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Non Ruminant Nutrition

Effects of dietary spray-dried plasma protein on nutrient digestibility and growth performance in nursery pigs

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Abstract

The objectives were to determine the digestible energy and standardized ileal digestibility of amino acids (AA; Exp. 1) and to determine growth performance (Exp. 2) of two sources of dietary spray-dried plasma protein (SDPP) in nursery pigs. In Exp. 1, twelve nursery barrows (9.8 ± 0.9 kg) were assigned to a quadruplicated 3 × 2 Latin square design with three diets and two periods. Each period consisted of 5 d of adaptation, 2 d of fecal sampling, and 2 d of ileal collection. A basal diet was composed of corn, soybean meal, whey, and sucrose as the sole energy and AA sources. Experimental diets were prepared by replacing 15% of the energy and AA sources in the basal diet with SDPP 1 (manufactured in the United States; 78.2% crude protein and 4,862 kcal gross energy/kg as-is) or SDPP 2 (manufactured in Korea; 74.3% crude protein and 4,636 kcal gross energy/kg as-is). Spray-dried plasma protein 1 had greater digestible energy ($P < 0.05$), but less ($P < 0.05$) standardized ileal digestibility of Lys, Met, Trp, and Thr compared with SDPP 2. In Exp. 2, eighty-four nursery pigs (7.9 ± 0.7 kg) were allotted to three dietary treatments in a randomized complete block design with seven replicate pens and four pigs per pen. Three corn–soybean meal–whey–based diets contained fish meal (6% and 3.5% for days 0 to 14 and 14 to 28, respectively), SDPP 1 (4.5% and 2.7%), or SDPP 2 (5.0% and 3.0%) to maintain same energy and nutrient concentrations. During days 0 to 14 and overall period, pigs fed the diets containing SDPP gained more weight ($P < 0.05$) than those fed the fish meal diet with no difference between two SDPP sources. In conclusion, SDPP 1 contains greater digestible energy but less AA digestibility compared with SDPP 2. Growth-promoting effects of both SDPP sources in nursery diets have been clearly demonstrated in this work.

Lay Summary

Dietary spray-dried plasma protein (SDPP) is widely used in nursery pig diet due to its high nutrient contents and growth-promoting effects. In the present work, two sources of SDPP were evaluated for energy and amino acid (AA) digestibility and growth performance in nursery pigs. The SDPP 1 produced in the United States contained 78.2% crude protein and 4,862 kcal gross energy/kg and SDPP 2 produced in Korea contained 74.3% crude protein and 4,636 kcal gross energy/kg. Spray-dried plasma protein 1 had a greater digestible energy concentration, but less AA digestibility compared with SDPP 2. Pigs fed the diets containing SDPP consumed more feed and grew faster than those fed the fish meal diet with no difference between the two sources of SDPP. Taken together, SDPP 1 contains greater digestible energy but less AA digestibility compared with SDPP 2. Growth-promoting effects of two sources of SDPP on nursery pigs are greater than fish meal with no difference between the two sources of SDPP.

Key words: digestibility, growth performance, pigs, spray-dried plasma protein

Abbreviations: AA, amino acid; ADFI, average daily feed intake; ADG, average daily gain; AID, apparent ileal digestibility; ATTD, apparent total tract digestibility; BEL, basal endogenous losses; BW, body weight; CBC, complete blood count; CP, crude protein; DE, digestible energy; DM, dry matter; GE, gross energy; G:F, gain to feed ratio; IgG, gamma immunoglobulin; IR, inclusion rate; ME, metabolizable energy; SBM, soybean meal; SDPP, spray-dried plasma protein; SID, standardized ileal digestibility

Introduction

An adequate provision of nutrients is critical for the health and maximal growth of nursery pigs (Torrallardona, 2009). Moreover, anorexia during the nursery period due to the post-weaning stress causes malnutrition, affects the integrity and functionality of the intestinal morphology (van Beers-Schreurs et al., 1998), and eventually deteriorates growth performance (Sève et al., 1985). To overcome the post-weaning anorexia, producers provide ingredients with high nutrient contents, high digestibility, and high palatability to weaned pigs (Dong and Pluske, 2007).

Dietary spray-dried plasma protein (SDPP) manufactured from porcine blood has been shown to improve growth performances of nursery pigs (Kats et al., 1994; Angulo and Cubiló, 1998; Bikker et al., 2004) coupled with high palatability (van Dijk et al., 2001; Bikker et al., 2004) and high digestible amino acid (AA) concentrations (Gottlob et al., 2006; Mateo and Stein, 2007; Almeida et al., 2013). Porcine SDPP contains gamma immunoglobulins (IgG) as the major type of antibody (Balan et al., 2021). Dietary SDPP has been shown to improve growth performance, immune status, and gut health in weaning pigs possibly due to IgG in SDPP (Coffey and Cromwell, 1995; Pierce et al., 2005; Moreto and Perez-Bosque, 2009).

Effects of dietary SDPP 1 (AP 920, American Protein Corporation Inc., Ankeny, IA) on growth performance and nutrient digestibility have been demonstrated in many experiments (Kats et al., 1994; Angulo and Cubiló, 1998; van Dijk et al., 2001; Gottlob et al., 2006; Mateo and Stein, 2007;

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Almeida et al., 2013); however, information of dietary SDPP 2 (NongHyup Feed Inc., LTD, Seoul, Korea) on nursery pigs is not available. Therefore, the objectives of the present work were to determine the digestible energy (DE), apparent ileal digestibility (AID) of AA, and standardized ileal digestibility (SID) of AA in two sources of SDPP (Exp. 1) and to investigate the effects of two SDPP sources on the growth performance and fecal score in nursery pigs (Exp. 2).

Materials and Methods

Protocols of animal experiments (KU20109 for Exp. 1, KU20044 for trial 1 in Exp. 2, and KU21053 for trial 2 in Exp. 2) were reviewed and approved by the Institutional Animal Care and Use Committee of Konkuk University. Two experiments were conducted in an environmentally controlled room at Konkuk University.

Experiment 1

Animals, diets, and experimental design

In Exp. 1, twelve barrows with an initial body weight (BW) of 9.8 ± 0.9 kg were housed individually in fully slatted pens (2.0 × 2.0 m). Room temperature was controlled and each pen had a feeder and a nipple drinker. Pigs were surgically fitted with T-cannula at the distal ileum as described by Stein et al. (1998). Pigs were allowed to recover from surgery for 10 d prior to feeding experimental diets. After recovery from the surgery, the pigs were allotted to three diets in a quadruplicated 3 × 2 Latin square design with three diets and two periods (Kim and Kim, 2010). A basal diet was composed of corn, soybean meal (SBM), whey, and sucrose as the sole energy and AA sources. Experimental diets were prepared by replacing 15% of the energy and AA sources in the basal diet with SDPP 1 or SDPP 2 (Tables 1 and 2). The ratios of corn, SBM, whey, and sucrose among the experimental diets were kept constant. Chromic oxide was included in all diets at 0.5% as an indigestible index and all diets were prepared in a mash form.

Table 1. Analyzed chemical composition of fish meal and two sources of spray-dried plasma protein (SDPP; as-fed basis)[1]

Item, %	Fish meal	SDPP 1	SDPP 2
Dry matter	91.5	91.5	96.1
Gross energy, kcal/kg	4,808	4,862	4,636
Crude protein	70.3	78.2	74.3
Ether extract	8.6	0.3	0.5
Ash	12.2	7.5	13.5
Immunoglobulin G	–	21.5	10.2
Sodium	–	1.8	3.4
Chloride	–	1.6	3.0
Indispensable amino acids			
Arg	–	4.6	4.5
His	–	2.4	2.3
Ile	–	2.6	2.6
Leu	–	7.5	7.3
Lys	–	6.7	6.5
Met	–	0.4	0.5
Phe	–	4.4	4.1
Thr	–	4.5	4.2
Trp	–	1.0	1.0
Val	–	4.8	4.6
Dispensable amino acids			
Ala	–	4.3	4.2
Asp	–	7.3	7.2
Cys	–	2.5	3.0
Glu	–	10.9	10.5
Gly	–	2.7	2.9
Pro	–	4.4	4.1
Ser	–	4.4	4.3
Tyr	–	3.5	3.4

[1]Fish meal was sourced from Vedde Herring Oil Factory (Egersund, Norway); SDPP 1 was sourced from APC Inc. (Ankeny, IA); and SDPP 2 was sourced from NongHyup Feed Inc., LTD. (Seoul, Korea).

Feeding and sample collection

The quantity of feed provided daily per pig was calculated as 3.0 times the estimated energy requirement for maintenance (i.e., 197 kcal of metabolizable energy [ME] per kg $BW^{0.60}$; NRC, 2012) and was provided to pigs as 2 equal meals at 0800 and 1700 h. Pigs had free access to water. Each period consisted of 5 d of adaptation, 2 d of fecal sampling, and 2 d of ileal digesta collection. On days 6 and 7 of each experimental period, feces were collected using the grab sampling procedure (Choi and Kim, 2019). On days 8 and 9, a plastic bag with wire (Whirl-Pak bag, NASCO, Fort Atkinson, WI) was fixed to the T-cannula for the ileal digesta collection from 0830 to 1700 h. A sample bag was changed whenever the bag was filled with ileal digesta or every 30 min to prevent microbial fermentation. The collected feces and ileal digesta samples were immediately frozen at −20 °C.

Chemical analyses

Ileal digesta were lyophilized and fecal digesta were dried in a forced-air drying oven at 55 °C until constant weight. Ingredients, diets, dried ileal digesta, and dried fecal samples were finely ground for chemical analysis (< 1 mm). Dry matter (DM; 2 h at 135 °C; method 930.15), ash [method 942.05; AOAC (2007)], and gross energy (GE; Parr 6200, Parr Instruments Co., Moline, IL) in ingredients, diets, and feces were determined. Ingredients and diets were analyzed for ether extract (method 920.39; AOAC, 2007). Diets, ileal digesta, and fecal samples were analyzed for chromium (method 990.03; AOAC, 2007). Ingredients, diets, and ileal digesta were analyzed for crude protein (CP; method 990.03; AOAC, 2007) and AA concentrations using ion-exchange chromatography with post-column derivatization with ninhydrin. Samples were hydrolyzed with 6 *N* HCl for 24 h at 110 °C (method 982.30 E; AOAC, 2007). Methionine and Cys were analyzed as Met sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis. Tryptophan was determined after NaOH hydrolysis for 22 h at 110 °C. The IgG concentrations in SDPP 1 and 2 were quantified by the method described by Rodriguez et al. (2007). Each SDPP source was mixed with phosphate buffer saline (pH 7.4) at the ratio of 1:4 (w/w) and stirred for 30 min at 20 °C. After stirring, a homogeneous solution was obtained using a homogenizer (Ultra-Turrax T25, IKA Works Inc., Wilmington, NC) and centrifuged at 17,500 ×

Table 2. Ingredient and chemical composition of experimental diets in Exp. 1 (as-fed basis)[1]

Item, %	Basal diet	Spray-dried plasma protein 1	Spray-dried plasma protein 2
Ingredient composition			
Ground corn	46.87	39.69	39.89
Soybean meal, 48% crude protein	20.00	16.94	17.02
Whey powder	20.00	16.94	17.02
Sucrose	10.00	8.47	8.51
Spray-dried plasma protein 1	–	15.00	–
Spray-dried plasma protein 2	–	–	15.00
Limestone	0.88	1.36	1.36
Dicalcium phosphate	1.10	0.45	0.45
Sodium chloride	0.40	0.40	–
Chromic oxide	0.50	0.50	0.50
Vitamin-mineral premix[2]	0.25	0.25	0.25
Analyzed composition			
Dry matter	89.5	89.7	90.6
Gross energy, kcal/kg	3,807	3,930	3,911
Crude protein	14.8	25.3	24.1
Ether extract	2.1	2.0	1.8
Ash	6.7	6.6	7.0
Indispensable amino acids			
Arg	0.81	1.45	1.37
His	0.36	0.69	0.66
Ile	0.62	0.97	0.92
Leu	1.26	2.28	2.20
Lys	0.87	1.80	1.74
Met	0.22	0.25	0.25
Phe	0.68	1.27	1.23
Thr	0.66	1.24	1.23
Trp	0.18	0.28	0.31
Val	0.70	1.33	1.30
Dispensable amino acids			
Ala	0.77	1.35	1.30
Asp	1.50	2.50	2.36
Cys	0.33	0.74	0.65
Glu	2.63	4.04	3.86
Gly	0.57	0.97	0.89
Pro	0.88	1.42	1.40
Ser	0.75	1.35	1.29
Tyr	0.33	0.82	0.80
Calculated composition			
Crude protein[3]	–	24.4	23.8
Gross energy, kcal/kg[3]	–	3,953	3,935
Digestible energy, kcal/kg[4]	3,425	3,583	3,555

[1]Spray-dried plasma protein 1 was sourced from APC Inc. (Ankeny, IA); spray-dried plasma protein 2 was sourced from NongHyup Feed Inc., LTD. (Seoul, Korea).
[2]The vitamin-mineral premix provided the following quantities per kilogram of complete diet: vitamin A as retinyl acetate, 20,000 IU; vitamin D_3 as cholecalciferol, 3,000 IU; vitamin E as $_{DL}$-α-tocopheryl acetate, 100 IU; vitamin K as menadione nicotinamide bisulfite, 2.5 mg; thiamine as thiamine mononitrate, 5.0 mg; riboflavin, 7.5 mg; pyridoxine as pyridoxine hydrochloride, 3.5 mg; vitamin B_{12}, 0.03 mg; $_{D}$-pantothenic acid as $_{D}$-calcium pantothenate, 22.5 mg; niacin as nicotinamide, 1.0 mg; nicotinic acid, 27.5 mg; folic acid, 0.5 mg; biotin, 0.5 mg; vitamin C as $_{L}$-ascorbic acid, 100 mg; Co as cobalt sulfate, 5 μg; Cu as copper sulfate, 11 mg; Fe as iron sulfate, 69 mg; I as calcium iodate, 0.97 mg; Mn as manganese sulfate, 11 mg; Se as selenium yeast, 0.17 mg; and Zn as zinc oxide, 30 mg.
[3]Calculated crude protein and gross energy concentrations were based on the analyzed crude protein and gross energy concentrations and the inclusion rate of a basal diet and a test ingredient.
[4]Digestible energy was calculated based on inclusion rate of each ingredient and their digestible energy concentrations presented in NRC (2012).

g for 30 min at 4 °C. After centrifugation, the supernatant was recovered, weighed, and frozen at −20 °C until analysis. The supernatant was analyzed for IgG using an ELISA kit (Immunology Consultants Laboratory Inc., Portland, OR) following the manufacturer instruction.

Calculations and statistical analyses

The apparent total tract digestibility (ATTD) of GE and nutrients, and AID of CP and AA were calculated using the index method (Kong and Adeola, 2014):

$$\text{Apparent digestibility (\%)} = 100 \times [1 - (CI_{out}/CI_{in}) \times (CC_{in}/CC_{out})],$$

where CI_{out} and CI_{in} represent the concentration of the component of interest (kcal/kg or g/kg) in fecal or ileal digesta and experimental diets, respectively; CC_{in} and CC_{out} represent the concentration of Cr (g/kg) in experimental diets and fecal or ileal digesta, respectively. To calculate SID of CP and AA in diets, AID of CP and AA were corrected for the basal endogenous losses (BEL) of CP and AA (Lee et al., 2020):

$$\text{SID (\%)} = \text{AID} + 100 \times (\text{BEL}/\ CI_{in}),$$

where BEL of CP and AA values (g/kg feed intake) were from Sung et al. (2020) who determined BEL in nursery pigs.

The GE, CP, and AA concentrations of corn–SBM–whey–sucrose in the basal diet were calculated by dividing the analyzed concentrations of GE, CP, and AA in the basal diet by the inclusion rate (IR) of corn–SBM–whey–sucrose (i.e., 0.969). The DE and digestible nutrient (i.e., apparent and standardized ileal digestible AA) concentrations of energy- and AA-containing ingredients in the basal diet were calculated by dividing the concentration of CI_{in} in the basal diet by the IR of corn–SBM–whey–sucrose (i.e., 0.969). The DE and digestible nutrient concentrations in the 2 SDPP sources were calculated using the following equation for the difference procedure (Kong and Adeola, 2014):

DE and digestible nutrient concentrations in SDPP (kcal/kg or g/kg) = [CI_{in} in SDPP diet – (CI_{in} in corn-SBM-whey-sucrose × IR of corn-SBM-whey-sucrose)] / IR of SDPP.

The ME concentrations in two sources of SDPP were calculated using the following equation (Sung and Kim, 2021):

$$\text{ME (kcal/kg DM)} = 0.97 \times \text{DE (kcal/kg DM)} - 0.386 \times \text{CP (g/kg DM)},$$ with root mean square of error = 120 and $R^2 = 1.00$.

Data were analyzed using the MIXED procedure of SAS (SAS Inst. Inc., Cary, NC). For the comparison of digestibility among experimental diets, dietary treatment was considered as a fixed variable while replication, period within replication, and animal within replication were considered as random variables. For the comparison of digestibility between two SDPP sources, dietary treatments were considered as a fixed variable while period was considered as a random variable. The least squares means for each treatment were calculated, and differences among least squares means were tested using the PDIFF option with Tukey's adjustment. An experimental unit was a pig and an alpha level of 0.05 was used to determine significance.

Experiment 2

Animals, diets, and experimental design

In Exp. 2, twenty-four gilts and 24 barrows (8.3 ± 0.6 kg) were weaned at day 28 of age and allotted to three dietary treatments in a randomized complete block design using the BW as a blocking factor with four replicate pens per treatment and two gilts and two barrows per pen (trial 1). Three corn–SBM–whey–based experimental diets were formulated to contain fish meal (Herring meal; Norse LT-94, Vedde Herring Oil Factory, Egersund, Norway), SDPP 1, or SDPP 2 with constant ME and digestible nutrient concentrations in all diets (Table 3). Energy and nutrient concentrations in all diets met or exceeded requirement estimates suggested by NRC (2012). Room temperature was controlled and each pen had a feeder and a nipple drinker. All diets were prepared in a mash form. Three additional replications for each diet were obtained in trial 2 employing 36 barrows (7.5 ± 0.6 kg) fed the same experimental diets and housed in the same room as in trial 1. The experimental design used in trial 2 was a randomized complete block design using the BW as a blocking factor with three replicate pens per treatment and four barrows per pen.

Feeding, fecal scoring, and sample collection

Pigs were allowed ad libitum access to feed and water. Individual pigs were weighed on days 0, 14, and 28. The amount of feed offered was recorded daily and the amount of feed left in the feeders was recorded on days 14 and 28. The fecal score was recorded to categorize the piglet fecal consistency using the following 5-grade score categories by visually assessing feces in nursery pens: 1 = watery, liquid stool that can be poured; 2 = soft, unformed stool that assumes the shape of the container; 3 = soft, formed, and moist stool that retains its shape; 4 = hard, formed stool that remains firm and soft; and 5 = hard, dry pellets in a small, hard mass. Fecal scores were recorded daily by two individuals. Blood samples were obtained from the jugular vein of all pigs on days 14 and 28 in trial 1 using serum separate tubes (serum, No. 367955; Becton Dickinson, Franklin Lakes, NJ) for IgG assays and ethylene diamine tetra-acetic acid tubes (plasma, No. 367844) for complete blood count (CBC) assays and were kept at 4 °C before analysis. On day 28 of trial 1, one barrow and two gilts per pen were euthanized to measure organ weight and small intestine length. A mid-jejunum sample was collected from each small intestine and promptly fixed with 10% neutral buffered formalin for histological analysis.

Chemical and histological analyses

Diets were analyzed for DM (2 h at 135 °C; method 930.15), ash (method 942.05), ether extract (method 920.39), CP (method 990.03; AOAC, 2007), and GE (Parr 6200, Parr Instruments Co., Moline, IL). The CBC analysis was performed immediately after collecting blood using the HM2 (VetScan HM2 Hematology System, Abaxis, Union City, CA). Blood samples collected in serum separate tubes were centrifuged (10 min, 1,157 × *g*, and 4 °C). After centrifugation, the supernatant was recovered and frozen at −20 °C until analysis. The IgG concentration in supernatant was determined using IgG ELISA kit (Immunology Consultants Laboratory Inc., OR) following manufacturer instructions. The fixed jejunal samples were dehydrated in ethanol, cleared in xylene, and embedded in paraffin. The samples were sectioned at a

Table 3. Ingredient and chemical composition of experimental diets in Exp. 2 (as-fed basis)[1]

Item[2], %	Phase 1, day 0 to 14			Phase 2, day 14 to 28		
	Fish meal	SDPP 1	SDPP 2	Fish meal	SDPP 1	SDPP 2
Ingredient, %						
Ground corn	46.98	47.63	47.33	59.22	59.46	59.36
Soybean meal, 48% CP	23.00	23.00	23.00	24.00	24.00	24.00
Whey powder	20.00	20.00	20.00	10.00	10.00	10.00
Fish meal	6.00	–	–	3.50	–	–
SDPP 1	–	4.50	–	–	2.70	–
SDPP 2	–	–	5.00	–	–	3.00
Soybean oil	2.00	2.00	2.00	1.00	1.00	1.00
Limestone	0.85	1.20	1.20	0.80	0.98	0.98
Dicalcium phosphate	0.10	0.60	0.60	0.35	0.70	0.70
$_{L}$-Lys·HCl,78.8%	0.32	0.28	0.28	0.36	0.33	0.33
$_{DL}$-Met, 99.0%	0.13	0.11	0.11	0.12	0.11	0.11
$_{L}$-Thr, 98.5%	0.07	0.03	0.03	0.10	0.07	0.07
Sodium chloride	0.30	0.40	0.20	0.30	0.40	0.20
Vitamin-mineral premix[3]	0.25	0.25	0.25	0.25	0.25	0.25
Analyzed composition, %						
Dry matter	89.1	88.9	89.4	88.5	88.8	88.4
Gross energy, kcal/kg	4,031	3,974	3,971	3,998	3,936	3,942
CP	21.4	20.5	20.5	20.3	19.1	18.5
Ether extract	4.7	4.2	5.0	4.6	4.6	4.8
Ash	5.8	6.0	6.1	5.0	5.8	5.3

[1]Fish meal was sourced from Vedde Herring Oil Factory (Egersund, Norway); spray-dried plasma protein (SDPP) 1 was sourced from APC Inc. (Ankeny, IA); and SDPP 2 was sourced from NongHyup Feed Inc., LTD. (Seoul, Korea).
[2]CP, crude protein.
[3]The vitamin-mineral premix provided the following quantities per kilogram of complete diet: vitamin A as retinyl acetate, 20,000 IU; vitamin D_3 as cholecalciferol, 3,000 IU; vitamin E as $_{DL}$-α-tocopheryl acetate, 100 IU; vitamin K as menadione nicotinamide bisulfite, 2.5 mg; thiamine as thiamine mononitrate, 5.0 mg; riboflavin, 7.5 mg; pyridoxine as pyridoxine hydrochloride, 3.5 mg; vitamin B_{12}, 0.03 mg; $_{D}$-pantothenic acid as $_{D}$-calcium pantothenate, 22.5 mg; niacin as nicotinamide, 1.0 mg; nicotinic acid, 27.5 mg; folic acid, 0.5 mg; biotin, 0.5 mg; vitamin C as $_{L}$-ascorbic acid, 100 mg; Co as cobalt sulfate, 5 µg; Cu as copper sulfate, 11 mg; Fe as iron sulfate, 69 mg; I as calcium iodate, 0.97 mg; Mn as manganese sulfate, 11 mg; Se as selenium yeast, 0.17 mg; and Zn as zinc oxide, 30 mg.

5 µm thickness, installed on glass slides, and stained with hematoxylin-eosin solution. The structure of mucosa was observed at 4 × magnification using an Olympus BX 43 digital microscope (Olympus, Tokyo, Japan) and photographed using a digital camera (eXcope T500, Olympus, Tokyo, Japan). In each jejunal sample, 3 villus height and crypt depth were measured for each well-oriented and intact intestinal cross section, and the means of these measurements were used for statistical analysis.

Calculations and statistical analyses

Average daily gain (ADG), average daily feed intake (ADFI), and gain to feed ratio (G:F) were calculated for each pen. Individual feed intake of animals excluded from trials 1 and 2 was estimated using the procedure suggested by Lindemann and Kim (2007) and corrected pen feed intake was used for further statistical analysis.

Normality of residuals was verified using the UNIVARIATE procedure of SAS (SAS Inst. Inc., Cary, NC) and homogeneity was also confirmed. Data were analyzed using MIXED procedures of SAS (SAS Inst. Inc., Cary, NC). For the growth performances and fecal score, two trials employing the same dietary treatment were pooled for statistical analysis. The statistical model for growth performances included dietary treatment as fixed effect and trials and blocks within trial as random effects. Additionally, fecal score data were analyzed using the repeated measures analysis procedure over time (Littell et al., 1998). Dietary treatments, days, and their interactions were included in the statistical model as fixed effects. The autoregressive covariance structure was selected based on a better Bayesian information criterion relative to the compound symmetry or unstructured covariance matrix (56.0 for autoregressive vs. 58.2 and 64.3 for compound symmetry and unstructured, respectively). The statistical model for blood parameters, organ weight, and intestinal morphology for trial 1 included diet as a fixed effect and block as a random effect. The least squares means were separated using the PDIFF option with Tukey's adjustment. The experimental unit was a pen and an alpha level of 0.05 was used to determine statistical significance.

Results

Experiment 1

Digestible energy (as-fed basis) and ATTD of DM, organic matter, and GE in SDPP 1 and SDPP 2 diets were greater ($P < 0.01$) than those in the basal diet with no difference between two sources of SDPP (Table 4). The pigs fed the SDPP 2 diet had greater ($P < 0.05$) AID and SID of CP and all indispensable AA compared with those fed the SDPP 1 diet (Table 5). Based on the calculation of DE concentration and ileal AA

Table 4. Apparent total tract digestibility (ATTD) of nutrients and energy and concentration of digestible energy (DE) in experimental diets (Exp. 1)[1]

Item	Diet[2]			SEM	*P*-value
	Basal	SDPP 1	SDPP 2		
ATTD, %					
Dry matter	91.1[b]	92.8[a]	92.5[a]	0.3	0.005
Organic matter	92.4[b]	94.1[a]	93.8[a]	0.3	0.004
Gross energy	90.4[b]	92.5[a]	92.0[a]	0.4	0.004
Ash	74.5	76.5	76.5	1.0	0.187
DE, kcal/kg (as-fed basis)	3,441[b]	3,635[a]	3,597[a]	16	<0.001
DE, kcal/kg (dry matter basis)	3,843[c]	4,053[a]	3,970[b]	18	<0.001

[1]Data are least squares means of 8 observations except for the spray-dried plasma protein (SDPP) 1 diet (7 observations).
[2]Spray-dried plasma protein 1 was sourced from APC Inc. (Ankeny, IA); SDPP 2 was sourced from NongHyup Feed Inc., LTD. (Seoul, Korea).
[a–c]Within a row, means without a common superscript letter differ ($P < 0.05$).

digestibility values in the ingredients using the difference procedure, DE concentration in SDPP 1 were greater ($P < 0.05$) than in SDPP 2 (Table 6) and ileal digestibility values of CP and indispensable AA in SDPP 2 were greater ($P < 0.05$) than in SDPP 1 (Table 7).

Experiment 2

Two pigs fed the fish meal diet in trial 1 and two pigs fed the SDPP 1 diet in trial 2 were removed from the pen due to lameness and edema. During days 0 to 14 and the overall period, pigs fed the diets containing SDPP gained more weight ($P < 0.05$) than those fed the fish meal diet with no difference between the two sources of SDPP (Table 8). During days 0 to 14, pigs fed the SDPP 1 diets consumed more feed ($P < 0.05$) than those fed the fish meal diet with no difference between the two sources of SDPP. The fecal score was improved as the experimental days passed (Table 9). The pigs fed the SDPP 2 diet had greater ($P < 0.05$) fecal scores than those fed the SDPP 1 diet. Complete blood cell count traits were not different among the experimental diets on day 14 (Table 10); however, white blood cell concentrations in pigs fed the fish meal and SDPP 1 diets were greater ($P < 0.05$) than in pigs fed the SDPP 2 diet on day 28 (Table 11). Organ weight, small intestine length, and jejunal morphology were not different among the dietary treatments (Tables 12 and 13).

Discussion

Porcine blood is produced at the abattoir during the exsanguination process and is an inevitable by-product of the livestock industry representing approximately 4% of the live animal weight (Bah et al., 2013). The amount of porcine blood produced annually has increased in parallel with increasing number of slaughtered pigs (Woonwong et al., 2020). Porcine blood is often disposed of as waste; therefore, a considerable amount of wasted porcine blood needs to be treated for disposal on land that requires separate purification treatment facilities (Jeon et al., 2016). Thus, porcine blood recycling as animal feeds is important for sustainable swine production.

The first step of SDPP production is the separation of porcine blood into the plasma and the cellular fraction, which is comprised of approximately 56% and 44%, respectively, by centrifugation (Gatnau, 1990; Torrallardona, 2009). Anticoagulants used in this procedure include sodium citrate, sodium phosphate, sodium pyrophosphate, and ammonium oxalate (Gatnau, 1990; Blázquez et al., 2020). The cellular fraction is not used for the SDPP production as due to the unpleasant flavors (Lynch et al., 2017) and the intense red color (Gatnau, 1990). Porcine plasma is mainly composed of water, minerals, and protein, which is mainly composed of globulins and albumins (Torrallardona, 2009). Plasma is then concentrated by filtration or vacuum evaporation with inverse osmotic membranes, ultrafiltration, or vacuum drying and stored at –4 °C until spray-drying (Torrallardona, 2009; Blázquez et al., 2020).

The spray-drying process transforms a liquid plasma into a dried powder produced by the atomization of liquid using a rotating wheel or a nozzle in the drying chamber (Blázquez et al., 2020). Atomized plasma droplets immediately contact with hot and dried air. Porcine plasma is exposed to drying times that range from 0.5 to 240 min under temperatures varying from 92 to 500 °C (Moughan and Schuttert, 1991). In this process, rapid evaporations are generated in the chamber that minimally influences the protein quality of SDPP. This is the major advantage of the spray-drying process coupled with a high tonnage production with relatively simple equipment (Gatnau, 1990). Residual moisture, finally, is removed by heating for 1 to 2 min at 93 °C.

The analyzed composition of fish meal and SDPP 1 in the present work was comparable to the values in the literature (Refstie et al., 2006; NRC, 2012; Zhang et al., 2019). The GE, CP, and most AA concentrations in SDPP 1 were greater than that in the SDPP 2 likely due to the lower ash and salt concentrations in SDPP 1 compared with SDPP 2 (Torrallardona, 2009). The protein content in plasma ranges between 70% and 80% depending on the production processes. Gatnau (1990) suggested that salt concentrations vary depending on the plasma concentration procedure used before drying and on the anticoagulant used. Plasma sources concentrated by ultrafiltration have a higher protein concentration than those concentrated by reverse osmosis or vacuum drying (Delaney, 1975). Also, SDPP sources concentrated by vacuum drying or reverse osmosis have a greater salt concentration compared with the SDPP sources concentrated by ultrafiltration (Torrallardona, 2009). Additionally, the salt concentration in the SDPP anticoagulated using sodium citrate has been reported to be greater compared with the SDPP anticoagulated using sodium phosphate (Torrallardona, 2009).

The IgG has been suggested to be one of the major bioactive compounds in SDPP (Coffey and Cromwell, 1995; Pierce et al., 2005; Moreto and Perez-Bosque, 2009). The

Table 5. Apparent ileal digestibility (AID) and standardized ileal digestibility (SID) of crude protein and amino acids (AA) in experimental diets (Exp. 1)[1],[2]

Item, %	AID			SEM	*P*-value	SID[3]			SEM	*P*-value
	Basal	SDPP 1	SDPP 2			Basal	SDPP 1	SDPP 2		
Crude protein	81.8[b]	83.5[b]	86.2[a]	3.3	0.028	94.8[a]	91.1[b]	94.3[a]	3.3	0.017
Indispensable AA										
Arg	91.5[b]	91.2[b]	94.6[a]	1.5	0.006	99.2[a]	95.8[b]	98.9[a]	1.5	0.003
His	87.9[b]	88.5[b]	92.2[a]	2.1	0.002	94.7[a]	92.1[b]	95.7[a]	2.1	0.002
Ile	88.6[b]	87.4[b]	91.6[a]	2.2	0.001	95.0[a]	91.7[b]	95.7[a]	2.2	0.001
Leu	89.9[b]	89.1[b]	93.2[a]	1.9	0.001	95.2[a]	92.2[b]	96.2[a]	1.9	0.001
Lys	87.2[b]	88.1[b]	91.5[a]	2.3	0.006	94.8[a]	91.8[b]	95.2[a]	2.3	0.006
Met	91.5[a]	89.0[b]	90.9[a]	2.0	0.018	97.1[a]	94.0[b]	95.9[a]	2.0	0.007
Phe	88.5[b]	88.7[b]	92.7[a]	2.1	0.002	94.8[a]	92.2[b]	96.1[a]	2.1	0.001
Thr	83.2[b]	83.6[b]	88.7[a]	3.1	0.004	95.6[a]	90.3[b]	95.4[a]	3.1	0.002
Trp	88.0[b]	85.5[c]	90.7[a]	2.7	0.002	97.0[a]	90.8[b]	96.6[a]	2.7	0.001
Val	87.2[b]	86.9[b]	91.7[a]	2.4	0.002	95.8[a]	91.5[b]	96.2[a]	2.4	0.001
Dispensable AA										
Ala	84.0[b]	84.3[b]	88.9[a]	3.0	0.004	94.0[a]	90.3[b]	94.7[a]	3.0	0.002
Asp	85.8[b]	84.2[b]	88.7[a]	2.9	0.008	92.8[a]	88.7[b]	93.0[a]	2.9	0.004
Cys	81.1[a]	73.0[b]	81.9[a]	4.9	0.005	89.1[a]	77.1[b]	85.5[a]	4.9	0.002
Glu	88.3[a]	83.8[b]	86.9[ab]	3.1	0.040	93.7[a]	87.4[b]	90.4[ab]	3.1	0.013
Gly	72.3[b]	77.0[b]	84.2[a]	5.1	0.027	97.1	92.8	98.9	5.1	0.140
Pro	69.3	79.5	86.9	6.2	0.071	101.1	99.6	106.9	6.2	0.485
Ser	85.5[b]	84.5[b]	90.0[a]	2.8	0.004	96.3[a]	90.8[b]	96.1[a]	2.8	0.002
Tyr	89.1[b]	90.0[b]	94.7[a]	1.8	0.002	100.1[a]	94.5[b]	99.2[a]	1.8	0.001

[1]Data are least square means of 6, 8, and 7 observations for basal diet, spray-dried plasma protein (SDPP) 1 diet, and SDPP 2 diet, respectively.
[2]Spray-dried plasma protein 1 was sourced from APC Inc. (Ankeny, IA); SDPP 2 was sourced from NongHyup Feed Inc., LTD. (Seoul, Korea).
[3]Values for the SID of crude protein and AA were calculated by correcting the AID values for basal endogenous losses of crude protein and AA from Sung et al. (2020). Basal endogenous losses (g/kg feed intake) used for the calculation of SID values were crude protein, 19.90; Arg, 0.64; His, 0.25; Ile, 0.41; Leu, 0.70; Lys, 0.67; Met, 0.13; Phe, 0.44; Thr, 0.85; Trp, 0.17; Val, 0.62; Ala, 0.80; Asp, 1.09; Cys, 0.27; Glu, 1.46; Gly, 1.45; Pro, 2.88; Ser, 0.84; and Tyr, 0.37.
[a–c]Within a row, means without a common superscript letter differ ($P < 0.05$).

Table 6. Apparent total tract digestibility of gross energy, digestible energy, and metabolizable energy in test ingredients determined by difference procedure (Exp. 1)[1]

Item[2]	SDPP 1	SDPP 2	SEM	*P*-value
Apparent total tract digestibility of gross energy, %	98.7	96.4	2.2	0.478
Digestible energy, kcal/kg, as-is basis	4,799	4,469	105	0.046
Digestible energy, kcal/kg, dry matter basis	5,246	4,649	112	0.003
Metabolizable energy, kcal/kg, as-is basis[3]	4,353	4,048	102	0.055
Metabolizable energy, kcal/kg, dry matter basis	4,758	4,212	108	0.004

[1]Data are least square means of 7 observations for spray-dried plasma protein (SDPP) 1 and 8 observations for SDPP 2.
[2]Spray-dried plasma protein 1 was sourced from APC Inc. (Ankeny, IA); SDPP 2 was sourced from NongHyup Feed Inc., LTD. (Seoul, Korea).
[3]Metabolizable energy was calculated based on Sung and Kim (2021) using the following equation: metabolizable energy = 0.97 × digestible energy – 3.86 × crude protein with root mean square of error = 120 and R^2 = 1.00.

IgG concentration in SDPP 1 was similar to the previously reported values (van Dijk et al., 2002; Pierce et al., 2005; Niewold et al., 2007) and was greater than that in SDPP 2 (Table 1). In a spray-drying process, the removal of moisture from a liquid plasma involves simultaneous heat, pressure, and mass transfer (Handscomb et al., 2009). This condition may cause polymerization and denaturation of protein by Maillard reactions and oxidation, and eventually may decrease blood plasma solubility (Koca et al., 2015). Saguer et al. (2009) suggested that particularly globulin fractions in plasma protein are susceptible to pH changes. Moreover, blood mixing procedure may also affect IgG concentrations in SDPP (Polo et al., 2004). Therefore, different production processes for SDPP 1 and 2 are likely the major reason for the different IgG concentrations.

Experiment 1

In the present study, the GE, CP, and AA concentrations in the two SDPP diets were reasonably close between analyzed and calculated values, and the analyzed GE and nutrient concentrations were used for the digestibility calculations. Digestible energy concentrations in basal, SDPP 1, and SDPP

Table 7. Apparent ileal digestibility (AID) and standardized ileal digestibility (SID) of crude protein and amino acids (AA) in test ingredients determined by difference procedure (Exp. 1)[1]

Item, %[2]	AID		SEM	*P*-value	SID[3]		SEM	*P*-value
	SDPP 1	SDPP 2			SDPP 1	SDPP 2		
Crude protein	85.3	90.0	1.3	0.023	87.8	92.8	1.3	0.018
Indispensable AA								
Arg	91.0	97.1	1.0	0.001	92.4	98.6	1.0	0.001
His	88.9	94.5	1.0	0.002	89.9	95.7	1.0	0.002
Ile	85.8	94.2	1.4	<0.001	87.3	95.8	1.4	<0.001
Leu	88.4	95.4	1.1	<0.001	89.3	96.4	1.1	<0.001
Lys	88.8	93.7	0.9	0.002	89.8	94.8	0.9	0.002
Met	81.0	87.5	1.9	0.032	83.9	90.0	1.9	0.042
Phe	89.0	95.4	1.0	<0.001	90.0	96.5	1.0	<0.001
Thr	84.2	92.2	1.3	0.001	86.1	94.2	1.3	<0.001
Trp	83.3	91.6	1.7	0.005	84.9	93.3	1.7	0.004
Val	86.8	94.5	1.1	<0.001	88.1	95.9	1.1	<0.001
Dispensable AA								
Ala	84.8	92.2	1.4	0.003	86.6	94.2	1.4	0.002
Asp	82.2	89.9	1.7	0.006	83.7	91.4	1.7	0.006
Cys	66.9	81.1	2.7	0.003	68.0	82.1	2.7	0.003
Glu	77.3	83.5	2.3	0.075	78.6	84.9	2.3	0.070
Gly	82.5	95.9	3.1	0.010	87.8	101.0	3.1	0.010
Pro	91.5	105.7	5.9	0.114	98.0	113.0	5.9	0.098
Ser	83.8	93.3	1.5	<0.001	85.7	95.3	1.5	<0.001
Tyr	90.7	96.7	1.0	<0.001	91.8	97.9	1.0	<0.001

[1]Data are least square means of 8 observations for spray-dried plasma protein (SDPP) 1 and 7 observations for SDPP 2.
[2]Spray-dried plasma protein 1 was sourced from APC Inc. (Ankeny, IA); SDPP 2 was sourced from NongHyup Feed Inc., LTD. (Seoul, Korea).
[3]Values for the SID of crude protein and AA were calculated by correcting the AID values for basal endogenous losses of crude protein and AA from Sung et al. (2020). Basal endogenous losses (g/kg feed intake) used for the calculation of SID values were crude protein, 19.90; Arg, 0.64; His, 0.25; Ile, 0.41; Leu, 0.70; Lys, 0.67; Met, 0.13; Phe, 0.44; Thr, 0.85; Trp, 0.17; Val, 0.62; Ala, 0.80; Asp, 1.09; Cys, 0.27; Glu, 1.46; Gly, 1.45; Pro, 2.88; Ser, 0.84; and Tyr, 0.37.

2 diets were similar to the expected values calculated based on the values in NRC (2012). The greater DE concentrations in SDPP-containing diets compared with the basal diet were likely attributed to the high GE digestibility of SDPP coupled with a high GE concentration in SDPP. The DE concentration in SDPP 1 determined by difference procedure in growing pigs was reasonably close to the previously reported values (Gottlob et al., 2006; Wu et al., 2018). The greater DE concentration in SDPP 1 compared with SDPP 2 was mainly attributed to the greater GE concentration in SDPP 1 as ATTD of GE was similar between SDPP 1 and SDPP 2. In the present work, ME of two sources of SDPP were calculated using a prediction equation (Sung and Kim, 2021), and ME:DE is known to have a very strong negative correlation with CP concentrations. The deviation of ME values between SDPP 1 and SDPP 2 was less than the deviation of DE values likely due to the greater CP concentration in SDPP 1 compared with SDPP 2.

The SID of AA is practically the most accurate AA bioavailability measurement for swine feed formulations (Stein et al., 2005; Xue et al., 2014; Lee et al., 2017). The AID and SID of CP and AA in SDPP 1 were in good agreement with previously reported values (Kim et al., 2000; Gottlob et al., 2006; Mateo and Stein, 2007; Almeida et al., 2013; Jeong et al., 2016; Wu et al., 2018) except for the Cys, Gly, and Pro. The reason for the relatively low AID and SID of Cys in SDPP 1 may be the deviation between analyzed and calculated concentrations of Cys in the SDPP 1 diet. Calculated AA concentrations in the experimental diets were obtained using the analyzed AA concentrations in the ingredients and the IR. The relatively high AID and SID of Gly and Pro in the present work may be explained by the high variability in BEL of Gly and Pro (Moughan and Schuttert, 1991; Dilger et al., 2004; Lee et al., 2020; Sung et al., 2020).

The reason for greater AID and SID of CP and most AA in SDPP 2 than in SDPP 1 is unknown, although in different experiments, SID of CP and AA in SDPP had a large variability among experiments (Kim et al., 2000; Gottlob et al., 2006; Mateo and Stein, 2007; Almeida et al., 2013; Jeong et al., 2016; Wu et al., 2018). Different production procedures for SDPP may be involved in AA digestibility. Delaney (1975) suggested that pH during the concentration process and drying temperature for SDPP production are critical for AA digestibility. The factors affecting the different AA digestibility between two sources of SDPP were not only heating and pH under the processing but also the following factors: sources of blood, transportation and storage conditions, sources of anticoagulant, plasma ultrafiltration methods, and spray drying conditions such as inlet and outlet air temperature, speeds, and time (Delaney, 1975).

One of the limitations of the present work is the relatively low IR of SDPP in the experimental diets. In the preliminary

Table 8. Effects of dietary spray-dried plasma protein (SDPP) on growth performance in weaning pigs (Exp. 2)[1,2]

Item[3]	Diet[4]			SEM	*P*-value
	Fish meal	SDPP 1	SDPP 2		
Body weight, kg					
Day 0	7.95	7.91	7.90	0.37	0.324
Day 14	13.01[b]	13.77[a]	13.59[a]	0.45	0.005
Day 28	21.64	22.66	22.60	1.86	0.055
Days 0 to 14					
ADG, g/d	365[b]	423[a]	410[a]	58	0.004
ADFI, g/d	494[b]	573[a]	551[ab]	77	0.023
G:F	0.744	0.741	0.745	0.022	0.984
Days 14 to 28					
ADG, g/d	602	631	643	104	0.139
ADFI, g/d	950	1,011	1,017	192	0.320
G:F	0.637	0.634	0.639	0.021	0.961
Overall					
ADG, g/d	484[b]	527[a]	527[a]	81	0.021
ADFI, g/d	722	792	784	135	0.115
G:F	0.674	0.673	0.676	0.021	0.981

[1]A total of 84 weaned pigs were randomly allotted to three dietary treatments with two castrated and two female pigs per pen and four replicate pens per treatment in trial 1 and four castrated pigs per pen and three replicate pens per treatment in trial 2.
[2]Data are least squares means of 7 observations for all treatments.
[3]ADG, average daily gain; ADFI, average daily feed intake; and G:F, gain to feed ratio.
[4]Fish meal was sourced from Vedde Herring Oil Factory (Egersund, Norway); SDPP 1 was sourced from APC Inc. (Ankeny, IA); and SDPP 2 was sourced from NongHyup Feed Inc., LTD. (Seoul, Korea).
[a,b]Means within a row without a common superscript letter differ ($P < 0.05$).

Table 9. Effects of dietary spray-dried plasma protein (SDPP) on fecal score in weaning pigs (Exp. 2)[1]

Item	Diet[2]			Mean, Day	SEM	*P*-values for contrast		
	Fish meal	SDPP 1	SDPP 2			Diet	Day	Diet × Day
Days 0 to 7	2.29	2.07	2.52	2.29[d]	0.12	0.047	< 0.001	0.576
Days 7 to 14	2.51	2.45	2.80	2.59[c]				
Days 14 to 21	2.72	2.85	3.09	2.88[b]				
Days 21 to 28	3.13	3.02	3.25	3.13[a]				
Mean (Diet)	2.66[ab]	2.60[b]	2.91[a]					

[1]1, watery, liquid stool that can be poured; 2, soft, unformed stool that assumes the shape of the container; 3, soft, formed, and moist stool that retains its shape; 4, hard, formed stool that remains firm and soft; and 5, hard, dry pellets in a small, hard mass. Scores were recorded on a pen basis and each least squares mean represents 7 observations.
[2]Fish meal was sourced from Vedde Herring Oil Factory (Egersund, Norway); SDPP 1 was sourced from APC Inc. (Ankeny, IA); and SDPP 2 was sourced from NongHyup Feed Inc., LTD. (Seoul, Korea).
[a–d]Means within a row (diet comparison) or a column (day comparison) without a common superscript letter differ ($P < 0.05$).

test to determine the maximum IR of SDPP, the inclusion of SDPP at greater than 20% in diets resulted in feed refusals in nursery pigs (data not shown). In the present digestibility experiment, SDPP was included in the diets at 15%. High ash and salt contents in SDPP have been suggested to be major reasons for reduced feed intake by high SDPP IR (Torrallardona, 2009). In the present work, the basal diet was based on corn, SBM, whey, and sucrose, and experimental diets were formulated by adding SDPP at the expense of energy- and AA-containing ingredients to enable the digestibility calculations using difference procedure. In many AA digestibility experiments, a test ingredient is included in the experimental diets as a sole source of AA (Jeon et al., 2019; Son et al., 2019; Lee et al., 2020; Sung et al., 2020), which often inevitably causes AA deficiency and imbalance. Compared with purified or semi-purified basal diets, the experimental diet formulations in the present work provide more balanced nutrients to the pigs and prevent potential feed refusals. Pigs readily consumed the provided diets in a few minutes with almost no feed leftover. In a difference procedure to determine available energy and AA digestibility in test ingredients, a low IR of ingredient potentially cause a greater variation due to the extrapolation during the calculation procedure (Kong and Adeola, 2014). In the present work, the proportion of GE in experimental diets contributed by SDPP was only 0.18, whereas the proportion of CP in diets from SDPP was greater than 0.47 due to considerably high CP contents in SDPP.

Table 10. Effects of dietary spray-dried plasma protein (SDPP) on immunoglobulin G concentration and complete blood count traits on day 14 in weaning pigs (Exp. 2)[1]

Item	Diet[2]			SEM	*P*-value
	Fish meal	SDPP 1	SDPP 2		
Immunoglobulin G, g/L	8.7	7.7	7.7	0.6	0.385
White blood cell, 10^9/L	29.9	28.3	25.9	2.6	0.588
Red blood cell (RBC), 10^{12}/L	7.5	7.4	7.3	0.2	0.896
Hemoglobin, g/dL	8.2	10.7	8.0	1.5	0.407
Hematocrit, %	21.1	32.6	20.2	4.8	0.211
Mean corpuscular volume, fL	−7.6	−3.4	−19.8	12.8	0.666
RBC distribution width, %	25.5	25.1	25.1	1.4	0.967
Mean corpuscular hemoglobin (MCH), pg	−13.2	−7.3	−8.7	2.2	0.222
MCH concentration, g/dL	33.1	32.8	32.8	0.7	0.912
Platelet (PLT), 10^9/L	593.8	585.8	539.3	52.7	0.743
Mean PLT volume, fL	9.8	9.8	9.8	0.3	0.979
PLT percentage, %	0.6	0.6	0.6	0.0	0.682
PLT distribution width concentration, %	38.2	38.5	37.9	0.7	0.828
Lymphocyte, 10^9/L	21.8	21.4	16.0	2.2	0.196
Monocyte, 10^9/L	1.1	0.0	1.2	0.4	0.192
Granulocyte, 10^9/L	5.4	4.9	6.6	1.7	0.795

[1]All pigs in trial 1 were bled and data are least squares means of 4 observations for all treatments.
[2]Fish meal was sourced from Vedde Herring Oil Factory (Egersund, Norway); SDPP 1 was sourced from APC Inc. (Ankeny, IA); and SDPP 2 was sourced from NongHyup Feed Inc., LTD. (Seoul, Korea).

Table 11. Effects of dietary spray-dried plasma protein (SDPP) on immunoglobulin G concentration and complete blood count traits on day 28 in weaning pigs (Exp. 2)[1]

Item[2]	Diet[2]			SEM	*P*-value
	Fish meal	SDPP 1	SDPP 2		
Immunoglobulin G, g/L	9.1	8.3	8.7	0.5	0.569
White blood cell, 10^9/L	25.4[a]	28.0[a]	21.2[b]	0.9	0.005
Red blood cell (RBC), 10^{12}/L	7.0	6.5	6.5	0.7	0.818
Hemoglobin, g/dL	7.8	10.7	7.8	1.8	0.462
Hematocrit, %	19.8	28.7	23.5	8.0	0.741
Mean corpuscular volume, fL	9.5	1.7	−3.1	9.7	0.670
RBC distribution width, %	24.8	23.3	24.1	1.1	0.643
Mean corpuscular hemoglobin (MCH), pg	−1.1	−5.6	−7.1	2.9	0.377
MCH concentration, g/dL	33.0	28.9	32.8	2.2	0.402
Platelet (PLT), 10^9/L	127.8	298.1	146.3	92.2	0.413
Mean PLT volume, fL	88.1	73.4	76.6	6.0	0.269
PLT percentage, %	1.8	1.1	2.8	1.2	0.630
PLT distribution width concentration, %	−5.5	6.3	−6.7	5.9	0.301
Lymphocyte, 10^9/L	9.6	9.5	9.6	0.3	0.937
Monocyte, 10^9/L	0.3	0.4	0.3	0.0	0.335
Granulocyte, 10^9/L	37.2	38.5	37.7	0.8	0.587

[1]All pigs in trial 1 were bled and data are least squares means of 4 observations for all treatments.
[2]Fish meal was sourced from Vedde Herring Oil Factory (Egersund, Norway); SDPP 1 was sourced from APC Inc. (Ankeny, IA); and SDPP 2 was sourced from NongHyup Feed Inc., LTD. (Seoul, Korea).
[a,b]Within a row, means without a common superscript letter differ ($P < 0.05$).

Experiment 2

Increased weight gain in pigs fed the diet containing SDPP was mainly attributed to the increased feed intake. Similar results were reported in previous studies (Kats et al., 1994; De Rodas et al., 1995; van Dijk et al., 2001). Palatability may be one of the major factors for the greater ADFI of pigs fed the SDPP than those containing fish meal (Kats et al., 1994). Preference for the diet containing SDPP was also

Table 12. Effects of spray-dried plasma protein (SDPP) on organ weight and small intestine length in weaning pigs (Exp. 2)[1]

Item	Diet[2]			SEM	*P*-value
	Fish meal	SDPP 1	SDPP 2		
Liver, g	580	556	583	16	0.463
Stomach, g	136	138	135	6	0.928
Kidney, g	111	107	115	3	0.301
Lung, g	277	302	263	11	0.107
Heart, g	101	102	103	3	0.923
Small intestine, g	842	866	933	41	0.330
Large intestine, g	901	911	906	67	0.994
Small intestine length, m	11.2	10.8	11.1	0.4	0.798

[1]Organ weight and small intestine length were determined on day 28. One male and two females in each pen were euthanized and estimated. Data are least squares means of 4 observations for all treatments.
[2]Fish meal was sourced from Vedde Herring Oil Factory (Egersund, Norway); SDPP 1 was sourced from APC Inc. (Ankeny, IA); and SDPP 2 was sourced from NongHyup Feed Inc., LTD. (Seoul, Korea).

Table 13. Effects of spray-dried plasma protein (SDPP) on villus height (VH) and crypt depth (CD) in weaning pigs (experiment 2)[1]

Item	Diet[2]			SEM	*P*-value
	Fish meal	SDPP 1	SDPP 2		
VH, mm	2.47	2.26	2.17	0.13	0.279
CD, mm	0.46	0.44	0.46	0.03	0.825
VH-to-CD ratio	5.63	5.44	4.92	0.30	0.275

[1]Intestinal morphology was determined on day 28 in trial 1. One male and two females in each pen were euthanized and middle section of jejunum was collected. Data are least squares means of 4 observations for all treatments.
[2]Fish meal was sourced from Vedde Herring Oil Factory (Egersund, Norway); SDPP 1 was sourced from APC Inc. (Ankeny, IA); and SDPP 2 was sourced from NongHyup Feed Inc., LTD. (Seoul, Korea).

greater than the diet containing dried skim milk in nursery pigs (Ermer et al., 1994). In some previous studies (Grinstead et al., 2000; Lawrence et al., 2004), however, dietary SDPP did not result in any beneficial effects. In these two studies, the experimental diets were provided in pigs in pellet form, whereas the diets were provided in mash form to the pigs in other studies (Kats et al., 1994; De Rodas et al., 1995; van Dijk et al., 2001) and the present experiment showed positive effects of dietary SDPP on performance. The pelleting process may have masked the good flavor of SDPP. In addition, pelleting process can damage the nutrients and the bioactive components in SDPP, such as IgG (van Dijk et al., 2001). The negative effects of heat processing on nutrient digestibility in animal protein sources are well documented in multiple studies (Bax et al., 2012; Hodgkinson et al., 2018; Kim et al., 2021). In the present work, the experimental diets were prepared in mash form that prevented potential deteriorating effects of thermal process on SDPP. In the present study, the effects of dietary SDPP on ADG and ADFI were mainly pronounced during the first 2 wk after weaning compared with the third and fourth weeks after weaning. The relative changes of growth performance compared to the control diet induced by the supplementation of SDPP were 21.0% for 2 wk after weaning and 2.4% for the following 2 wk in ADG and 20.9% for 2 wk after weaning and 0.9% for the following 2 wk in ADFI (van Dijk et al., 2001), which were similar to the present results and previously reported in vivo study (Kats et al., 1994).

The greater fecal consistency in pigs fed SDPP 2 diet compared with the SDPP 1 group in the present work may be partially explained by the amount of nitrogen introduced to the hindgut. Greater nitrogen concentrations in the hindgut are often associated with greater frequencies of diarrhea in pigs due to the proliferation of pathogens and generation of toxic metabolites (Nyachoti et al., 2006; Wellock et al., 2008). The fecal score was increased as the experimental days passed in the present work that coincided with the previously reported studies in nursery pigs (Castillo et al., 2008; Koo et al., 2017; Gebhardt et al., 2020).

Müller et al. (2017) reported that CBC traits including erythrocytes, hematocrit, hemoglobin, leukocyte, neutrophil, lymphocyte, and monocyte were not affected by dietary SDPP in nursery pigs. Serum IgG is one of the indicators representing immune competence in nursery pigs (Sutherland et al., 2005). In the present work, IgG concentrations were not affected by dietary SDPP that concurs with a previous study (Weaver et al., 2014). Dietary IgG is relatively well reflected in IgG concentrations in pigs before 7 wk of age but not in pigs after 7 wk of age due to the ability of de novo IgG synthesis in older pigs (Edwards et al., 2012). In the present work, the blood samples were collected at the age of 7 and 9 wk, which was quite old to show the response in serum IgG. Organ weight and jejunal morphology were not affected by dietary SDPP in this work, which is consistent with a previous study (Owusu-Asiedu et al., 2002). Similarly, duodenal, jejunal, and ileal morphology were not different between the pigs fed the control diet and the SDPP-supplemented diet (Pan et al., 2019).

Conclusions

In conclusion, digestible energy in spray-dried plasma protein 1 manufactured from the United States is greater compared with spray-dried plasma protein 2 manufactured in Korea. However, standardized ileal digestibility of crude protein and indispensable amino acids is greater in spray-dried plasma protein 2 compared with spray-dried plasma protein 1. During days 0 to 14 and 0 to 28, pigs fed the diets

containing spray-dried plasma protein gain more weight than those fed the fish meal diet with no difference between two sources of spray-dried plasma protein. Overall, two sources of spray-dried plasma protein have different energy and nutritional values, but similar growth-promoting effects in nursery pigs.

Conflict of Interest Statement

The authors declare no real or perceived conflicts of interest.

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