.72	7.06	44.0	56.0	59.4	59.5	54.3	64.1	51.8
SD	3.40	3.07	2.53	4.82	0.84	4.18	30.51	—	—	—	3.30	4.25	1.23
Ca	132	700	49,941	7,525	4,733	57,727	95,674	3,671	13,525	11,744	1,451	7,285	2,088
SD	74.4	819.3	9,911	2,062	198	5,356	25,384	—	—	—	121	3,114	52.17
Cd	ND	ND	ND	0.06	ND	ND	0.00	ND	ND	ND	0.02	0.08	0.02
SD	—	—	—	0.18	—	—	0.02	—	—	—	0.04	0.00	0.00
Cr	2.68	2.73	3.82	2.91	2.07	4.70	8.22	2.90	2.89	2.65	4.72	3.35	2.95
SD	0.25	0.17	3.63	0.25	0.42	1.03	4.45	—	—	—	6.13	0.25	0.06
Cu	2.22	6.41	19.9	0.23	12.8	5.41	14.8	0.35	ND	ND	16.3	0.33	10.9
SD	0.28	2.95	7.26	0.30	1.81	1.12	7.79	—	—	—	6.29	0.12	2.56
Fe	3,552	2,937	432	5.19	759	1,092	885	36.7	1.14	10.1	120	37.0	64.3
SD	140	463	208.8	4.88	170.8	267	670.1	—	—	—	47.0	37.21	18,715
K	4,760	3,264	7,085	22,343	1,387	11,569	5,378	659	17,433	14,309	2,123	23,890	4,02
SD	2,195	1,186	1,690	3,722	198	1,656	1,644	—	—	—	434	2,710	623
Mg	168	202	1,531	1,506	316	2,455	2,179	395	1,263	1,212	326	1,518	2,057
SD	98.8	71.3	112.2	369	13.5	245	395	—	—	—	34.4	246	6
Min	ND	0.43	10.6	0.03	11.4	53.5	15.7	ND	ND	ND	0.46	0.27	7.29
SD	—	0.61	2.74	0.11	2.73	14.81	6.99	—	—	—	0.81	0.38	1.60
Na	5,157	4,271	4,473	9,465	1,742	7,182	8,116	16,885	4,447	5,486	28,338	7,786	268
SD	2,790	2,507	305.1	4,759	486	970	2,178	—	—	—	3,121	1,272	3.8
Ni	0.35	0.32	2.31	0.19	0.74	1.67	4.50	0.09	ND	ND	0.09	0.70	2.13
SD	0.10	0.11	2.25	0.30	0.33	0.56	2.92	—	—	—	0.11	0.14	0.48
P	2,156	1,715	26,564	8,222	3,117	31,594	47,841	9,647	10,644	8,893	15,394	7,155	14,342
SD	726	741	3,239	2,119	222	2,068	12,018	—	—	—	1,677	492	379
Pb	ND	ND	ND	0.36	ND	0.22	1.95	ND	ND	ND	ND	1.13	ND
SD	—	—	—	0.57	—	0.30	4.23	—	—	—	—	0.10	—
S	5,333	7,204	8,364	2,341	18,412	9,148	4,634	7,141	3,514	2,848	11,786	2,770	4,217
SD	464	1,922	1,301	874	218	630	658	—	—	—	434	800	143
Zn	20.0	31.4	115	5.14	113	120	112	62.4	47.0	41.7	17.4	1.19	90.8
SD	3.68	15.26	6.2	10.13	6.0	8.9	13.5	—	—	—	1.73	0.02	16.92
Thermal combustion analysis													
S	5,453	7,238	8,349	2,467	17,926	9,374	4,860	7,308	3,694	2,949	11,922	2,690	4,396
SD	620	1,722	1,242	853	1,036	620	716	—	—	—	364	776	146

¹All mineral data expressed as mg/kg, DM basis.

Table 3. Mineral composition of mineral-based feedstuffs¹

Item	Ca		Co		Cu		Defluorinated phosphate		Dicalcium phosphate		Fe sulfate		K iodide		Limestone		Mn sulfate		Monocalcium phosphate		Na chloride		Tribasic copper chloride		Zn oxide		Zn sulfate	
	6	6	2	2	9	9	5	5	15	15	3	3	2	2	27	27	5	5	23	23	19	19	3	3	6	6	9	9
Samples	99.85	95.70	95.80	95.80	73.49	73.49	99.97	99.97	97.63	97.63	99.35	99.35	99.7	99.7	99.89	99.89	99.95	99.95	97.28	97.28	99.89	99.89	99.50	99.50	99.92	99.92	99.77	99.77
DM, %	0.11	2.28	1.08	1.08	0.93	0.93	0.03	0.03	0.35	0.35	0.28	0.28	0.02	0.02	0.14	0.14	0.03	0.03	0.34	0.34	0.09	0.09	0.06	0.06	0.02	0.02	0.08	0.08
Inductively coupled plasma-mass spectrometry analysis																												
Al	93.8	3,743	747	747	487	487	5,700	5,700	6,589	6,589	360	360	89.7	89.7	984	984	358	358	6,849	6,849	385	385	720	720	3,583	3,583	3,588	3,588
SD	9.64	89	8.4	8.4	6.1	6.1	782	782	2,442	2,442	1.0	1.0	0.01	0.01	840.1	840.1	0.1	0.1	2,501	2,501	416.8	416.8	0.4	0.4	1	1	3	3
B	285	481	354	354	470	470	294	294	ND	ND	337	337	276	276	ND	ND	367	367	ND	ND	284	284	320	320	460	460	461	461
SD	4.8	11.4	16.5	16.5	16.0	16.0	12.0	12.0	—	—	15.5	15.5	5.4	5.4	—	—	9.7	9.7	—	—	9.7	9.7	11.2	11.2	0.1	0.1	0.4	0.4
Ca	104,144	16,849	171	171	2,947	2,947	342,370	342,370	222,948	222,948	212	212	7,677	7,677	399,920	399,920	1,924	1,924	170,318	170,318	5,601	5,601	165	165	13,409	13,409	989	989
SD	1,462	17,703	1.9	1.9	3,405	3,405	5,095	5,095	12,864	12,864	59.4	59.4	471	471	10,712	10,712	142	142	9,862	9,862	3,549	3,549	0.1	0.1	5,685	5,685	351.9	351.9
Cd	3.00	318	169	169	16.3	16.3	12.0	12.0	3.53	3.53	12.1	12.1	3.01	3.01	0.06	0.06	12.1	12.1	5.09	5.09	7.92	7.92	24.1	24.1	120	120	120	120
SD	0.00	153.7	0.10	0.10	0.21	0.21	0.00	0.00	1.16	1.16	0.03	0.03	0.00	0.00	0.21	0.21	0.18	0.18	4.56	4.56	8.34	8.34	0.01	0.01	0.1	0.1	0.1	0.1
Cr	10.1	293	58.5	58.5	38.1	38.1	28.0	28.0	88.2	88.2	31.5	31.5	7.02	7.02	1.71	1.71	28.0	28.0	103	103	36.2	36.2	56.3	56.3	311	311	281	281
SD	3.44	7.0	0.66	0.66	0.48	0.48	0.01	0.01	7.77	7.77	2.96	2.96	0.00	0.00	2.70	2.70	0.01	0.01	30.5	30.5	66.48	66.48	0.03	0.03	34.5	34.5	0.2	0.2
Cu	13.0	544	109	109	370,497	370,497	279	279	6.89	6.89	86.3	86.3	13.0	13.0	3.71	3.71	52.0	52.0	2.99	2.99	26.9	26.9	630,889	630,889	520	520	521	521
SD	0.01	12.9	1.2	1.2	10,057	10,057	370.5	370.5	6.56	6.56	56.65	56.65	0.00	0.00	1.41	1.41	0.01	0.01	6.37	6.37	3.57	3.57	6,219	6,219	0.1	0.1	0.4	0.4
Fe	212	406	71.0	71.0	537	537	8,003	8,003	9,165	9,165	323,326	323,326	31.0	31.0	1,644	1,644	34.0	34.0	10,709	10,709	205	205	236	236	29,988	29,988	2,099	2,099
SD	230.7	72.9	0.80	0.80	310.0	310.0	734	734	1,216	1,216	8,541	8,541	29.75	29.75	1,745	1,745	0.01	0.01	798	798	275.6	275.6	146.6	146.6	6,621	6,621	2,527	2,527
K	3,016	14,782	2,953	2,953	1,924	1,924	1,414	1,414	576	576	1,423	1,423	70,661	70,661	55.6	55.6	1,415	1,415	651	651	708	708	2,843	2,843	14,150	14,150	14,173	14,173
SD	2,928	352	33	33	24.3	24.3	1	1	608	608	4	4	657	657	207.46	207.46	1	1	300.5	300.5	0.7	0.7	2	2	3	3	11	11
Mg	217	3,973	79.3	79.3	1,793	1,793	2,607	2,607	4,410	4,410	1,874	1,874	95.2	95.2	3,350	3,350	1,266	1,266	4,710	4,710	478	478	764	764	3,803	3,803	6,813	6,813
SD	134.2	94	9.0	9.0	1,680	1,680	46	46	1,087	1,087	2,169	2,169	0.02	0.02	2,594	2,594	1,341	1,341	1,381	1,381	475.4	475.4	0.5	0.5	1	1	4,510	4,510
Mn	8.59	62.7	12.5	12.5	87.1	87.1	399	399	352	352	3,167	3,167	6.91	6.91	168	168	264,200	264,200	425	425	23.6	23.6	12.1	12.1	2,850	2,850	4,126	4,126
SD	7.07	1.49	0.14	0.14	226.1	226.1	9.2	9.2	33.4	33.4	1,090	1,090	6.70	6.70	335.7	335.7	29,437	29,437	76.9	76.9	28.28	28.28	0.01	0.01	699	699	5,089	5,089
Na	3,740	6,351	752	752	582	582	55,186	55,186	594	594	362	362	90.2	90.2	33.0	33.0	360	360	626	626	359,092	359,092	724	724	4,541	4,541	6,966	6,966
SD	3,134	2,927	8.5	8.5	184.1	184.1	1,743	1,743	175.6	175.6	1.0	1.0	0.01	0.01	106.35	106.35	0.1	0.1	215.7	215.7	8,656	8,656	0.4	0.4	1,031	1,031	3,163	3,163
Ni	11.2	2,097	1,082	1,082	87.2	87.2	44.0	44.0	8.55	8.55	71.8	71.8	11.0	11.0	0.14	0.14	89.9	89.9	8.85	8.85	22.0	22.0	88.5	88.5	440	440	509	509
SD	0.28	483	24	24	63.69	63.69	0.01	0.01	3.86	3.86	6.50	6.50	0.00	0.00	0.73	0.73	42.00	42.00	2.53	2.53	0.02	0.02	0.05	0.05	0.1	0.1	204.9	204.9
P	188	732	146	146	131	131	202,945	202,945	181,905	181,905	71.7	71.7	51.1	51.1	126	126	1,300	1,300	205,696	205,696	56.7	56.7	209	209	701	701	702	702
SD	150.6	17.4	1.7	1.7	49.2	49.2	2,255	2,255	5,780	5,780	2.08	2.08	0.01	0.01	156.0	156.0	163	163	6,419	6,419	65.27	65.27	112.5	112.5	0.1	0.1	0.6	0.6
Pb	42.1	1,756	351	351	229	229	168	168	1.12	1.12	169	169	42.1	42.1	ND	ND	168	168	0.07	0.07	84.1	84.1	338	338	1,681	1,681	1,684	1,684
SD	0.05	42	4.0	4.0	2.9	2.9	0.1	0.1	2.46	2.46	0.5	0.5	0.01	0.01	—	—	0.1	0.1	0.25	0.25	0.07	0.07	0.2	0.2	1	1	1	1
S	307	12,669	185,166	185,166	17,8047	17,8047	565	565	11,321	11,321	174,872	174,872	44.1	44.1	1,497	1,497	194,779	194,779	10,395	10,395	4,007	4,007	48.2	48.2	1,222	1,222	185,973	185,973
SD	64.8	13,718	3,880	3,880	3,987	3,987	25.2	25.2	2,048	2,048	5,807	5,807	20.41	20.41	556	556	1,778	1,778	1,482	1,482	2,846	2,846	0.03	0.03	813	813	4,009	4,009
Zn	116	249	144	144	1,145	1,145	42.8	42.8	95.4	95.4	2,724	2,724	14.7	14.7	18.2	18.2	120	120	105	105	35.9	35.9	915	915	798,837	798,837	382,343	382,343
SD	93.2	131.7	146.1	146.1	933	933	7.20	7.20	22.55	22.55	811	811	5.62	5.62	31.11	31.11	93.4	93.4	26.4	26.4	79.7	79.7	27.5	27.5	8,379	8,379	22,139	22,139
Thermal combustion analysis																												
S	408	11,419	183,841	183,841	180,447	180,447	167	167	11,347	11,347	189,633	189,633	766	766	769	769	188,474	188,474	10,634	10,634	4,943	4,943	497	497	1,253	1,253	181,565	181,565
SD	124.7	12,106	2,316	2,316	3,179	3,179	134.0	134.0	2,028	2,028	2,835	2,835	496	496	1,016	1,016	2,732	2,732	1,709	1,709	2,930	2,930	113.4	113.4	744	744	3,811	3,811

¹All mineral data expressed as mg/kg, DM basis

to have high concentrations of sulfur-containing amino acids, 4.1 and 2.6% Cys, respectively (NRC, 1998); thus they had high concentrations of total S (Table 2). For comparison purposes, the value for feather meal is close to that listed in the most recent swine NRC (1998), but no such value exists for plasma protein.

The range in S concentration in mineral-based feedstuffs was the greatest, depending on whether the mineral source was sulfate- or nonsulfate-based. In addition, the method used to process specific minerals also affected its total S concentration. For example, sulfuric acid is used in the production of dicalcium- and monocalcium-phosphate, whereas phosphoric acid is used in the production of defluorinated phosphate. Consequently, total S in defluorinated phosphate is approximately 5% of that found in dicalcium- and monocalcium-phosphate (Table 3).

One key aspect of our research results is the large variation that can be noted in feedstuff mineral concentrations. Overall, the variability of S content in whole grains (corn, oats, rice, and wheat) was relatively low, usually less than 10%. Depending upon the processing technology, variation in S content may or may not be affected. For example, the S concentration in corn from the ICP analysis was 1,132 mg/kg with a CV of 9.4%, whereas the S concentration for dried distillers grains was 6,866 mg/kg with a CV of 33%. In contrast, no such increase in variation was noted in the S content of corn gluten feed and corn gluten meal (CV of 6.3 and 10.8%, respectively). There was no consistent effect of wheat milling on the variability of S analysis where the CV for S was 14.8, 25.7, and 11.9% for wheat, wheat flour, and wheat middlings, respectively (Table 1). Although our data are limited, this suggests that technology that uses S containing compounds in their process may add additional variability to S analysis. Mineral sources were not immune to variability. For example, the analyzed S value for cobalt carbonate was 12,669 mg/kg with a CV of 108%. However, among the 6 samples, 3 samples from one supplier averaged 25,082 mg/kg of S, whereas 3 samples from a different supplier averaged 256 mg/kg of S. Likewise, calcium concentrations of these samples was also variable, with the 3 high S samples having a high Ca content (32,821 mg/kg), whereas the 3 low S samples had a low Ca concentration (876 mg/kg).

With potential linkages of dietary S to chronic intestinal disease (Deplancke et al., 2000; Attene-Ramos et al., 2006; Burrin and Stoll, 2007), scour scores (Anderson and Stothers, 1978; Paterson et al., 1979; Maenz et al., 1994), protein digestibility (Anderson et al., 1994), and hydrogen sulfide emissions (Sutton et al., 1998; Whitney et al., 1999; Apgar et al., 2002), data on total dietary S is vital. In evaluation of the data in Tables 1, 2, and 3, a 3-pronged approach to reduce total dietary S would be to 1) lower dietary protein and still maintain Met and Cys requirements; 2) use defluorinated as the P source; and 3) use oxide-based trace minerals.

Table 4. Chloride composition of selected feedstuffs¹

Item	Distiller dried grains with solubles		Dried whey	Fish meal	Limestone	Meat and bone meal	Monocalcium phosphate	Plasma protein	Sodium chloride	Soybean meal	Wheat middlings
	Corn	5									
Samples	5	5	4	5	5	5	2	5	2	4	5
DM, %	85.72	88.29	94.74	92.93	99.99	97.16	96.87	92.97	99.96	89.03	87.94
SD	0.50	2.30	1.49	0.98	0.01	0.83	0.38	0.63	0.05	0.58	0.88
Cl	716	2,185	18,718	9,673	270	9,283	ND	7,751	608,148	316	948
SD	88.0	622	8,398	2,238	292.0	6,868	—	4,017	15,067	58.7	261.5

¹Chloride data expressed as mg/kg, DM basis. All feedstuffs analyzed by inductively coupled plasma-mass spectrophotometer.

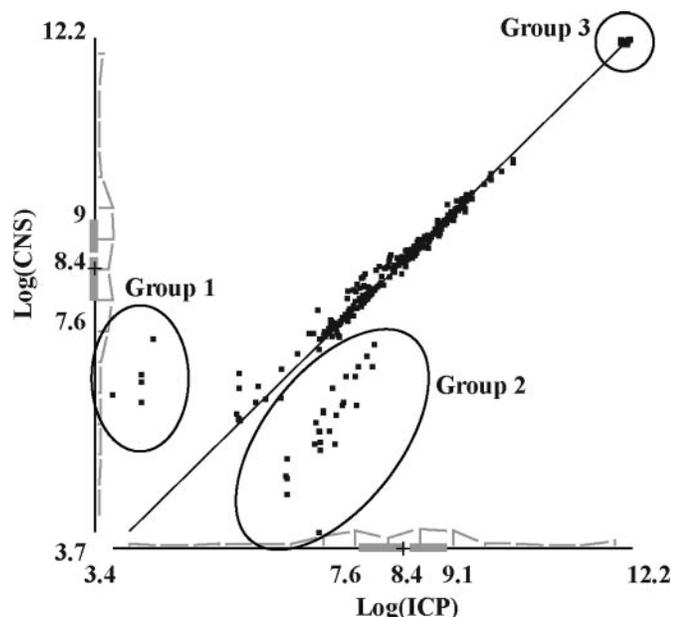


Figure 1. Bivariate plot and correspondence correlation between the log of thermal combustion analysis (CNS) and the log of inductively coupled plasma-mass spectrometry analysis (ICP; correspondence correlation coefficient, $r = 0.941$). Group 1 feedstuffs (potassium iodide and tribasic copper chloride) show that S values determined by ICP were lower than S determined by CNS [bias = 2.51 ± 0.15 (SE), $P < 0.01$]. Group 2 feedstuffs (defluorinated phosphate and limestone) show that S concentrations determined by ICP were greater than S determined by CNS [bias = -1.46 ± 0.51 (SE), $P < 0.01$]. Group 3 feedstuffs (cobalt-, copper-, iron-, manganese-, and zinc-sulfate) were high in total S but had similar S concentrations whether measured by CNS or ICP. The gray lines refer to an empirical histogram representing the distribution of the data.

Comparison of our values to table values is a daunting task depending upon which ingredient and mineral to compare. In light of this, we chose to compare 3 plant- and 3 animal-based feedstuffs in terms of their P content and variability. On a DM basis, analyzed P concentration compared with NRC (1998) values were corn, 0.30 vs. 0.31; distillers dried grains with solubles, 0.89 vs. 0.83; soybean meal, 0.80 vs. 0.77; dried whey, 0.82 vs. 0.75; meat and bone meal, 4.78 vs. 5.35; and plasma protein, 1.53 vs. 1.88% P, respectively. Despite differences of when the samples were obtained and location differences among samples, the average values reported herein are similar to tabular values. Similar to that in discussing the S concentrations previously, there can be a large range of concentrations within an ingredient. Coefficients of variations in corn, distillers dried grains with solubles, soybean meal, dried whey, meat and bone meal, and plasma protein were 14.1, 12.7, 28.7, 25.8, 25.1, and 10.9%, respectively. Consequently, fine tuning of dietary levels of minerals, in this case P, requires continual evaluation of each specific ingredient.

For mineral-based feedstuffs, the NRC (1998) does not report DM for minerals, consequently values we reported in Table 3 were converted to an as-is basis for comparison. In general, our values were relatively close to those reported in the swine NRC (1998). For macro-minerals, we reported 34.2% Ca and 20.3% P for defluorinated phosphate vs. 32.0% Ca and 18.0% P in the NRC (1998), 21.8% Ca and 17.8% P for dicalcium phosphate vs. 22% Ca and 18.5% P in the NRC (1998), 16.6% Ca and 20.0% P for monocalcium phosphate vs. 17.0% Ca and 21.1% P in the NRC (1998), and 39.9% Ca and 0.01% P for limestone vs. 38.5% Ca and 0.02% P in the NRC (1998). Comparative evaluation of a several micro-minerals were: copper sulfate, 27.2 vs. 25.2% Cu; iron sulfate, 32.1 vs. 30.0% Fe; manganese sulfate, 26.4 vs. 29.5% Mn; tribasic copper chloride, 62.8 vs. 58.0% Cu; zinc oxide, 79.8 vs. 72.0% Zn; zinc sulfate, 38.1 vs. 35.5% Zn; for the current data vs. NRC (1998), respectively. Similar to plant- and animal-based feedstuffs, mineral content of mineral-based feedstuffs was variable.

We were only able to analyze a few feedstuffs for chloride (Table 4). We selected ingredients that might be used in swine nursery rations because past research on electrolyte balance has generally focused in this size of pig (Haydon and West, 1990; Patience, 1990; Patience and Chaplin, 1997) but may also affect sow and litter performance (Dove and Haydon, 1994) and water consumption (Shaw et al., 2006). Our values were comparable to the NRC (1998) for corn (0.08 vs. 0.05% Cl, respectively), distiller grains with solubles (0.19 vs. 0.20% Cl, respectively), dried whey (1.77 vs. 1.40% Cl, respectively), meat and bone meal (0.90 vs. 0.69% Cl, respectively), soybean meal (0.03 vs. 0.05% Cl, respectively), and wheat middlings (0.08 vs. 0.04% Cl, respectively). Our values were greater for fish meal (0.90 vs. 0.55% Cl, respectively) but lower for plasma protein (0.72 vs. 1.40% Cl, respectively). We did not detect chloride in our dicalcium or monocalcium phosphate sources, and like the NRC (1998), a very low level was found in limestone. Sodium chloride was analyzed to contain 35.9% Na and 60.8% Cl, similar to the 39.5% Na and 59.0% Cl reported in the NRC (1998).

Data from this study show the relative abundance of minerals in a wide array of ingredients and that dietary manipulation of mineral intake can be achieved by altering feedstuff inclusion rates. In addition, data from this feed ingredient survey indicate that care is needed to determine the actual concentration of minerals, due to potential wide variation in mineral content due to ingredient source or processing. These results provide researchers and nutritionists relative concentrations of the mineral composition of feedstuffs commonly used in the livestock diets.

LITERATURE CITED

- Anderson, D. M., and S. C. Stothers. 1978. Effects of saline water high in sulfates, chlorides and nitrates on the performance of young weanling pigs. *J. Anim. Sci.* 47:900-907.

- Anderson, J. S., D. M. Anderson, and J. M. Murphy. 1994. The effect of water quality on nutrient availability for grower/finisher pigs. *Can. J. Anim. Sci.* 74:141–148.
- Anderson, K. L. 2003. The complex world of gastrointestinal bacteria. *Can. J. Anim. Sci.* 83:409–427.
- Apgar, G., K. Griswold, B. Jacobson, and J. Salzar. 2002. Effects of elevated and reduced dietary N and S concentration upon growth and concentration of odor causing components in waste of finishing pigs. *J. Anim. Sci.* 80(Suppl. 1):395. (Abstr.)
- ASAE. 2003. Manure Production and Characteristics. ASAE Data D384.1. Am. Soc. Agric. Eng., St. Joseph, MI.
- Attene-Ramos, M. S., E. D. Wagner, M. J. Plewa, and H. R. Gaskins. 2006. Evidence that hydrogen sulfide is a genotoxic agent. *Mol. Cancer Res.* 4:9–14.
- Baker, D. H. 1977. Sulfur in Nonruminant Nutrition. *Natl. Feed Ingredients Assoc.*, West Des Moines, IA.
- Baker, D. H. 2006. Comparative species utilization and toxicity of sulfur amino acids. *J. Nutr.* 136:1670S–1675S.
- Burrin, D. G., and B. Stoll. 2007. Emerging aspects of gut sulfur amino acid metabolism. *Curr. Opin. Clin. Nutr. Metab. Care* 10:63–68.
- Deplancke, B., K. R. Hristova, H. A. Oakley, V. J. McCracken, R. Aminov, R. I. Mackie, and H. R. Gaskins. 2000. Molecular ecological analysis of the succession and diversity of sulfate-reducing bacteria in the mouse gastrointestinal tract. *Appl. Environ. Microbiol.* 66:2166–2174.
- Dove, C. R., and K. D. Haydon. 1994. The effect of various diet nutrient densities and electrolyte balances on sow and litter performance during two seasons of the year. *J. Anim. Sci.* 72:1101–1106.
- Du Vigneaud, V. 1952. *A Trail of Research in Sulfur Chemistry and Metabolism and Related Fields*. Cornell Univ. Press, Ithaca, NY.
- Dziewiatkowski, D. D. 1962. Sulfur. Pages 175–220 in *Mineral Metabolism: An Advance Treatise, Volume II, The Elements Part B*. C. L. Comar and F. Bronner, ed. Academic Press, New York, NY.
- Florin, T., G. Neale, G. R. Gibson, J. J. Christl, and J. H. Cummings. 1991. Metabolism of dietary sulphate: Absorption and excretion in humans. *Gut* 32:766–773.
- Gibson, G. R. 1990. Physiology and ecology of the sulphate-reducing bacteria. *J. Appl. Bacteriol.* 69:769–797.
- Gomez, G. G., R. S. Sandler, and D. Seal Jr. 1995. High levels of inorganic sulfate cause diarrhea in neonatal piglets. *J. Nutr.* 125:2325–2332.
- Haydon, K. D., and J. W. West. 1990. Effect of dietary electrolyte balance on nutrient digestibility determined at the end of the small intestine and over the total digestive tract in growing pigs. *J. Anim. Sci.* 68:3687–3693.
- Lewis, H. B. 1924. Sulfur metabolism. *Physiol. Rev.* 4:394–423.
- Lin, L. I. 1989. A concordance correlation coefficient to evaluate reproducibility. *Biometrics* 45:255–268.
- Maenz, D. D., J. F. Patience, and M. S. Wolynetz. 1994. The influence of the mineral level in drinking water and the thermal environment on the performance and intestinal fluid flux of newly-weaned pigs. *J. Anim. Sci.* 72:300–308.
- McLeese, J. M., J. F. Patience, M. S. Wolynetz, and G. I. Christison. 1991. Evaluation of the quality of ground water supplies used on Saskatchewan swine farms. *Can. J. Anim. Sci.* 71:191–203.
- Meek, D. W. 2007. Two macros for producing graphs to assess agreement between two variables, paper D6. Pages 28–30 in *Data Visualization and Graphics Section*. A. Katschke, ed. 2007 Midwest SAS Users Group Annu. Conf. Proc., Des Moines, IA. SAS Inst., Cary, NC.
- Miller, R. O. 1998. Chapter 6. Nitric-perchloric acid wet digestion in an open vessel. Pages 57–61 in *Handbook of Reference Methods for Plant Analysis*. Y. P. Kalra, ed. CRC Press, Boca Raton, LA.
- NRC. 1998. *Nutrient Requirements of Swine*. 10th rev. ed. Natl. Acad. Press, Washington, DC.
- Paterson, D. W., R. C. Wahlstrom, G. W. Libal, and O. E. Olson. 1979. Effects of sulfate in water on swine reproduction and young pig performance. *J. Anim. Sci.* 49:664–667.
- Patience, J. F. 1990. A review of the role of acid-base balance in amino acid nutrition. *J. Anim. Sci.* 68:398–408.
- Patience, J. F., and R. K. Chaplin. 1997. The relationship among dietary underdetermined anion, acid-base balance, and nutrient metabolism in swine. *J. Anim. Sci.* 75:2445–2452.
- Pedersen, C., M. G. Boersma, and H. H. Stein. 2007. Digestibility of energy and phosphorus in ten samples of distillers dried grains with solubles fed to growing pigs. *J. Anim. Sci.* 85:1168–1176.
- Shaw, M. I., A. D. Beaulieu, and J. F. Patience. 2006. Effect of diet composition on water consumption in growing pigs. *J. Anim. Sci.* 84:3123–3132.
- Shoveller, A. K., B. Stoll, R. O. Ball, and D. G. Burrin. 2005. Nutritional and functional importance of intestinal sulfur amino acid metabolism. *J. Nutr.* 135:1609–1612.
- Spiehs, M. J., M. H. Whitney, and G. C. Shurson. 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.
- Stein, H. H., M. L. Gibson, C. Pedersen, and M. G. Boersma. 2006. Amino acid and energy digestibility in ten samples of distillers dried grain with solubles fed to growing pigs. *J. Anim. Sci.* 84:853–860.
- Stipanuk, M. H. 2004. Sulfur amino acid metabolism: Pathways for production and removal of homocysteine and cysteine. *Annu. Rev. Nutr.* 24:539–577.
- Sutton, A. L., J. A. Paterson, O. L. Adeola, B. A. Richert, D. T. Kelly, A. J. Heber, K. B. Kephart, R. Mumma, and E. Bodus. 1998. Reducing sulfur-containing odors through diet manipulation. Pages 125–130 in *Proceedings Volume 1: Oral Presentations, Animal Production Systems and the Environment*, Iowa State University. Iowa State University, Ames.
- Veenhuizen, M. F., G. C. Shurson, and E. M. Kohler. 1992. Effect of concentration and source of sulfate on nursery pig performance and health. *J. Am. Vet. Med. Assoc.* 201:1203–1208.
- Whitney, M. H., R. Nicolai, and G. C. Shurson. 1999. Effects of feeding low sulfur starter diets on growth performance of early weaned pigs and odor, hydrogen sulfide, and ammonia emissions in nursery rooms. *J. Anim. Sci.* 77(Suppl. 1):70. (Abstr.)

References

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