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Metabolizable energy and apparent total tract digestibility of energy and nutrients differ among samples of sunflower meal and sunflower expellers fed to growing pigs

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Abstract

An experiment was conducted to test the hypothesis that there are no differences among samples of sunflower coproducts in apparent total tract digestibility (**ATTD**) of gross energy (**GE**), crude protein (**CP**), and acid hydrolyzed ether extract (**AEE**), total dietary fiber (**TDF**), insoluble dietary fiber, soluble dietary fiber (**SDF**), or in metabolizable energy (**ME**) regardless of where the ingredient was produced. Six samples of sunflower meal (**SFM**) were obtained from the United States (two samples), Ukraine (two samples), Hungary, and Italy. A sample of sunflower expellers (**SFE**) from the United States was also used. A corn-based control diet and 7 diets containing corn and each sample of sunflower coproducts were formulated. Sixty-four barrows (initial weight = 31.5 ± 3.2 kg) were allotted to 8 diets using a randomized complete block design with four blocks of pigs from four different weaning groups. Pigs were housed individually in metabolism crates and feed was provided at three times energy requirement for maintenance. Feces and urine were collected for four days after seven days of adaptation to diets. Results indicated that the ATTD of GE and CP in SFE was less ($P < 0.05$) than in SFM, but ATTD of AEE in SFE was greater ($P < 0.05$) compared with SFM. No difference in ME between SFM and SFE was observed. The ATTD of GE and TDF in SFM from Ukraine and Hungary was greater ($P < 0.05$) than in SFM from the United States or Italy. The ATTD of AEE did not differ among SFM samples with the exception that ATTD of AEE in the U.S. 2 sample was greater ($P < 0.05$) than in the other samples. The ATTD of SDF was less ($P < 0.05$) in the U.S. 1 sample and the sample from Italy than in the other samples. The ATTD of TDF was greater in the Ukraine 2 sample of SFM ($P < 0.05$) than in the two U.S. samples. The ME in the SFM samples from Ukraine and in the SFM from Hungary was greater ($P < 0.05$) than in the U.S. 1 sample and the SFM from Italy. In conclusion, ATTD of GE and nutrients differed between SFM and SFE, but the ATTD of TDF and the ME in SFM was not different from value for SFE. Among SFM samples, relatively small variations in ATTD of GE, AEE, and CP were observed, but ME and digestibility of TDF varied.

Lay Summary

Global oilseed production has been increasing due to the increased demand for oil as well as the increased demand for amino acids for livestock feeding. In addition to providing amino acids, sunflower meal (SFM) and sunflower expellers (SFE) also provide energy and other nutrients to the diets. Because the concentration of residual oil is less in SFM than in SFE, it is expected that SFE provides more energy to diets than SFM. However, data for the digestibility of nutrients and gross energy and concentrations of digestible energy and metabolizable energy in different samples of SFM or SFE are limited. Therefore, the objective of this research was to test the null hypothesis that there are no differences in the apparent total tract digestibility of nutrients and gross energy and concentration of digestible energy and metabolizable energy among SFM and SFE when fed to growing pigs. Results demonstrated that values for apparent total tract digestibility of nutrients and gross energy differed among samples of SFM produced in different countries. However, concentrations of digestible energy and metabolizable energy were not different in SFE compared with SFM despite a greater concentration of fat in SFE.

Key words: digestibility, energy, fat, pig, sunflower expellers, sunflower meal

Abbreviations: AA, amino acids; ATTD, apparent total tract digestibility; AEE, acid hydrolyzed ether extract; CP, crude protein; DE, digestible energy; DM, dry matter; GE, gross energy; IDF, insoluble dietary fiber; ME, metabolizable energy; OM, organic matter; SDF, soluble dietary fiber; SFE, sunflower expellers; SFM, sunflower meal; TDF, total dietary fiber.

Introduction

The majority of the global production of sunflower seeds in the 2021/22 crop year was in Ukraine, Russia, and the European Union (USDA, 2022), although the U.S. and Argentina have sizeable production as well. The oil from sunflower seeds is used for human consumption, but the defatted sunflower meal (**SFM**) or sunflower expellers (**SFE**) may be used as a source of protein for livestock and poultry (Musharaf, 1991). In addition to providing amino acids (**AA**), SFM, and SFE also provide energy and other nutrients to the diets, but because of the high concentration of fiber, SFM and SFE do not contain as much energy as other oilseed meals (Rodríguez et al., 2013).

The nutritive value of oilseed coproducts including sunflower coproducts vary due to differences in the growing area, harvesting procedures, degree of de-hulling, and oil extraction process (Rodríguez et al., 2013; Maison and Stein, 2014; Lopez et al., 2020). Sunflower meal is the coproduct obtained after a prepress-solvent extraction procedure is used to remove oil from the seeds, whereas SFE is produced after a double-press

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oil extraction method (Ibagon et al., 2021). Because the solvent extraction procedure is more effective in removing oil from the seeds than the double press method, the concentration of residual oil in SFE is greater than in SFM. Therefore, it is expected that SFE provides more energy to diets than SFM. However, data for the digestibility of nutrients and energy and concentrations of digestible energy (**DE**) and metabolizable energy (**ME**) in different samples of SFM are limited and to our knowledge, research to determine the difference in DE and ME between SFE and SFM has not been reported. Likewise, there are limited data comparing the DE and ME among samples of SFM produced in different geographical regions and it is not known if DE and ME in SFM from the United States is in agreement with values for SFM from Europe where variety, growing conditions, and oil extraction methods may be different. Therefore, the objective of this research was to test the null hypothesis that there are no differences in the apparent total tract digestibility (**ATTD**) of nutrients and gross energy (**GE**) or concentrations of DE and ME among sunflower coproducts when fed to growing pigs regardless of production area and production process.

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 samples of SFM and one sample of SFE were used in the experiment (Table 1). The six samples of SFM included two samples from Ukraine (i.e., Ukraine 1, Ukraine 2), two samples from the United States (i.e., U.S. 1, U.S. 2), and one sample from both Hungary and Italy. The SFE was procured from the United States. A corn-based basal diet and 7 diets containing corn and each sample of sunflower coproducts were formulated. Thus, a total of 8 diets were used (Table 2). Vitamins and minerals were included in all diets to meet or exceed current requirement estimates for growing pigs (NRC, 2012). All diets were fed in meal form. The daily feed allowance was calculated as 3.0 times the maintenance requirement for ME (i.e., 197 kcal ME 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 daily in two equal meals that were provided at 0800 h and 1600 h.

Animals and housing

Sixty-four growing pigs with an average initial body weight of 31.5 ± 3.8 kg were used. Pigs were the offspring of Line 359 males mated to Camborough females (Pig Improvement Company, Hendersonville, TN, USA). Pigs were allotted to a randomized complete block design with four different weaning groups as the block. Four weaning groups consisted of 24, 16, 16, and eight pigs each and there were three replicate pigs per diet in the first block, two replicate pigs per diet in the second and third block, and one pig per diet in the last block. Therefore, there were a total of eight replicates per diet in the experiment. Pigs were housed individually in metabolism crates that were equipped with a self-feeder, a nipple waterer, a fully slatted floor, a screen floor, and urine trays that allowed for the total, but separate, collection of urine and fecal materials from each pig. Throughout the experiment, pigs had free access to water.

Sample collection

Pigs were fed experimental diets for 14 d with feed disappearance recorded daily. The initial seven days were considered the adaptation period to the diet, whereas urine and fecal materials were collected from feed provided during the following five days according to the marker-to-marker approach (Adeola, 2001). The start marker (i.e., chromic oxide) was

Table 1. Analyzed nutrient composition of six samples of sunflower meal (SFM) and one sample of sunflower expellers (SFE), dry matter basis[1]

Item	SFM									SFE
Sample:	U.S. 1	U.S. 2	Ukraine 1	Ukraine 2	Hungary	Italy	Average	SD	CV, %	U.S.
Gross energy, kcal/kg	4,914	4,808	4,738	4,747	4,683	4,788	4,779	78.78	1.64	5,598
Dry matter, %	92.33	88.60	89.43	91.21	90.38	90.89	90.47	1.32	1.50	96.18
Crude protein, %	37.07	31.07	41.63	41.76	37.50	36.88	37.65	3.92	10.42	30.53
AEE[2], %	0.68	3.53	1.03	0.97	1.24	1.43	1.48	1.04	70.10	9.97
Ash, %	6.84	6.67	7.25	7.49	8.51	6.49	7.21	0.74	10.21	6.13
Acid detergent fiber, %	31.31	34.23	22.82	21.36	23.55	23.39	26.11	5.30	20.29	27.57
Neutral detergent fiber, %	40.73	43.82	28.65	29.44	30.86	37.89	35.23	6.43	18.26	35.35
Insoluble dietary fiber, %	36.72	47.18	32.53	33.88	35.18	40.82	37.72	5.45	14.43	41.90
Soluble dietary fiber, %	4.66	4.63	4.25	0.66	3.10	11.23	4.75	3.51	73.89	4.68
Total dietary fiber, %	41.48	51.81	36.78	34.42	38.17	52.05	42.45	7.69	18.10	46.58
Ca, %	0.30	0.32	0.36	0.39	0.42	0.41	0.37	0.05	13.91	0.25
P, %	0.77	0.70	1.05	1.16	1.02	0.70	0.90	0.20	22.26	0.55
Phytic acid, %	2.83	2.24	3.81	4.16	3.86	2.92	3.30	0.75	22.66	2.47
Sucrose, %	4.38	3.95	6.03	6.08	4.11	4.98	4.92	0.95	19.18	3.93
Raffinose, %	1.72	1.74	3.50	3.35	2.68	2.91	2.65	0.77	29.12	1.65

[1]Data for concentrations of amino acids in the ingredients were published elsewhere (Ibagon et al., 2021).
[2]AEE, acid hydrolyzed ether extract.

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Table 2. Ingredient composition and analyzed composition of experimental diets containing sunflower meal or sunflower expellers (SFE), as-fed basis

Item,	Basal	Sunflower meal						SFE
		U.S. 1	U.S. 2	Ukraine 1	Ukraine 2	Hungary	Italy	U.S
Ingredient composition								
Ground corn	97.30	57.95	57.95	57.95	57.95	57.95	57.95	57.95
Sunflower coproduct	-	40.00	40.00	40.00	40.00	40.00	40.00	40.00
Limestone	0.75	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Dicalcium phosphate	1.40	0.50	0.50	0.50	0.50	0.50	0.50	0.75
Sodium chloride	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
Analyzed composition								
Gross energy, kcal/kg	3,725	3,928	3,960	3,907	3,876	3,877	3,861	4,121
Dry matter, %	86.87	88.59	88.12	88.62	88.24	88.37	88.09	89.00
Crude protein, %	6.88	17.26	15.36	18.64	18.68	17.52	16.99	15.05
AEE[3], %	2.90	2.35	3.17	2.29	2.27	2.13	1.86	5.75
Ash, %	3.44	4.98	4.84	5.28	5.40	5.46	5.04	4.63
IDF[2], %	10.2	21.0	21.5	20.0	21.4	20.5	21.6	25.4
SDF[2], %	0.4	1.3	2.5	2.5	1.8	2.1	1.2	1.9
TDF[2], %	10.6	22.3	24.0	22.5	23.2	22.6	22.8	27.3
Organic matter, %	83.43	83.61	83.27	83.34	82.84	82.91	83.05	84.37

[1]The vitamin-micromineral premix provided the following quantities of vitamins and microminerals per kg of complete diet: vitamin A as retinyl acetate, 11,150 IU; vitamin D_3 as cholecalciferol, 2,210 IU; vitamin E as DL-alpha-tocopheryl acetate, 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]AEE, acid hydrolyzed ether extract; IDF, insoluble dietary fiber; SDF, soluble dietary fiber; TDF, total dietary fiber.

included in the morning meal on day 8 and the stop marker (i.e., ferric oxide) was included in the morning meal on day 13. Urine was collected in urine buckets over a preservative of 50 mL of 6 *N* HCl. Orts were collected daily prior to feeding the morning meal, pooled for the duration of the collection period, dried in a 50 °C forced air-drying oven, and weighed at the conclusion of the experiment. Fecal samples, orts, and 20% of the collected urine were stored at –20 °C immediately after collection.

Chemical analysis

At the conclusion of the experiment, urine samples were thawed and mixed within animal and diet, and filtered through a Fisher grade P4 filter paper (Fisher Scientific International, Inc., Waltham, MA, USA) prior to being sub-sampled. Ten milliliters of the subsampled urine was subsequently dripped onto cotton balls and lyophilized (Kim et al., 2009). Fecal samples were thawed and mixed within pig and diet, dried in a 50 °C forced air-drying oven, and ground using a 1-mm screen in a Wiley mill (model 4; Thomas Scientific, Swedesboro, NJ, USA). One sample of each diet and of each sample of SFE and SFM was collected at the time of diet mixing. All samples were analyzed in duplicate. Diets, ingredients, and fecal samples were analyzed for dry matter (**DM**) after oven drying at 135 °C for two hours (method 930.15; AOAC Int., 2019) and for ash (method 942.05; AOAC Int., 2019). Nitrogen in feed ingredients, diets, and fecal 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 crude protein (**CP**) was calculated as analyzed $N \times 6.25$.

Diet, ingredient, and fecal samples were analyzed for insoluble dietary fiber (**IDF**) and soluble dietary fiber (**SDF**) on an Ankom Total Dietary Fiber Analyzer (Ankom Technology, Macedon, NY, USA) using method 991.43 (AOAC Int., 2019). Total dietary fiber (**TDF**) was calculated as the sum of IDF and SDF. Insert new sentence: Ingredients were also analyzed for acid detergent fiber and neutral detergent fiber using Ankom technology methods 12 and 13, respectively, on an Ankom 2000 Fiber Analyzer (Ankom Technology, Macedon, NY, USD). In addition, ingredients were analyzed for sucrose and raffinose using high-performance liquid chromatography (Dionex App Notes 21 and 92).

The GE of ingredients, diets, fecal samples, and lyophilized urine samples was measured using an isoperibol bomb calorimeter (Model 6400, Parr Instruments, Moline, IL, USA) and benzoic acid was used as the standard for calibration. Ingredients, diets, and fecal samples were also analyzed for acid-hydrolyzed ether extract (**AEE**) by acid hydrolysis using 3 *N* HCl (AnkomHCL; Ankom Technology, Macedon, NY, USA) followed by crude fat extraction using petroleum ether (method 2003.06, AOAC Int., 2019; Ankom^{XT15}, Ankom Technology, Macedon NY, USA).

Calculations and statistical analyses

Organic matter (**OM**) was calculated as the difference between DM and ash. The ATTD (%) of DM, OM, ash, GE, AEE, CP, IDF, SDF, and TDF was calculated for each diet using the following equation (Adeola, 2001):

$$\text{ATTD}_{\text{nutrient}},\ \% = [(\text{nutrient}_{\text{intake}} - \text{nutrient}_{\text{feces}})/\ \text{nutrient}_{\text{intake}}] \times 100$$

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where $nutrient_{intake}$ and $nutrient_{feces}$ represent the daily intake (kg/d), and fecal output (kg/d) of the nutrient, respectively.

The DE (kcal/kg) and ME (kcal/kg) in diets were calculated by subtracting GE in feces (kcal/d) and GE in feces (kcal/d) and urine (kcal/d), respectively, from the intake of GE (kcal/d) in the diet (NRC, 2012). The DE and ME in the basal diet was divided by the inclusion rate of corn in the basal diet to calculate DE and ME in corn. The contribution of DE and ME from corn to the DE and ME in the diets containing SFM or SFE was subtracted from the DE and ME of each diet, and the DE and ME of each sample of SFM or SFE were calculated by difference (Adeola, 2001). The difference procedure was also used to calculate the ATTD of DM, OM, GE, AEE, CP, SDF, IDF, and TDF in SFE and the 6 samples of SFM.

Data were analyzed using the MIXED procedure of SAS (SAS Inst. Inc., Cary, NC, USA). Normality of residuals was confirmed with PROC MIXED of SAS and homogeneity of the variance of the residuals was tested using Brown-Forsythe test of the GLM procedure of SAS. An outlier was defined as an observation with a studentized residual of greater than 3 or less than – 3 and was subsequently removed from statistical analysis. To analyze differences among samples of SFM, the model included SFM sample as fixed effect and block (i.e., group of pigs) as random effects. Least squares means were calculated using the LSMeans statement in SAS, and if the model was significant, means were separated using the PDIFF option with Tukey's adjustment. A second analysis was performed to compare SFE and SFM using a contrast statement and the model used for this analysis included all diets as fixed effect and block and animal within block as random effects.

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 nutrient composition in sunflower coproducts and DE and ME and ATTD of GE and nutrients were determined using the CORR procedure of SAS (SAS Inst. Inc., Cary, NC, USA). 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.

Results

Feed intake of pigs fed the diets containing SFM from Ukraine, Hungary, Italy and the U.S. 2 was greater ($P < 0.05$) than that of pigs fed the corn diet, and daily GE intake of the corn diet was less ($P < 0.05$) than of all diets containing SFM or SFE (Table 3). Likewise, the intake of DM and ash was greater ($P < 0.05$) in all diets containing SFM or SFE except for one of the diets containing the U.S. 2 SFM compared with the corn diet. Intake of OM from the corn diet was not different from one of the diets containing the U.S. 2 SFM and the diet containing SFE, but less ($P < 0.05$) than from the other diets containing SFM. Intake of CP by pigs fed the corn diet was also less ($P < 0.05$) than by pigs fed diets containing SFM or SFE, but pigs fed the diet containing SFE had a greater ($P < 0.05$) intake of AEE compared with pigs fed all other diets.

The quantity of feces from pigs fed the corn diet was less ($P < 0.05$) than from pigs fed diets containing SFM or SFE, and excretions of GE, OM, CP, IDF, SDF, and TDF, and ash in feces were also less ($P < 0.05$) from pigs fed the corn diet than from pigs fed diets containing SFM or SFE. The weight of urine was not influenced by diet, but urine excretion of GE tended to be less ($P < 0.10$) for pigs fed the corn diet than for pigs fed diets containing SFM or SFE. The ATTD of DM, GE, and OM was greater ($P < 0.05$) for the corn diet than for pigs fed diets containing SFM or SFE. The ATTD of CP was less ($P < 0.05$) in the corn diet than in the diets containing Ukraine 2 SFM and SFM from Hungary, but not different from the other diets. The ATTD of AEE was less ($P < 0.05$) for the corn diet and diets containing SFM than for the diet containing SFE. The ATTD of ash in the corn diet was greater ($P < 0.05$) than in diets containing SFM or SFE with the exception that there was no difference between the corn diet and the diet containing the U.S. 2 SFM. The ATTD of IDF was greater ($P < 0.05$) in the corn diet than in diets containing SFM from the United States or Italy, but not different from the other in diets. However, the ATTD of SDF was less ($P < 0.05$) in the corn diet than diets containing SFM or SFE, but the ATTD of SDF did not differ among the corn diet and diets containing SFM from Italy or the U.S. 1 SFM. The ATTD of TDF was greater ($P < 0.05$) in pigs fed the corn diet than in pigs were fed diets containing SFM from Italy or the U.S. 1 SFM. The DE and ME were greater ($P < 0.05$) in the corn diet than in diets containing SFE or SFM, and DE in diets containing SFM from Ukraine was greater ($P < 0.05$) than in the diet containing SFM from Italy. The diet containing SFM from Hungary and the diet containing Ukraine 1 SFM had a greater ($P < 0.05$) ME than the diet containing SFM from Italy. The DE and ME in the diet containing SFE were not different from that of any of the diets containing SFM.

The ATTD of GE in SFM from Ukraine and Hungary was greater ($P < 0.05$) than in the U.S. 1 SFM and the SFM from Italy (Table 4), but the ATTD of GE was not different among the samples of SFM from Hungary and Ukraine. The ATTD of CP did not differ among SFM from Hungary, the U.S. 1, and Ukraine, but the Ukraine 2 SFM and the SFM from Hungary had greater ($P < 0.05$) ATTD of CP than the U.S. 2 sample and the SFM from Italy. The ATTD of AEE did not differ among SFM samples with the exception that in the U.S. 2 sample was greater ($P < 0.05$) than the ATTD of AEE in the other samples. The ATTD of IDF was greater ($P < 0.05$) in the Ukraine 2 SFM, than in the other SFM samples, but the ATTD of IDF was not different between the SFM from Hungary and the Ukraine 2 SFM. The ATTD of SDF did not differ among SFM samples, with the exception that the ATTD of SDF in the SFM from Italy and the U.S. 1 SFM was less ($P < 0.05$) than in the other samples. The ATTD of TDF in SFM from Hungary and the two SFM samples from Ukraine was greater ($P < 0.05$) than in the two SFM samples from the U.S. and the SFM from Italy. The ATTD of GE and CP in SFE was less ($P < 0.05$) than in SFM, but the ATTD of AEE was greater ($P < 0.05$) in SFE compared with SFM. The ATTD of IDF, SDF, and TDF was not different ($P < 0.05$) between SFM and SFE. Concentrations of DE and ME in SFM from Ukraine and Hungary were greater ($P < 0.05$) than the U.S. 1 sample and the SFM from Italy. There were no differences in DE and ME between SFM and SFE.

There was a positive correlation ($P < 0.01$) between GE and DM or AEE (Table 5). The GE concentration was also positively correlated ($P < 0.05$) with the ATTD of AEE, but tended to be negatively correlated with the ATTD of DM and GE ($P < 0.10$) and the ATTD of CP ($P < 0.05$). There was a tendency for a positive correlation ($P < 0.10$) between DM and AEE concentration, whereas CP concentration was

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Table 3. The apparent total tract digestibility (ATTD) of nutrients and gross energy and concentrations of digestible energy (DE) and metabolizable energy (ME) in the basal diet and diets containing sunflower meal (SFM) or sunflower expellers (SFE), as-fed basis[1]

	Basal	SFM						SFE		
Item		U.S. 1	U.S. 2	Ukraine 1	Ukraine 2	Hungary	Italy	U.S.	SEM	*P*-value
Intake										
Feed intake, kg/d	1.27^{b}	1.47^{a}	1.44^{ab}	1.53^{a}	1.47^{a}	1.51^{a}	1.52^{a}	1.43^{ab}	0.05	0.002
Gross energy, kcal/d	4,751^{b}	5,770^{a}	5,687^{a}	5,978^{a}	5,693^{a}	5,858^{a}	5,864^{a}	5,902^{a}	194	< 0.001
Dry matter, kg/d	1.11^{b}	1.30^{a}	1.27^{ab}	1.36^{a}	1.30^{a}	1.33^{a}	1.34^{a}	1.27^{a}	0.05	< 0.001
Organic matter, kg/d	1.06^{b}	1.23^{a}	1.20^{ab}	1.28^{a}	1.22^{a}	1.25^{a}	1.26^{a}	1.21^{ab}	0.04	0.002
Crude protein, g/d	88^{d}	254^{b}	221^{c}	284^{a}	274^{ab}	265^{ab}	257^{ab}	216^{c}	8	< 0.001
AEE[2], g/d	37^{c}	35^{c}	45^{b}	35^{c}	33^{c}	32^{cd}	28^{d}	83^{a}	1	<0.001
Ash, g/d	44^{e}	73^{bcd}	70^{cd}	81^{ab}	79^{ab}	83^{a}	76^{abc}	66^{d}	3	<0.001
IDF[2], g/d	130^{c}	309^{b}	309^{b}	305^{b}	314^{b}	310^{b}	326^{b}	364^{a}	10	<0.001
SDF[2], g/d	5^{e}	19^{d}	36^{a}	38^{a}	26^{c}	32^{b}	18^{d}	27^{c}	1	<0.001
TDF[2], g/d	135^{c}	328^{b}	345^{b}	343^{b}	342^{b}	342^{b}	345^{b}	393^{a}	11	<0.001
Fecal excretion										
Dry feces output, g/d	120^{b}	319^{a}	298^{a}	283^{a}	267^{a}	282^{a}	313^{a}	328^{a}	18	<0.001
Gross energy, kcal/d	594^{c}	1,503^{ab}	1,411^{ab}	1,315^{ab}	1,228^{b}	1,283^{ab}	1,466^{ab}	1,582^{a}	86	<0.001
Organic matter, g/d	106^{b}	280^{a}	261^{a}	253^{a}	236^{a}	248^{a}	276^{a}	283^{a}	18	0.002
Crude protein, g/d	21^{b}	56^{a}	50^{a}	55^{a}	54^{a}	51^{a}	58^{a}	52^{a}	4	<0.001
AEE, g/d	20^{b}	21^{b}	21^{b}	22^{b}	21^{b}	20^{b}	18^{b}	31^{a}	1	<0.001
Ash, g/d	16^{d}	35^{bc}	29^{c}	39^{ab}	41^{ab}	42^{a}	39^{ab}	34^{bc}	2	0.002
IDF, g/d	56^{d}	185^{a}	174^{ab}	143^{bc}	125^{c}	144^{bc}	176^{ab}	187^{a}	10	<0.001
SDF, g/d	4^{b}	13^{a}	11^{a}	11^{a}	12^{a}	12^{a}	12^{a}	15^{a}	1	<0.001
TDF, g/d	61^{d}	198^{a}	185^{ab}	154^{bc}	136^{c}	156^{bc}	188^{ab}	202^{a}	10	<0.001
Urine excretion										
Urine output, kg/d	4.0	7.1	5.8	8.6	5.8	6.1	8.0	3.3	1.4	0.162
Gross energy, kcal/d	121	215	182	208	199	156	221	157	30	0.086
ATTD, %										
Gross energy	87.54^{a}	74.11^{c}	75.39^{bc}	78.04^{b}	78.40^{b}	78.19^{b}	74.93^{bc}	73.34^{c}	1.0	<0.001
Dry matter	89.19^{a}	75.67^{cd}	76.67^{bcd}	79.20^{b}	79.34^{b}	78.95^{bc}	76.55^{bcd}	74.40^{d}	0.9	<0.001
Organic matter	90.23^{a}	77.01^{d}	77.74^{cd}	80.94^{bc}	81.14^{b}	80.90^{bc}	78.19^{bcd}	75.81^{d}	0.9	<0.001
Crude protein	76.41^{bc}	77.96^{abc}	77.56^{abc}	81.02^{a}	80.34^{ab}	80.84^{a}	77.49^{abc}	75.96^{c}	1.4	<0.001
AEE	46.35^{bc}	40.95^{cd}	54.23^{ab}	35.91^{cd}	35.73^{cd}	35.10^{d}	33.90^{d}	62.88^{a}	2.5	<0.001
Ash	63.57^{a}	52.88^{bc}	58.54^{ab}	51.25^{bc}	48.43^{c}	49.04^{c}	49.27^{c}	48.59^{c}	2.2	<0.001
IDF	56.10^{ab}	40.53^{d}	44.19^{d}	53.52^{abc}	59.92^{a}	53.42^{abc}	46.05^{cd}	48.88^{bcd}	2.0	<0.001
SDF	18.62^{d}	33.82^{cd}	72.33^{a}	69.92^{a}	56.67^{ab}	63.0^{ab}	34.51^{cd}	45.09^{bc}	5.4	<0.001
TDF	54.60^{abc}	40.15^{e}	46.89^{cde}	55.36^{ab}	59.52^{a}	54.04^{abc}	45.44^{de}	48.69^{bcd}	2.0	<0.001
Energy in diets, kcal/kg										
DE	3,261^{a}	2,911^{bc}	2,986^{bc}	3,050^{b}	3,039^{b}	3,032^{bc}	2,894^{c}	3,023^{bc}	39	<0.001
ME	3,163^{a}	2,763^{bc}	2,859^{bc}	2,913^{b}	2,903^{bc}	2,927^{b}	2,746^{c}	2,911^{bc}	46	<0.001

[a-d]Within a row, means without a common superscript differ ($P < 0.05$).
[1]Each least squares means represent 8 observations except for the diets containing the U.S. 2, Ukraine 1, and Hungry samples ($n = 7$).
[2]AEE, acid hydrolyzed ether extract; IDF, insoluble dietary fiber; SDF, soluble dietary fiber; TDF, total dietary fiber.

negative correlated ($P < 0.05$) with AEE and IDF ($P < 0.01$). The concentration of CP tended to be correlated ($P < 0.10$) positively with the ATTD of GE, and was also positively correlated ($P < 0.01$) with the ATTD of DM, and the ATTD of CP, but CP was negatively correlated ($P < 0.05$) with the ATTD of AEE. The AEE was positively correlated ($P < 0.05$) with the ATTD of AEE, but negatively correlated ($P < 0.05$) with ATTD of CP. Concentration of IDF was negatively correlated ($P < 0.05$) with the ATTD of DM and the ATTD of CP, but positively correlated with the ATTD of AEE. The concentration of SDF tended to be negatively correlated ($P < 0.10$) with DE and ME, and a tendency ($P < 0.10$) for a negative correlation between TDF and the ATTD of GE and the ATTD of DM was observed. Concentrations of DE and ME were positively correlated ($P < 0.01$) and had a positive correlation ($P < 0.05$) with the ATTD of GE. The ATTD of GE was positively correlated ($P < 0.01$) with the ATTD of DM and the ATTD of CP, but the ATTD of AEE had a tendency for a negative correlation ($P < 0.10$) with the ATTD of DM and the ATTD of CP ($P < 0.05$).

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Table 4. Apparent total tract digestibility (ATTD) of nutrients and gross energy and concentrations of digestible energy (DE) and metabolizable energy (ME) in sunflower meal (SFM) and sunflower expellers (SFE)[1]

	SFM								SFM		SFE	SFM vs. SFE	
Item	U.S. 1	U.S. 1	Ukraine 1	Ukraine 2	Hungary	Italy	Mean	SD	SEM	*P*-value	U.S.	SEM	*P*-value
ATTD, %													
Dry matter	56.5^{d}	56.9^{cd}	63.5^{ab}	62.6^{abc}	65.1^{a}	58.6^{bcd}	60.51	3.7	1.75	<0.001	54.0	1.8	<0.001
Gross energy	56.1^{b}	59.7^{ab}	64.8^{a}	65.4^{a}	64.2^{a}	56.5^{b}	61.1	4.2	1.9	<0.001	55.3	1.9	0.002
Organic matter	58.0^{d}	59.5^{cd}	67.3^{ab}	65.8^{abc}	67.8^{a}	60.6^{bcd}	63.2	4.3	2.10	<0.001	55.3	2.1	<0.001
Crude protein	79.7^{abc}	78.8^{c}	82.2^{ab}	82.7^{a}	82.5^{a}	79.4^{bc}	80.9	1.6	2.0	0.018	76.6	2.0	0.002
AEE[2]	31.0^{b}	64.7^{a}	16.7^{b}	16.1^{b}	12.8^{b}	5.8^{b}	24.5	21.3	6.6	<0.001	74.9	6.2	<0.001
Ash	41.6^{ab}	51.6^{a}	39.3^{ab}	35.8^{b}	34.1^{b}	34.9^{b}	39.6	6.6	4.16	0.004	33.2	4.2	0.085
IDF[2]	28.3^{d}	34.8^{d}	50.5^{bc}	63.8^{a}	54.9^{ab}	40.9^{cd}	45.6	13.3	3.2	<0.001	44.2	3.5	0.724
SDF[2]	38.1^{b}	82.8^{a}	79.9^{a}	65.4^{a}	72.7^{a}	39.4^{b}	63.1	19.8	6.3	<0.001	51.3	6.4	0.057
TDF[2]	29.3^{b}	41.6^{b}	55.2^{a}	63.8^{a}	55.7^{a}	40.4^{b}	47.7	12.7	3.3	<0.001	45.0	3.4	0.445
Energy in ingredients, kcal/kg DM													
DE	$2,627^{b}$	$2,855^{ab}$	$3,020^{a}$	$2,995^{a}$	$2,926^{a}$	$2,621^{b}$	2,840	208	86.9	0.001	2,837	92	0.882
ME	$2,369^{b}$	$2,657^{ab}$	$2,768^{a}$	$2,773^{a}$	$2,772^{a}$	$2,370^{b}$	2,618	230	120.9	0.001	2,679	116	0.585

[a-c] Within a row, means without a common superscript differ ($P < 0.05$).
[1]Each least squares means represent 8 observations except for the U.S. 2, Ukraine 1, and Hungry samples (n = 7).
[2]AEE = acid hydrolyzed ether extract; IDF = insoluble dietary fiber; SDF = soluble dietary fiber; TDF = total dietary fiber.

Table 5. Correlation coefficients between the chemical compositions, concentration of digestible energy (DE) and metabolizable energy (ME) and apparent total tract digestibility (ATTD) of dry matter (DM) and nutrients in ingredients (n = 53)[1]

	Correlation coefficient											
Item	DM	CP	AEE	IDF	SDF	TDF	DE	ME	ATTD of GE	ATTD of DM	ATTD of AEE	ATTD of CP
GE	0.90***	−0.65	0.94***	0.37	0.05	0.29	−0.17	−0.05	−0.64	−0.72*	0.75*	−0.80**
DM	–	−0.38	0.73*	0.06	0.00	0.05	−0.26	−0.15	−0.58	−0.54	0.44	−0.59
CP	–	–	−0.76**	−0.90***	−0.26	−0.77**	0.36	0.19	0.69*	0.88***	−0.85**	0.88***
AEE	–	–	–	0.53	0.03	0.40	0.00	0.15	−0.51	−0.67	0.83**	−0.79**
IDF	–	–	–	–	0.41	0.91***	−0.41	−0.30	−0.62	−0.75**	0.70*	−0.79**
SDF	–	–	–	–	–	0.75*	−0.73*	−0.73*	−0.62	−0.44	−0.14	−0.44
TDF	–	–	–	–	–	–	−0.63	−0.55	−0.74*	−0.75*	0.45	−0.78**
DE	–	–	–	–	–	–	–	0.97***	0.77**	0.55	0.10	0.44
ME	–	–	–	–	–	–	–	–	0.85**	0.66	−0.02	0.55
ATTD of GE	–	–	–	–	–	–	–	–	–	0.93***	−0.49	0.89***
ATTD of DM	–	–	–	–	–	–	–	–	–	–	−0.74*	0.96***
ATTD of AEE	–	–	–	–	–	–	–	–	–	–	–	−0.79**

*$P < 0.10$; ** $P < 0.05$; *** $P < 0.01$.
[1]AEE, acid hydrolyzed ether extract; IDF, insoluble dietary fiber; GE, gross energy; SDF,soluble dietary fiber; TDF, total dietary fiber.

Discussion

Approximately 51.30 million metric tons of sunflower seeds were produced worldwide in 2022, and after soybeans and rapeseeds, sunflower seed was the third-most-produced oilseed (USDA, 2022). Sunflower seeds contain more oil (40%-45%) than other oilseeds, but the fiber concentration is also greater due to the hulls that are between 20% and 30% of the total weight of the seeds (Le Clef and Kemper, 2015). Before oil extraction, sunflower seeds are decorticated (i.e., dehulled), and expeller pressed for oil extraction, but a solvent extraction procedure follows the initial oil expelling to maximize oil extracted from the seed (Feedipedia, 2020). However in some crushing plants, the first expeller-press of oil is followed by a second press to avoid the use of a solvent, which results in production of SFE that contain more residual oil than SFM produced after the solvent extraction procedure. Some of the sunflower hulls from the decortication process may be added to the final SFM, which results in variation in the concentration of fiber in the final product (Rodríguez et al., 2013). The major producers of SFM, which are Ukraine, Russia, and the European Union, along with the United States and Argentina, generate approximately 21 million metric tons of sunflower coproducts annually (USDA, 2022).

Concentrations of GE in SFM and SFE were in agreement with reported values from the United States (NRC, 2012; Rodríguez et al., 2013), but lower compared with samples from China (Liu et al., 2015). This is likely a result of the fact that the concentration of AEE in SFM used in this experiment was less compared with the SFM used by Liu et al. (2015), but values for AEE in SFM were within the range of values reported by González-Vega and Stein (2012) and Almeida et al. (2014) with the exception that one of the SFM from the

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United States contained more AEE (3.11%) than the previously used samples. The concentration of AEE in SFE was also within the range of reported values (Pedroche, 2015).

Concentrations of AEE in SFE are greater than values in SFM because oil extraction via a mechanical press procedure is less complete than extraction with a solvent, and the greater GE that was analyzed in SFE than in SFM is the result of the greater oil content because oil has a greater energy concentration than other nutrients (Rodriguez et al., 2020a). The variation in the concentration of TDF among the different samples of SFM indicate that different quantities of hulls where added to the meals and the negative correlation between TDF and the ATTD of GE indicates that increased hulls in the final meal negatively impacts ATTD of GE and ME in the final product as would be expected. High IDF in ingredients results in a lower ATTD of GE because the rate of passage of digesta increases with increased IDF, and therefore reduces the time for fermentation (Navarro et al., 2018; Liu et al., 2021). However, values for the ATTD of GE in SFM and SFE were within the range of values reported (Sauvant et al., 2004; Liu, et al., 2015; Li et al., 2018).

There is limited information about the ATTD of AEE in SFM, but the ATTD of AEE increases as the concentration of fat increases due to the reduced contributions of endogenous fat to the total output of fat as dietary fat increases (Kil et al., 2010). This is probably the reason one of the SFM samples from the United States and the SFE, which contained more AEE than the other samples, had greater ATTD of AEE compared with the other SFM samples. Intact fat in grains and oilseeds also have a lower ATTD of fat than extracted oils (Adams and Jensen, 1984; Kim et al., 2013), which may also have contributed to the low ATTD of AEE that was observed.

Concentrations of calculated ME in the basal diet and the diets containing SFM or SFE were 3,303 and 2,995 kcal/kg, respectively (NRC, 2012). Because daily feed allowance was determined based on the calculated ME in diets, pigs fed the corn diet were provided less kg of feed per day compared with diets containing SFE or SFM, which resulted in reduced feed intake in pigs fed the corn diet. Values for the ATTD of GE and CP of corn used in the corn diet were within the range of values previously reported (NRC, 2012; Rodriguez et al., 2020b; Trindade Neto et al., 2020; Ma et al., 2021). Concentrations of DE and ME in corn were less than reported values (NRC, 2012; Trindade Neto et al., 2020) because of the lower GE in the corn used in this experiment compared with corn used in other experiments. Nevertheless, DE and ME in corn were greater than DE and ME in SFM or SFE, which is likely a result of the starch and reduced fiber in corn compared with SFM or SFE (Le Gall et al., 2009).

The negative correlation between the concentration of TDF and ATTD of CP indicates that fiber in the diet may limit the digestibility of CP in pigs, which has also been reported for other ingredients (Wilfart et al., 2007; Le Gall et al., 2009). This may be a result of transfer of N from the blood to the hindgut resulting in increasing usage of N for bacterial metabolism and growth and subsequent excretion in feces, as well as a reduction in N excretion in urine from pigs fed higher fiber diets (Zervas and Ziljlstra, 2002; Navarro et al., 2018). The negative correlation between TDF and the ATTD of DM is the result of more excretion of fiber by the pigs when fed diets with high content of fiber than diets with lower content of fiber. The observation that there was no negative correlation between IDF and ATTD of GE or DE and ME, may be a result of some of the IDF being fermented in the hind gut with a subsequent contribution of energy in the form of short chained fatty acids (Nelson and Cox, 2008; Jaworski and Stein, 2017). The variation in DE and ME among samples of SFM demonstrates that differences in the production area and (or) processing procedures impact the energy value of final ingredients. The large variations in TDF concentrations among the 6 samples of SFM indicates that different quantities of hulls were added to the meals which also impacted DE and ME of the ingredients.

Conclusions

Sunflower meal from Ukraine and Hungary had greater ATTD of GE and greater DE and ME compared with SFM from Italy and the United States. Although SFE contained more AEE than SFM this did not affect DE and ME between SFE or SFM. The reason for this was that SFE contained more TDF than SFM, which negated the positive effect of AEE on DE and ME.

Conflict of Interest Statement

The authors declare no real or perceived conflicts of interest.

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