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Non Ruminant Nutrition

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Sunflower expellers have greater ileal digestibility of amino acids than sunflower meal, but there are only minor variations among different sources of sunflower meal when fed to growing pigs

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Abstract

The objective was to test the hypothesis that there is no effect of origin or processing procedure on the standardized ileal digestibility (**SID**) of amino acids (**AA**) and crude protein (**CP**) in sunflower coproducts. Six sources of sunflower meal (**SFM**) and one source of sunflower expellers (**SFE**) were obtained from Ukraine, Italy, Hungary, and the United States. Each source of SFM or SFE was the only source of CP and AA in one diet, and an N-free diet was also used for a total of eight diets. Eight barrows (body weight: 28.5 ± 2.4 kg) had a T-cannula installed in the distal ileum and were allotted to one of the eight diets using an 8 × 8 Latin square design with eight periods. The Lys:CP ratio in the six sources of SFM ranged from 3.10% to 3.96% with CP concentrations ranging from 27.34% to 36.75%. CP in SFE was 26.87% and the Lys:CP ratio was 3.51%. Concentrations of acid-hydrolyzed ether extract in the six sources of SFM ranged from 0.60% to 3.11%, but SFE contained 8.77%. Results indicated that the SID of CP was lower ($P < 0.05$) in SFM from Hungary compared with all other sources of SFM except for one of the sources from Ukraine. There were no differences in the SID of Lys, Met, and Trp among sources of SFM, but for most of the remaining indispensable AA, the SFM from Hungary had less ($P < 0.05$) SID than the other sources. However, only a few differences in the SID of indispensable AA were observed among the other sources of SFM, but the SID of CP and all AA except Trp was greater ($P < 0.05$) in SFE compared with SFM. In conclusion, there were only a few differences in the SID of the first-limiting AA among SFM obtained from Ukraine, Hungary, Italy, and the United States, but the SID of CP and AA was greater in SFE than in SFM indicating that processing of sunflower seeds influence the nutritional value.

Key words: amino acids, pigs, standardized ileal digestibility, sunflower expellers, sunflower meal

Introduction

The global oilseed production is increasing due to increased demand for oil as well as increased demand for amino acids (**AA**) for poultry and livestock feeding (Goldsmith, 2008). Soybean meal is the primary source of AA for pigs and poultry (Stein et al., 2008), but sunflower coproducts may be used as alternative and less expensive protein sources. In 2020, global sunflower seed production was approximately 54.89 million metric tons, and sunflowers were the third most-produced oilseed after soybeans and rapeseeds (USDA, 2020a). Global

Abbreviations

AA	amino acids
AEE	acid-hydrolyzed ether extract
AID	apparent ileal digestibility
CP	crude protein
SFE	sunflower expeller
SFM	sunflower meal
SID	standardized ileal digestibility

production of sunflower meal (**SFM**) is approximately 22 million metric tons per year with Ukraine, Russia, and the European Union being the largest producers and with the United States and Argentina, also having significant production (USDA, 2020b). SFM contains more digestible AA than cereal grains and also much more fiber (Musharaf, 1991), but the nutritive value and quality of SFM may vary due to variation among climate conditions, soil, and cultivation methods (Senkoylu and Dale, 1999). The degree of dehulling and the oil extraction process also affect the final quality of the meal (Kocher et al., 2000; Liu et al., 2015). However, the high concentration of dietary fiber in non-dehulled SFM results in limited inclusion of SFM in diets for pigs due to poor digestibility of nutrients in the presence of fiber (Düsterhöft et al., 1992). The dehulling results in partial removal of dietary fiber because the hulls of sunflower seeds have a high concentration of fiber (Vieira and Penz, 1992). The crude protein (**CP**) in partially dehulled SFM ranges from 30% to 39% depending on the region where the sunflowers are cultivated and processing conditions (NRC, 2012; Liu et al., 2015).

Oil can be extracted from sunflower seeds using the prepress-solvent extraction method or by using a double mechanical expelling procedure. The prepress-solvent extraction procedure results in SFM that contains 1% to 3% oil, whereas the double-press procedure results in a sunflower product that contains 5% to 10% residual oil and commonly is referred to as sunflower expellers (**SFE**). During both oil extraction procedures, heat is applied to the sunflower seed, which may result in heat damage, leading to reduced AA digestibility because of the Maillard reaction (Almeida et al., 2014).

Variations in the apparent ileal digestibility (**AID**) and the standardized ileal digestibility (**SID**) of AA in soybean meal among growing regions and countries have been reported (Lagos and Stein, 2017; Sotak-Peper et al., 2017). Although the AID and the SID of CP and AA in SFM fed to pigs have been reported (Green et al., 1988; Jondreville et al., 2000; González-Vega and Stein, 2012; Almeida et al., 2014), there are no comparative values for the AID or SID of AA in SFM produced in different parts of the world, and it is not known if the AID and SID of AA in SFM are different from those in SFE. Therefore, the objective of the current experiment was to test the null hypothesis that there are no effects of growing region on the AID and SID of CP and AA in SFM and that the AID and SID of CP and AA in SFM are not different from values obtained in SFE when fed to growing pigs.

Materials and Methods

The protocol for the experiment was reviewed and approved by the Institutional Animal Care and Use Committee at the University of Illinois.

Experimental diets

Six sources of SFM and one source of SFE were included in the experiment (Table 1). The six sources of SFM included two sources from Ukraine, two sources from the United States, and one source from both Hungary and Italy. The SFE was from the United States. Each source of SFM or SFE was included in one diet as the sole source of AA. An N-free diet that was used to calculate basal endogenous losses of AA and CP was also formulated. Thus, a total of eight diets were used (Tables 2 and 3). Vitamins and minerals were included in all diets to meet or exceed the current requirement estimates for growing pigs (NRC, 2012). All diets contained 0.40% chromic oxide as an indigestible marker. The daily feed allowance was calculated as 3.0 times the maintenance requirement for metabolizable energy (i.e., 197 kcal metabolizable energy per kg body weight$^{0.60}$; NRC, 2012). Feed allowance was adjusted according to the body weight of pigs at the beginning of each period. Feed was provided once daily at 0800 hours because feeding frequency does not influence AA digestibility (Chastanet et al., 2007). Water was available on an ad libitum basis.

Animals and housing

Eight growing pigs with an average initial body weight of 28.5 ± 2.4 kg, which had a T-cannula installed in the distal ileum, were used (Stein et al., 1998). Pigs were the offspring of Line 359 males mated to Camborough females (Pig Improvement Company, Hendersonville, TN, USA) and were allotted to an 8 × 8 Latin square arrangement with eight diets and eight periods (Kim and Stein, 2009). Pigs were individually housed in pens (1.2 × 1.5 m) in an environmentally controlled room with the ambient temperature maintained between 20 and 24 °C. Pens had smooth sidings and fully slatted tribar floors. A feeder and a water nipple were installed in each pen.

Sample collection

Each period of the Latin square lasted 7 d with the initial 5 d being the adaptation period to the diet, whereas ileal digesta were collected on days 6 and 7 for 9 h each day (Stein et al., 1998). By attaching a plastic bag to the opened cannula barrel using a cable tie, digesta that flowed into the bag were collected. Bags were replaced every time they were filled with digesta or at least every 30 min. Digesta samples were immediately stored at −20 °C to prevent bacterial degradation of AA.

Chemical analysis

At the conclusion of the experiment, ileal digesta samples were thawed at room temperature and mixed within animal and diet, and a subsample was lyophilized, ground, and analyzed. One sample of each diet and of each source of SFE and SFM was collected at the time of mixing. All samples were analyzed in duplicate. The chromium concentration was determined in diets and ileal digesta samples using the Inductive-Coupled Plasma Atomic Emission Spectrometric method (method 990.08; AOAC Int., 2019). Samples were prepared using nitric acid-perchloric acid [method 968.08D(b); AOAC Int., 2019]. Diets, ingredients, and ileal digesta samples were analyzed for dry matter after oven drying at 135 °C for 2 h (method 930.15; AOAC Int., 2019) and ingredients for dry ash (method 942.05; AOAC Int., 2019). Nitrogen in feed ingredient and diet samples and in ileal digesta samples was determined by the combustion procedure using a LECO FP628 Nitrogen Analyzer (LECO Corp., St. Joseph, MI, USA; method 990.03; AOAC Int., 2019), and CP was calculated as analyzed N × 6.25. Ingredient, diet, and ileal digesta samples were also analyzed for AA on a Hitachi Amino Acid Analyzer, Model No. L8800 (Hitachi High Technologies America, Inc.; Pleasanton, CA, USA) using ninhydrin for postcolumn

Table 1. Analyzed nutrient composition of six sources of SFM and one source of SFE[1]

Item, %	SFM									SFE
Origin:	United States	United States	Ukraine	Ukraine	Hungary	Italy	Average	SD	Coefficient of variation, %	United States
Gross energy, kcal/kg	4,324	4,231	4,169	4,177	4,121	4,213	4,206	69.33	1.64	4,926
Dry matter	92.33	88.60	89.43	91.21	90.38	90.89	90.47	1.32	1.50	96.18
CP	32.62	27.34	36.63	36.75	33.00	32.45	33.13	3.45	10.42	26.87
AEE	0.60	3.11	0.91	0.85	1.09	1.26	1.30	0.91	70.10	8.77
Ash	6.02	5.87	6.38	6.59	7.49	5.71	6.34	0.65	10.21	5.39
Acid detergent fiber	27.55	30.12	20.08	18.8	20.72	20.58	22.98	4.66	20.29	24.26
Neutral detergent fiber	35.84	38.56	25.21	25.91	27.16	33.34	31.00	5.66	18.26	31.11
Insoluble dietary fiber	32.31	41.52	28.63	29.81	30.96	35.92	33.19	4.79	14.43	36.87
Soluble dietary fiber	4.10	4.07	3.74	0.58	2.73	9.88	4.18	3.09	73.89	4.12
Total dietary fiber	36.50	45.59	32.37	30.29	33.59	45.80	37.36	6.76	18.10	40.99
Ca	0.26	0.28	0.32	0.34	0.37	0.36	0.32	0.04	13.91	0.22
P	0.68	0.62	0.92	1.02	0.90	0.62	0.79	0.18	22.26	0.48
Phytic acid	2.49	2.06	3.46	3.70	3.48	2.61	2.97	0.67	24.47	2.17
Sucrose	3.85	3.48	5.31	5.35	3.62	4.38	4.33	0.83	19.18	3.46
Raffinose	1.51	1.53	3.08	2.95	2.36	2.56	2.33	0.68	29.12	1.45
Indispensable AA										
Arg	2.32	2.03	2.81	2.90	2.48	2.43	2.50	0.32	12.99	2.05
His	0.74	0.66	0.91	0.92	0.80	0.78	0.80	0.10	12.36	0.66
Ile	1.34	1.21	1.56	1.58	1.38	1.37	1.41	0.14	9.99	1.14
Leu	1.93	1.71	2.25	2.39	2.02	2.03	2.05	0.24	11.77	1.64
Lys	1.01	0.92	1.36	1.46	1.21	1.23	1.20	0.20	16.87	0.94
Met	0.65	0.59	0.82	0.87	0.72	0.73	0.73	0.10	14.30	0.56
Phe	1.43	1.26	1.65	1.74	1.43	1.48	1.50	0.17	11.42	1.22
Thr	1.06	0.93	1.27	1.40	1.13	1.13	1.15	0.16	14.09	0.90
Trp	0.34	0.30	0.42	0.42	0.38	0.37	0.37	0.05	13.01	0.31
Val	1.59	1.41	1.86	1.90	1.65	1.67	1.68	0.18	10.75	1.35
Total	12.41	11.01	14.92	15.58	13.19	13.23	13.39	1.66	12.41	10.77
Dispensable AA										
Ala	1.30	1.14	1.53	1.60	1.36	1.35	1.38	0.16	11.92	1.09
Asp	2.67	2.37	3.09	3.29	2.75	2.79	2.83	0.32	11.43	2.29
Cys	0.51	0.46	0.59	0.65	0.54	0.54	0.55	0.07	12.09	0.43
Glu	5.97	5.22	6.90	7.04	6.21	5.94	6.21	0.67	10.84	5.00
Gly	1.73	1.54	2.09	2.19	1.85	1.83	1.87	0.24	12.61	1.49
Pro	1.18	1.04	1.39	1.62	1.28	1.45	1.33	0.21	15.45	1.02
Ser	1.07	0.92	1.22	1.51	1.11	1.10	1.16	0.20	16.99	0.90
Tyr	0.68	0.62	0.84	0.92	0.72	0.73	0.75	0.11	14.63	0.59
Total	15.10	13.32	17.63	18.81	15.81	15.73	16.07	1.93	12.02	12.81
Total AA	27.51	24.33	32.55	34.4	29.01	28.96	29.46	3.59	12.19	23.58
Lys:CP[2]	3.10	3.38	3.71	3.96	3.66	3.79	3.60	0.31	8.65	3.51

[1] All values except dry matter are expressed on an 88% dry matter basis.

[2] Lys:CP ratio was calculated by expressing the concentration of Lys in each source of SFM or SFE as a percentage of the concentration of CP (Stein et al., 2009).

derivatization and norleucine as the internal standard. Prior to analysis, samples were hydrolyzed with 6N HCl for 24 h at 110 °C [method 982.30 E9(a); AOAC Int., 2019]. Methionine and Cys were determined after cold performic acid oxidation overnight before hydrolysis [method 982.30 E(b); AOAC Int., 2019]. Tryptophan was determined after NaOH hydrolysis for 22 h at 110 °C [method 982.30 E(c); AOAC Int., 2019].

The gross energy of ingredient samples was measured using an isoperibol bomb calorimeter (Model 6400, Parr Instruments, Moline, IL, USA). Benzoic acid was used as the standard for calibration. Ingredients were also analyzed for acid-hydrolyzed ether extract (**AEE**) by acid hydrolysis using 3N HCl (AnkomHCL; Ankom Technology, Macedon, NY, USA) followed by crude fat extraction using petroleum ether (Ankom^{XT15}, Ankom Technology, Macedon NY, USA). Acid detergent fiber and neutral detergent fiber were analyzed using Ankom Technology methods 12 and 13, respectively (Ankom 2000 Fiber Analyzer, Ankom Technology, Macedon, NY, USA). Insoluble dietary fiber and soluble dietary fiber were analyzed in ingredients according to method 991.43 (AOAC Int., 2019) using the Ankom^{TDF} Fiber Analyzer (Ankom Technology, Macedon, NY, USA). Total dietary fiber was calculated as the sum of soluble dietary fiber and insoluble dietary fiber. Calcium and P in ingredient samples were analyzed (method 985.01 A, B, and C; AOAC Int., 2019) using

Table 2. Ingredient composition of experimental diets containing SFM or SFE

Item, %	SFM						SFE	
Origin:	United States	United States	Ukraine	Ukraine	Hungary	Italy	United States	N-free
Sunflower coproduct	40.25	50.00	37.00	36.20	40.70	41.10	47.00	—
Corn starch	33.40	23.80	36.55	37.35	32.90	32.55	26.70	67.90
Soybean oil	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Sucrose	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
Limestone	0.55	0.60	0.55	0.55	0.60	0.55	0.60	0.50
Dicalcium phosphate	0.85	0.65	0.95	0.95	0.85	0.85	0.75	2.15
Sodium chloride	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Chromic oxide	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin–mineral premix[1]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Solka-floc[2]	—	—	—	—	—	—	—	4.00
Magnesium oxide	—	—	—	—	—	—	—	0.10
Potassium carbonate	—	—	—	—	—	—	—	0.40

[1] The vitamin–micromineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,150 IU; vitamin D_3 as cholecalciferol, 2,210 IU; vitamin E as selenium yeast, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 1.10 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 1.00 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.6 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 125 mg as iron sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc hydroxychloride.

[2] Fiber Sales and Development Corp., Urbana, OH, USA.

Table 3. Analyzed nutrient composition of experimental diets containing SFM or SFE, as-fed basis

Item, %	SFM						SFE	
Origin:	United States	United States	Ukraine	Ukraine	Hungary	Italy	United States	N-free
Dry matter	94.87	93.25	93.77	94.01	93.67	94.33	95.83	95.21
CP	13.11	13.93	10.49	13.86	9.89	13.92	12.96	0.53
Indispensable AA								
Arg	0.96	0.96	0.90	1.15	0.81	1.02	1.03	0.01
His	0.32	0.32	0.30	0.38	0.27	0.35	0.34	—
Ile	0.57	0.59	0.51	0.66	0.47	0.62	0.59	—
Leu	0.84	0.87	0.76	0.98	0.71	0.91	0.87	0.06
Lys	0.46	0.48	0.47	0.60	0.42	0.56	0.51	0.03
Met	0.27	0.27	0.27	0.34	0.24	0.31	0.27	—
Phe	0.62	0.63	0.55	0.71	0.52	0.66	0.63	0.01
Thr	0.47	0.47	0.44	0.57	0.4	0.52	0.48	0.01
Trp	0.15	0.14	0.14	0.18	0.11	0.16	0.16	0.02
Val	0.69	0.71	0.62	0.79	0.57	0.74	0.71	0.01
Total	5.35	5.44	4.96	6.36	4.52	5.85	5.59	0.13
Dispensable AA								
Ala	0.56	0.58	0.51	0.66	0.47	0.61	0.58	0.01
Asp	1.19	1.20	1.08	1.36	0.98	1.26	1.22	0.05
Cys	0.22	0.22	0.20	0.26	0.19	0.23	0.23	0.05
Glu	2.52	2.55	2.27	2.84	2.10	2.68	2.59	0.02
Gly	0.75	0.78	0.70	0.89	0.64	0.82	0.79	0.02
Pro	0.58	0.60	0.53	0.65	0.51	0.60	0.58	0.18
Ser	0.47	0.48	0.44	0.56	0.40	0.49	0.49	0.02
Tyr	0.25	0.26	0.23	0.30	0.22	0.20	0.26	0.04
Total	6.54	6.67	5.96	7.52	5.51	6.89	6.74	0.39
Total AA	11.89	12.11	10.92	13.88	10.03	12.74	12.33	0.52

inductively coupled plasma-optical emission spectrometry (ICP-OES; Avio 200, PerkinElmer, Waltham, MA, USA). Sample preparation included dry ashing at 600 °C for 4 h (method 942.05; AOAC Int., 2019) and wet digestion with nitric acids (method 3050 B; U.S. Environmental Protection Agency, 2000). Ingredients were also analyzed for phytic acid (Ellis et al., 1977) and for sucrose and raffinose using high-performance liquid chromatography (Dionex App Notes 21 and 92).

Calculations and statistical analyses

The AID of CP and AA in diets was calculated from analyzed concentrations of CP, AA, and Cr in diets and in ileal digesta (Stein et al., 2007). The basal endogenous losses of CP and AA were calculated from pigs fed the N-free diet, and the SID of CP and AA was calculated by correcting AID values for basal endogenous losses of CP and AA (Stein et al., 2007). Because SFM or SFE was the sole source of CP and AA in each diet, values for the AID and SID of CP and AA in diets were considered the AID or SID of CP and AA in SFM or SFE.

Data were analyzed using the PROC MIXED procedure (SAS Inst. Inc., Cary, NC, USA). Homogeneity of the variances and normality of residuals were confirmed. The statistical model included SFM source as fixed effect and period and animal as random effects. The least squares means were calculated using the LSMeans statement in SAS, and, if significant, means were separated using the PDIFF option with Tukey's adjustment. A second analysis was performed to compare results for SFE with results for SFM using a contrast statement, and this model included diet as fixed effect and period and animal as random effects. Results were considered significant at $P \leq 0.05$ and a trend at $P \leq 0.10$. The pig was the experimental unit for all analyses.

The correlation coefficient, *r*, is a measure of the degree of linear correlation between two variables and also indicates the direction of correlation (Taylor, 1990). Correlation coefficients between gross energy and nutrient concentrations in the sunflower coproducts were determined using PROC CORR of SAS (SAS Inst. Inc., Cary, NC, USA).

Results

All pigs recovered from surgery without complications and consumed their diets throughout the experiment without apparent problems. The gross energy among all sources of SFM ranged from 4,121 to 4,324 kcal/kg, but SFE contained 4,926 kcal/kg (Table 1). The CP in SFE was 26.87% and CP in SFM ranged from 27.34% to 36.75%. Values for AEE in SFM varied between 0.60% and 1.26% except for one of the sources from the United States, which contained 3.11% AEE. However, the concentration of AEE in SFE was 8.77% AEE.

The two sources of SFM from Ukraine contained 5.31% and 5.35% sucrose, respectively, whereas the other sources of SFM and SFE contained between 3.46% and 4.38% sucrose. The concentration of raffinose in the two sources of SFM from Ukraine was 3.08% and 2.95%, but raffinose in all other coproducts varied between 1.45% and 2.56%. The concentration of total dietary fiber in SFM from Italy and in one of the U.S. sources was greater than 45.00%, but the remaining sources of SFM contained between 30.29% and 36.50% total dietary fiber.

The two sources of SFM from Ukraine had the numerically greatest concentrations of all AA and also the greatest Lys:CP ratio among all sources of SFM and SFE. Likewise, the two sources of SFM from Ukraine and the SFM from Hungary contained more P and phytic acid than the other sources.

The AID of CP in SFM from Italy, one of the sources from Ukraine, and the two sources from the United States was greater ($P < 0.05$) than in the other sources of SFM (Table 4). The AID of most of the AA in SFM from Hungary and in one source from Ukraine was less ($P < 0.05$) than in the other sources of SFM, but only minor differences among the other sources were observed. The AID of CP and all AA in SFE was greater ($P < 0.05$) than in the six sources of SFM.

The SID of CP in the six sources of SFM ranged from 61.1% to 82.7%, and the SID of Lys and Cys ranged from 75.0% to 81.0% and 54.5% to 72.4%, respectively (Table 5). The SID of CP was less ($P < 0.05$) in SFM from Hungary compared with all other sources of SFM except for one of the sources from Ukraine. There were no differences in the SID of Lys, Met, and Trp among sources of SFM, but for most of the remaining indispensable AA, the SFM from Hungary had less ($P < 0.05$) SID than the other sources. However, only a few differences in SID of indispensable AA were observed among the other sources of SFM, but the SID of CP and all AA

Table 4. AID (%) of CP and AA in six sources of SFM and one source of SFE[1]

Item, %	SFM								SFM source		SFE	SFM vs. SFE	
Origin:	United States	United States	Ukraine	Ukraine	Hungary	Italy	Mean	SD	SEM	P-value	United States	SEM	P-value
CP	59.6^{a}	59.9^{a}	45.7^{b}	56.7^{a}	41.2^{b}	64.2^{a}	54.55	9.0	3.39	<0.001	66.5	3.31	<0.001
Indispensable AA													
Arg	79.9^{a}	79.8^{a}	72.4^{ab}	78.6^{a}	68.0^{b}	80.9^{a}	76.60	5.2	2.82	0.002	85.5	2.67	<0.001
His	73.1^{a}	74.3^{a}	67.6^{ab}	73.8^{a}	65.4^{b}	74.7^{a}	71.50	3.9	1.85	0.001	79.2	1.77	<0.001
Ile	75.8^{ab}	78.2^{a}	68.7^{c}	75.4^{ab}	69.5^{bc}	76.2^{a}	73.95	3.9	1.70	<0.001	80.3	1.62	<0.001
Leu	76.4^{ab}	78.2^{a}	69.3^{c}	75.6^{abc}	69.7^{bc}	76.4^{ab}	74.27	3.8	1.71	0.001	80.7	1.61	<0.001
Lys	64.6^{ab}	67.8^{ab}	65.5^{ab}	70.0^{ab}	63.5^{b}	72.3^{a}	67.28	3.4	2.23	0.016	73.1	2.17	<0.001
Met	85.9^{a}	86.1^{a}	82.8^{b}	85.8^{a}	82.7^{b}	86.0^{a}	84.91	1.7	1.11	0.037	87.7	1.05	0.005
Phe	79.9^{ab}	81.9^{a}	72.2^{c}	78.6^{abc}	74.7^{bc}	79.0^{ab}	77.69	3.6	1.67	0.001	83.8	1.58	0.008
Thr	65.7^{a}	66.6^{a}	61.4^{ab}	68.0^{a}	57.3^{b}	68.5^{a}	64.58	4.4	2.16	0.002	70.7	2.07	<0.001
Trp	81.3^{a}	82.5^{a}	79.3^{ab}	82.5^{a}	74.3^{b}	82.8^{a}	80.46	3.3	1.53	0.002	83.6	1.47	<0.001
Val	72.7^{a}	74.8^{a}	65.3^{b}	71.7^{ab}	64.7^{b}	73.2^{a}	70.40	4.3	1.89	<0.001	77.0	1.79	<0.001
Total	75.4^{ab}	76.8^{a}	69.5^{bc}	75.4^{ab}	68.2^{c}	76.5^{a}	73.6	3.8	1.77	0.001	80.2	1.68	<0.001
Dispensable AA													
Ala	63.6^{ab}	65.8^{a}	53.2^{bc}	62.3^{abc}	50.3^{c}	66.5^{a}	60.3	6.8	3.33	0.001	70.2	3.23	<0.001
Asp	71.5^{ab}	73.0^{a}	65.7^{ab}	71.7^{ab}	65.0^{b}	72.9^{a}	70.0	3.7	1.99	0.004	76.6	1.91	<0.001
Cys	62.4^{a}	55.4^{ab}	56.8^{a}	62.3^{a}	44.5^{b}	64.0^{a}	57.6	7.2	3.28	<0.001	64.9	3.16	<0.001
Glu	83.4^{ab}	85.0^{a}	78.6^{b}	82.5^{ab}	78.7^{b}	84.2^{ab}	82.1	2.8	1.58	0.008	86.7	1.52	0.001
Gly	27.6^{a}	28.8^{a}	12.6^{b}	26.3^{ab}	20.1^{ab}	36.5^{a}	25.3	8.2	5.36	0.001	41.3	5.29	<0.001
Ser	63.5^{a}	64.4^{a}	57.4^{ab}	64.2^{a}	50.4^{b}	64.5^{a}	60.7	5.8	2.52	<0.001	69.9	2.41	<0.001
Tyr	67.1^{ab}	70.2^{a}	60.3^{bc}	68.0^{ab}	62.0^{abc}	57.1^{c}	64.1	5.1	2.23	<0.001	73.6	2.12	<0.001
Total	69.1^{a}	70.2^{a}	61.9^{ab}	68.3^{a}	57.9^{b}	70.9^{a}	66.4	5.3	2.46	0.001	74.6	2.36	<0.001
Total AA	72.1^{ab}	73.4^{ab}	65.5^{bc}	71.7^{ab}	62.8^{c}	73.6^{a}	69.8	4.6	2.11	0.001	77.3	2.02	<0.001

[1] Each least squares means is the mean of seven observations with the exception that the AID of CP and AA in SFE is the mean of eight observations.

$^{a–c}$Within a row, means without a common superscript differ ($P < 0.05$).

Table 5. SID (%) of CP and AA in six sources of SFM and one source of SFE[1,2]

Item, %	SFM								SFM source		SFE	SFM vs. SFE	
Origin:	United States	United States	Ukraine	Ukraine	Hungary	Italy	Mean	SD	SEM	*P*-value	United States	SEM	*P*-value
CP	79.3^{a}	78.1^{a}	70.1^{ab}	75.2^{a}	61.1^{b}	82.7^{a}	74.4	9.5	4.25	0.001	86.7	4.06	0.001
Indispensable AA													
Arg[3]	93.4	93.0	86.6	89.7	83.7	93.5	90.0	4.1	2.82	0.023	98.1	2.67	0.002
His	80.7^{ab}	81.7^{a}	75.6^{ab}	80.1^{ab}	74.3^{b}	81.5^{a}	79.0	3.2	1.85	0.008	86.4	1.77	<0.001
Ile	82.5^{ab}	84.6^{a}	76.1^{b}	81.2^{ab}	77.5^{b}	82.3^{ab}	80.7	3.2	1.70	0.003	86.9	1.62	<0.001
Leu	83.5^{ab}	84.9^{a}	77.2^{b}	81.7^{ab}	78.1^{b}	82.9^{ab}	81.4	3.1	1.71	0.007	87.6	1.61	0.001
Lys	75.2	77.9	75.8	78.1	75.0	81.0	77.2	2.3	2.23	0.223	82.8	2.17	0.011
Met	89.5	89.6	86.3	88.6	86.6	89.0	88.3	1.4	1.11	0.093	91.3	1.05	0.008
Phe	85.6^{a}	87.4^{a}	78.5^{b}	83.5^{ab}	81.4^{ab}	84.3^{ab}	83.4	3.1	1.67	0.004	89.5	1.58	0.001
Thr	77.9^{a}	78.6^{a}	74.3^{ab}	78.0^{a}	71.5^{b}	79.5^{a}	76.6	3.1	2.16	0.047	82.7	2.07	0.005
Trp	89.3	90.8	87.7	89.1	85.0	90.2	88.7	2.1	1.53	0.088	91.1	1.47	0.121
Val	81.4^{ab}	83.2^{a}	74.9^{b}	79.2^{ab}	75.1^{b}	81.2^{ab}	79.2	3.5	1.89	0.005	85.5	1.79	0.001
Total	84.2^{a}	85.4^{a}	79.0^{b}	82.8^{a}	78.6^{b}	84.6^{a}	82.4	3.0	1.77	0.014	88.8	1.68	0.001
Dispensable AA													
Ala	81.5^{a}	82.7^{a}	72.6^{a}	77.4^{a}	71.3^{b}	82.8^{a}	78.0	5.1	3.33	0.018	87.7	3.23	0.004
Asp[3]	79.2	80.6	74.1	78.5	74.3	80.2	77.8	2.9	1.99	0.033	84.2	1.91	0.001
Cys	71.1^{a}	64.0^{ab}	66.4^{a}	69.6^{a}	54.5^{b}	72.4^{a}	66.3	6.6	3.28	<0.001	73.4	3.16	0.021
Glu[3]	87.7	89.3	83.4	86.3	83.9	88.2	86.5	2.4	1.58	0.028	91.0	1.52	0.005
Gly	64.7^{a}	63.8^{a}	51.9^{ab}	57.3^{ab}	34.2^{b}	70.3^{a}	57.0	12.9	7.50	0.002	76.9	7.20	0.002
Ser	76.2^{a}	76.6^{a}	70.8^{ab}	74.8^{a}	65.1^{b}	76.6^{a}	73.3	4.6	2.52	0.003	82.2	2.41	<0.001
Tyr	79.8^{ab}	82.1^{a}	73.8^{ab}	78.4^{ab}	76.2^{ab}	72.8^{b}	77.2	3.6	2.23	0.016	85.8	2.12	<0.001
Total	80.7^{a}	81.4^{a}	74.4^{ab}	78.2^{ab}	71.5^{b}	81.8^{a}	78.0	4.2	2.46	0.007	86.0	2.36	0.001
Total AA	82.4^{ab}	83.3^{a}	76.6^{ab}	80.4^{ab}	74.9^{b}	83.1^{a}	80.1	3.6	2.11	0.009	87.3	2.02	0.001

[1] Each least squares means is the mean of seven observations with the exception that the SID of CP and AA in SFE is the mean of eight observations.
[2] Values for SID were calculated by correcting the values for AID for basal ileal endogenous losses. Basal ileal endogenous losses were determined (g/kg of dry matter intake) as CP, 27.25; Arg, 1.36; His, 0.25; Ile, 0.40; Leu, 0.63; Lys, 0.52; Met, 0.10; Phe, 0.37; Thr, 0.61; Trp, 0.13; Val, 0.63; Ala, 1.05; Asp, 0.97; Cys, 0.20; Glu, 1.16; Gly, 2.93; Ser, 0.63; and Tyr, 0.33.
[3] Although the model in which SFM source was the fixed effect was significant for the SID of Arg, Asp, and Glu, the adjusted *P*-value of the pairwise multiple comparison for the SID of these AA was not significant.
[a–c] Within a row, means without a common superscript differ ($P < 0.05$).

Table 6. Correlation coefficients (*r*) among chemical compositions of SFM and SFE[1]

	AEE		Total dietary fiber	
Item	*r*	*P*-value	*r*	*P*-value
Gross energy	0.936	0.002	0.294	0.523
CP	−0.764	0.046	−0.769	0.043

[1] Only correlations that were significant or had a tendency for significance are shown.

except Trp was greater ($P < 0.05$) in SFE compared with SFM. There was a positive correlation ($r = 0.936$; $P = 0.002$) between the concentrations of gross energy and AEE in sunflower coproducts (Table 6), but the concentration of CP was negatively correlated ($r = -0.764$; $P = 0.046$) with the concentrations of AEE and total dietary fiber ($r = -0.769$; $P = 0.043$).

Discussion

Oilseed coproducts are commercially produced from the oilseed crushing industry after oil extraction from the seeds (Woyengo et al., 2017), and the chemical composition of oilseed coproducts depends on the degree of processing and the oil extraction method. Sunflower seeds contain 40% to 45% oil (Le Clef and Kemper, 2015), and, among the major oilseed crops, sunflower seeds have the greatest concentration of oil. Sunflower seeds contain between 20% and 30% hulls, and, before oil extraction, seeds may be decorticated (dehulled) or un-decorticated (partly dehulled; Feedipedia, 2020), and flaked, followed by a prepress procedure at approximately 100 °C to create friction ruptures of the seed coat, which results in some of the oil being expelled (Le Clef and Kemper, 2015). However, in some crushing plants, 30% of the removed hulls are added back to the dehulled kernels to maximize oil recovery (Rodríguez et al., 2013), and sometimes hulls are added to the final SFM product as well, which results in increased concentration of fiber. Because of the structure of sunflower hulls, it is inherently challenging to collect representative samples of SFM and SFE. This may result in some variability in analytical values for CP and AA because the small sample sizes (i.e., 0.1 to 0.2 g) needed for these analyses will be influenced by the amount of hulls in the sample. In the present experiment, this resulted in some discrepancies between analyzed diet values for CP and AA and values calculated from ingredient analyses.

The general procedure for prepress-solvent extraction includes the prepress step with medium pressure on the prepared decorticated or un-decorticated seeds followed by solvent extraction to maximize oil extraction from the seed (Le Clef and Kemper, 2015). During oil extraction and toasting, the seeds are heated up to 100 °C, which may result in heat damage. For the double expeller-pressed oil extraction procedure, seeds are prepared and pre-pressed as for the prepress-solvent extraction procedure, but instead of going through the solvent extraction step, a second pressing procedure is applied. The temperature may be greater in the second press to enhance oil extraction (Spragg and Mailer, 2007), but the double-press procedure is less efficient in removing oil than the prepress-solvent extraction procedure, and there is, therefore, more residual oil in SFE compared with SFM, which was also observed in this experiment.

Sunflower coproducts are free of anti-nutritional factors and provide AA and energy to the diets (Wahlstrom, 1992). Concentrations of CP and AA in SFM used in this experiment were within the range of reported values (Rostagno et al., 2011; NRC, 2012; Liu et al., 2015; Pereira and Adeola, 2016; Stein et al., 2016). The low CP in SFE compared with SFM is not only a result of the greater concentration of AEE, but also a result of the high concentration of total dietary fiber (Dinusson, 1990). The AEE in one of the SFM from the United States (3.11%) was greater than that reported by González-Vega and Stein (2012; 1.6%) and Almeida et al. (2014; 1.9%) for SFM from the United States. Variations in the concentration of AEE among SFM sources may be attributed to the gums that sometimes are added back to the meal after crushing. The gums are generated during oil refining and are not used for human consumption and may, therefore, be added to the meal, resulting in increased oil concentration (Spragg and Mailer, 2007; Dijkstra, 2015). Differences in the concentration of residual oil in SFM may also be due to differences among crushing plants in the extraction process (Dinusson, 1990).

Addition of hulls to the meal after oil extraction increases fiber concentration in SFM. Values for acid detergent fiber and neutral detergent fiber for most of the SFM used in this experiment were less than reported values (Gonzalez-Vega and Stein, 2012; NRC, 2012; Liu et al., 2015). However, concentrations of CP and acid detergent fiber in SFE were close to values reported by Qwele et al. (2013) and Berwanger et al. (2014).

The SID of CP and AA in the six sources of SFM was less than some previous values (NRC, 2012; Almeida et al., 2014) but greater than the average reported by Liu et al. (2015) and in agreement with values by Gonzalez-Vega and Stein (2012). Increased concentrations of AEE in diets may increase the SID of AA because of a reduction in the rate of passage for digesta in the intestinal tract, which allows more time for intestinal digestion and absorption of AA (Cervantes-Pahm and Stein, 2008). The observation that the SID of CP and most AA was greater in SFE than in SFM may, therefore, be a result of greater concentrations of AEE in SFE. Increased fiber results in a faster rate of passage and may reduce the SID of AA (Kim et al., 2007), but the concentration of fiber in SFE was not less than in SFM, and it is, therefore, unlikely that differences in fiber contributed to the different SID of AA in SFE compared with SFM. However, even if there is an adjustment in AEE concentrations among diets, the SID of CP and most of the AA in oilseed expellers is greater than in oilseed meals, indicating that protein in oilseed expellers is better digested compared with protein in solvent-extracted oilseeds meals (Maison and Stein, 2014; Rodriguez et al., 2020). It is, therefore, possible that expelling of oil is a more gentle procedure than solvent extraction, which may also contribute to a greater SID of AA in SFE than in SFM. The toasting that follows the solvent extraction of oils is necessary to remove residual solvents, but if not properly controlled, this may result in some damage or change to proteins that potentially reduces digestibility.

Heating of feed ingredients does in most cases not affect the concentration of CP although the concentration of Lys may be reduced if proteins are over-heated. Therefore, the concentration of Lys expressed as a percentage of the concentration of CP is used as an indicator of over-processing of feed ingredients (Stein et al., 2009; Kim et al., 2012). However, with the exception of one of the sources of SFM from the United States, all coproducts used in this experiment had a Lys to CP ratio that was greater than 3.4%, which indicates that these sources had not been or only minimally heat damaged during processing (Almeida et al., 2014).

It is not clear why the SID of CP and some AA in the SFM from Hungary was reduced compared with other sources because the concentrations of energy, AA, AEE, and fiber were within the range of values for the other sources of SFM. Based on the Lys to CP ratio, it is also not evident that this source was heat damaged. However, it is possible that processing or storage procedures that do not result in heat damage may influence the SID of AA. It is also possible that the SID of CP and AA in SFM is influenced by the variety and the growing area of the sunflower seeds as has been demonstrated for soybean meal (Sotak-Peper et al., 2017). However, we did not obtain information about the varieties and the exact growing areas of the sunflower seeds used to produce the SFM evaluated in this experiment, so, at this point, this hypothesis has not been verified.

The observation that gross energy was positively correlated with AEE is in agreement with previous data (Ewan, 1989). This positive correlation is a result of more energy being present in fat per unit weight compared with the energy in other nutrients. The negative correlation between CP and AEE and total dietary fiber is a result of CP being more concentrated in the meals as AEE and/or total dietary fiber is removed. However, this also indicates that one of the consequences of sunflower crushing plants adding hulls to SFM is that not only will the concentration of fiber increase, but the concentration of CP and AA will also be reduced. The concentration of fiber in sunflower coproducts can, therefore, be used as an indicator of CP and AA concentrations.

Conclusions

SFM from Ukraine had greater concentrations of CP and AA compared with SFM from Italy and the United States, but SFE had the least concentration of CP among the coproducts used in this experiment. In contrast, SFE contained more AEE than SFM. The concentration of total dietary fiber varied among sources of SFM, indicating differences among crushing plants in the amount of hulls added to the final product. Although differences in the SID of AA in SFM among countries were calculated, only minor differences in the SID of the most limiting AA were observed. The SID of AA, however, was less in SFM compared with SFE.

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Conflict of interest statement

The authors have no real or perceived conflicts of interest.

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