Dietary spray-dried plasma supplementation in late-gestation and lactation enhanced productive performance and immune responses of lactating sows and their litters

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Abstract

The study was conducted to evaluate the effects of spray-dried plasma (SDP) supplementation during late gestation and lactation on productive performance and immune responses of sows and their litters. Twelve sows (227.78 ± 2.16 kg average body weight; 2.0 average parity) were randomly allotted to two dietary treatments: a basal diet (CON) and the basal diet supplemented with 1% SDP. Sows were fed experimental diets from d 30 before farrowing to weaning of their piglets. Blood samples were collected from sows on d 1, 3, and 7 of lactation and from two randomly selected nursing pigs per litter on d 3 and 7 after birth, and d 1, 3, and 7 after weaning. Productive performance and immune responses of sows and their piglets were measured. There was a trend of less body weight loss in sows supplemented with SDP (p < 0.10) during the lactation period and a trend of greater (p < 0.10) average daily gain in SDP piglets compared to those in the CON group. Sows in the SDP group tended to have lower (p < 0.10) serum concentrations of tumor necrosis factor-α (TNF-α), transforming growth factor-β1 (TGF-β1), and cortisol on d 3 and lower serum concentration of TNF-α on d 7 compared with sows in CON group. In comparison with CON piglets, piglets from SDP sows tended to have lower (p < 0.10) serum concentrations of TNF-α, TGF-β1, and cortisol on d 7 after weaning, lower (p < 0.10) serum TNF-α and C-reactive protein on d 3 and 7 after weaning, and greater (p < 0.10) average daily gain after weaning. Moreover, weaned pigs from sows fed SDP had significantly lower (p < 0.05) serum concentrations of cortisol and TGF-β1 on d 3 and 7 postweaning, respectively, than CON piglets. In conclusion, SDP supplementation in sow diets from late gestation to weaning improved the productive performance of sows and
MATERIALS AND METHODS

Experimental protocol was reviewed and approved by the Animal Care and Use Committee at the Chungnam National University, Daejeon, Korea (Protocol # CNU-00611). The experiment was performed at the animal research facility at the Chungnam National University.
Animals, housing, experimental design, and diet
A total of twelve lactating sows (Yorkshire × Landrace; 227.78 ± 2.16 kg average body weight; 2.0 average parity) were stratified by parity and randomly assigned to one of the two dietary treatments on d 84 of gestation (6 sows/treatment). Sows were individually housed in farrowing crates since d 109 of gestation and had free access to water. Sows were fed either a basal diet (control, CON) or the basal diet supplemented with 1% (as-fed basis) SDP. The SDP used in this experiment was produced by APC (Ankeny, IA, USA). All diets met the current estimates for nutrient requirements of sows (Table 1) [21]. Sows were restricted fed the experimental diets (3.0 kg/day) from d 84 of gestation until farrowing, and then fed the experimental diets on an ad libitum basis from until weaning of their piglets.

Litters were weaned at 27 d of age (6.09 ± 0.26 kg average body weight) and each litter was allotted to individual nursery pen. Weaned pigs were subjected to a 3-phase feeding program and fed the phase 1 nursery diet at week 1, phase 2 diet at week 2 and phase 3 diet from week 3 to 6 postweaning. Weaned pigs had free access to water and diets throughout the experiment.

Table 1. Ingredient composition of experimental diets (as-fed basis)

| Item              | Gestation diet | Lactation diet |
|-------------------|----------------|----------------|
|                   | CON SDP       | CON SDP       |
| Ingredients (%)   | 100.00 100.00 | 100.00 100.00 |
| Corn              | 75.82 76.72   | 65.54 66.53   |
| Soybean meal      | 21.30 19.40   | 31.81 29.82   |
| SDP               | - 1.00        | - 1.00        |
| Limestone         | 0.90 0.90     | 0.85 0.85     |
| MDCP              | 1.58 1.58     | 1.40 1.40     |
| Vitamin premix    | 0.20 0.20     | 0.20 0.20     |
| Mineral premix    | 0.20 0.20     | 0.20 0.20     |

Calculated chemical composition

| Item      | Gestation diet | Lactation diet |
|-----------|----------------|----------------|
| ME (Mcal/kg) | 3.32 3.32     | 3.43 3.43     |
| CP (%)    | 15.86 15.82   | 19.76 19.72   |
| Crude fat (%) | 3.09 3.05    | 2.86 2.80     |
| Crude fiber (%) | 2.97 3.00   | 3.33 3.36     |
| NDF (%)   | 8.71 8.78     | 10.78 10.81   |
| ADF (%)   | 4.18 4.20     | 4.63 4.65     |
| Calcium (%) | 0.77 0.77    | 0.75 0.75     |
| Phosphorus (%) | 0.64 0.65   | 0.65 0.65     |
| Lysine (%) | 0.74 0.76     | 1.02 1.02     |
| Methionine (%) | 0.25 0.25   | 0.30 0.30     |
| Threonine (%) | 0.58 0.60   | 0.74 0.76     |
| Tryptophan (%) | 0.16 0.16   | 0.22 0.22     |

1) CON, control sow diet based on corn and soybean meal; SDP, CON + 1% spray-dried plasma.
2) Provided per kilogram of diet: vitamin A, 10,000 IU; vitamin D₃, 2,000 IU; vitamin E, 48 IU; vitamin K₃, 1.5 mg; riboflavin, 6 mg; niacin, 40 mg; D-pantothenic acid, 17 mg; biotin, 0.2 mg; folic acid, 2 mg; choline, 166 mg; vitamin B₁₂, 2 mg; and vitamin B₆, 28 μg.
3) Provided per kilogram of diet: Fe, 90 mg from iron sulfate; Cu, 15 mg from copper sulfate; Zn, 50 mg from zinc oxide; Mn, 54 mg from manganese oxide; I, 0.99 mg from potassium iodide; Se, 0.25 mg from sodium selenite.

SDP, spray-dried plasma; MDCP, monodicalcium phosphate; ME, metabolizable energy; CP, crude protein; NDF, neutral detergent fiber; ADF, acid detergent fiber.
Sample collection and measurements
Lactating sows and their litter’s body weight were measured on the day of farrowing and weaning. Body weight change of sows and average daily gain of piglets during the lactation period were calculated. The feed intake for each sow was recorded during lactation period to calculate the average daily feed intake. Measurements of sow backfat depth was performed on P2 position (65 mm down the left side from the spine at the same level as the last rib curve) using a real-time ultrasound scanner (Anyscan BF, SongKang GLC, Seongnam, Korea) on day of farrowing and weaning. The number of stillborn and liveborn piglets and weaned piglets were recorded to calculate productive performance.

Blood samples were collected from each sow on d 1, 3, and 7 of lactation and two randomly selected piglets (1 barrow and 1 gilt) per litter on d 3 and 7 after birth and d 1, 3, and 7 after weaning using vacutainers containing clot-activator or ethylenediaminetetraacetic acid (EDTA) to harvest whole blood or serum, respectively. Serum samples were collected from whole blood after centrifugation (1,200 ×g for 15 min at 4 °C) and kept at −20 °C until analysis.

Measurements of white blood cell counts, serum cytokines, acute phase protein, cortisol, and Immunoglobulins
Whole blood samples were analyzed by an automatic hematology analyzer (scil Vet abc hematology analyzer, Scil animal care company, Altorf, France) for total white blood cell (WBC) counts. The serum concentrations of tumor necrosis factor-α (TNF-α; R&D Systems, Minneapolis, MN, USA), transforming growth factor-β1 (TGF-β1; R&D Systems), C-reactive protein (Abnova, Taipei City, Taiwan), cortisol (Cusabio, Wuhan, China), and immunoglobulin G, M, and A (IgG, IgM, and IgA; Abnova) were measured using porcine-specific enzyme-linked immunosorbent assay (ELISA) kits by following the instruction manufacturers’ instructions.

Statistical analyses
All data were analyzed using the PROC GLM procedure of SAS (SAS, Carry, NC, USA) in a completely randomized design with the sow or their litter as an experimental unit, respectively. The model for productive performance and immune responses of sows and their litters included the fixed effect of dietary treatment and sow or litter as random terms; Parity of sows was used as a covariate in the model. Statistical significance and tendency were considered at \( p < 0.05 \) and \( 0.05 \leq p < 0.10 \), respectively.

RESULTS AND DISCUSSION
Sows supplemented with 1% SDP tended to have less \( (p < 0.10) \) body weight losses and improved \( (p < 0.10) \) piglet average daily gain during the time of lactation than those fed CON; however, there were no differences in other productive performances between the treatments (Table 2). Sows often mobilize body protein and fat reserves to support lactation, therefore body weight loss is commonly observed during lactation. However, excessive loss of body weight during lactation can compromise reproductive performance of sows in the subsequent pregnancy, including reduced rate of pregnancy and lower survival rates of embryos [22,23]. Therefore, appropriate feeding practices, such as high-energy rations and nutrient-rich feeds, are required to minimize lactation weight loss [24,25]. Previous research reported that supplementation of 0.25% SDP in lactation diets tended to reduce body weight losses of sows and significantly improved average litter weight at weaning [26]. In agreement with this study, results from the current study showed that dietary supplementation of 1% SDP in late gestation and lactation is effective in reducing weight loss of lactating sows and
improving the growth of nursing piglets. Taken altogether, SDP may mitigate body weight loss through enhancing nutrient utilization and lactation performance of sows and thus enhance the growth of their litters.

Compared with CON sows, addition of 1% SDP tended to reduce ($p < 0.10$) serum TNF-$\alpha$, TGF-$\beta$1, and cortisol concentrations on d 3 and serum TNF-$\alpha$ concentrations on d 7 after farrowing (Table 3). No difference was observed in the white blood cell counts and serum C-reactive protein throughout the experiments for sow. Parturition is the most stressful event of the reproduction cycle of sows, while improper pre- and peripartal management and nutrition may lead to chronic stress that has deleterious effects on immune functions [27,28]. As a result, these stress-related alterations reflect immunodeficiency, which may contribute to reproductive failure or death of sows and might adversely affect the performance of their litters [29]. It was reported previously that dietary supplementation of 1% or 8% SDP reduced serum concentrations of inflammation- and stress-related mediators (TNF-$\alpha$, C-reactive protein, and cortisol) and increased concentrations of anti-inflammatory cytokine (TGF-$\beta$1) in the uterine of pregnant mice that suffered from transportation stress [17]. In addition, pregnant mice that received 8% SDP had lower pro-inflammatory cytokines in uterine mucosa and placenta and had reduced lethargic response after lipopolysaccharide (LPS) challenge [30]. These observations suggest that SDP could attenuate inflammation and enhance immune competence in pregnant mice. Moreover, it was also reported that SDP maintained gut barrier function of weaned pigs [7] and rats [31] in a state of inflammation, respectively. Thus, in the present study, the reduced body weight change of sows and greater average daily gain of their litters by SDP supplementation may result from more robust immune functions of sows in response to farrowing and lactation stresses.

Piglets from sows supplemented with SDP tended to have lower ($p < 0.10$) serum concentrations

### Table 2. Productive performance of lactating sows fed diets supplemented with spray-dried plasma

| Item                      | Dietary treatments | SEM | $p$-value |
|---------------------------|--------------------|-----|-----------|
| Parity                    | CON2               | 0.30| 0.733     |
| Lactation days (d)        | 2.1                | 2.0 | 0.118     |
| Initial BW on d 1 after farrowing (kg) | 28.00              | 26.16| 3.12 | 0.471 |
| Final BW at weaning (kg)  | 208.80             | 218.61| 3.73 | 0.092 |
| Sow BW change (kg)        | -17.34             | -10.81| 2.45 | 0.081 |
| Total feed intake (kg)    | 183.83             | 180.48| 4.07 | 0.530 |
| ADFI (kg)                 | 6.57               | 6.89 | 0.114     |
| Initial backfat depth (mm)| 20.50              | 20.75| 1.88 | 0.789 |
| Final backfat depth (mm)  | 17.20              | 17.26| 1.53 | 0.987 |
| Backfat depth change (mm) | 3.30               | 3.49 | 1.50 | 0.856 |
| Born alive piglets (n)    | 11.16              | 10.20| 1.42 | 0.655 |
| Dead piglets (n)3         | 1.50               | 1.20 | 0.58 | 0.437 |
| Pre-weaning mortality (%) | 13.44              | 11.76| 3.47 | 0.563 |
| Weaned piglets (n)        | 9.66               | 9.00 | 0.28 | 0.284 |
| Piglets BW at birth (kg)  | 1.60               | 1.80 | 0.07 | 0.145 |
| Piglets BW at weaning (kg)| 5.82               | 6.35 | 0.41 | 0.439 |
| ADG of piglets (g/d)      | 150.15             | 173.03| 7.58 | 0.082 |

1) Values are presented as the least squares mean of 6 replicates.
2) CON, control sow diet based on corn and soybean meal; SDP, CON + 1% spray-dried plasma.
3) Stillborn and piglets died before weaning.

BW, body weight; ADFI, average daily feed intake; ADG, average daily gain.
of TNF-α, TGF-β1, and cortisol on d 7 of lactation (Table 4). However, no differences were found in serum immunoglobulins of nursing piglets during lactation (Table 5). After weaning, pigs from sows supplemented with SDP tended to have greater (p < 0.10) average daily gain compared with

### Table 3. Immune responses of lactating sows fed diets supplemented with spray-dried plasma

| Item               | Dietary treatments | SEM | p-value |
|--------------------|--------------------|-----|---------|
|                    | CON                | SDP |         |
| Day 1 of lactation |                    |     |         |
| WBC (× 10³/µL)     | 11.93              | 9.55| 1.77    | 0.893 |
| TNF-α (pg/mL)      | 312.30             | 289.80| 34.19 | 0.809 |
| TGF-β1 (pg/mL)     | 357.66             | 238.16| 59.23 | 0.745 |
| CRP (ng/mL)        | 241.43             | 268.87| 44.60 | 0.846 |
| Cortisol (ng/mL)   | 0.51               | 0.49 | 0.06   | 0.345 |
| Day 3 of lactation |                    |     |         |
| WBC (× 10³/µL)     | 15.33              | 14.08| 1.58   | 0.465 |
| TNF-α (pg/mL)      | 281.96             | 264.94| 5.06 | < 0.10 |
| TGF-β1 (pg/mL)     | 448.07             | 311.37| 63.21 | < 0.10 |
| CRP (ng/mL)        | 139.95             | 132.90| 18.71 | 0.723 |
| Cortisol (ng/mL)   | 0.56               | 0.48 | 0.03   | < 0.10 |
| Day 7 of lactation |                    |     |         |
| WBC (× 10³/µL)     | 13.71              | 13.98| 1.64   | 0.687 |
| TNF-α (pg/mL)      | 272.15             | 249.35| 10.21 | < 0.10 |
| TGF-β1 (pg/mL)     | 286.20             | 257.32| 46.00 | 0.854 |
| CRP (ng/mL)        | 136.92             | 105.27| 23.21 | 0.412 |
| Cortisol (ng/mL)   | 0.49               | 0.51 | 0.06   | 0.597 |

1) Values are presented as the least squares mean of 6 replicates.
2) CON, control sow diet based on corn and soybean meal; SDP, CON + 1% spray-dried plasma.
WBC, white blood cells; TNF-α, tumor necrosis factor-α; TGF-β1, transforming growth factor-β1; CRP, C-reactive protein.

### Table 4. Immune responses of nursing piglets from sows fed diets supplemented with spray-dried plasma

| Item               | Dietary treatments | SEM | p-value |
|--------------------|--------------------|-----|---------|
|                    | CON                | SDP |         |
| Day 3 of lactation |                    |     |         |
| WBC (× 10³/µL)     | 10.15              | 8.54 | 0.92   | 0.687 |
| TNF-α (pg/mL)      | 270.39             | 262.67| 40.86 | 0.741 |
| TGF-β1 (pg/mL)     | 788.76             | 607.40| 140.86| 0.874 |
| CRP (ng/mL)        | 72.14              | 78.15| 16.87  | 0.812 |
| Cortisol (ng/mL)   | 0.83               | 0.45 | 0.23   | 0.345 |
| Day 7 of lactation |                    |     |         |
| WBC (× 10³/µL)     | 13.15              | 12.98| 1.30   | 0.465 |
| TNF-α (pg/mL)      | 423.57             | 349.87| 38.99 | < 0.10 |
| TGF-β1 (pg/mL)     | 980.41             | 853.49| 58.99 | < 0.10 |
| CRP (ng/mL)        | 119.42             | 115.18| 26.95 | 0.586 |
| Cortisol (ng/mL)   | 1.05               | 0.62 | 0.15   | < 0.10 |

1) Values are presented as the least squares mean of 6 replicates.
2) CON, control sow diet based on corn and soybean meal; SDP, CON + 1% spray-dried plasma.
WBC, white blood cells; TNF-α, tumor necrosis factor-α; TGF-β1, transforming growth factor-β1; CRP, C-reactive protein.
CON piglets (Table 6). This result was supported by inflammatory and stress markers in serum. On d 3, weaned pigs from sows supplemented with SDP had reduced \( p < 0.05 \) serum cortisol concentrations, tended to have reduced \( p < 0.10 \) serum TNF-\( \alpha \) concentration than those from sows in CON group (Table 7). On d 7, serum concentrations of TGF-\( \beta 1 \) were decreased \( p < 0.05 \) and tended to have reduced \( p < 0.10 \) C-reactive protein concentrations in weaned pigs from sows fed SDP compared with those from sows fed CON. In order to acquire passive immunity, newborn piglets have to consume a sufficient volume of colostrum which contains high energy sources and immunoglobulins [32]. Previous studies reported that body weight and body conditions of sows during gestation are important factors that affect the quality and quantity of colostrum and milk production [33–35]. In the current study, increased piglet average daily gain at weaning and improved immune responses of nursing and weaned pigs could have been due to improved health status of sows fed SDP. Moreover, the possible modes of action include, but are not limited to 1) increase the growth rate of piglets from sows supplemented with SDP may have been due to increased production of colostrum and milk and thus increased consumption of colostrum and milk by suckling pigs; 2) sows fed SDP may have produced higher concentrations of immunoglobulins in colostrum and milk, however, the amounts of immunoglobulins contained in sow colostrum or milk were not analyzed, nor was colostrum or milk production of sows measured. Future

### Table 5. Serum immunoglobulins of nursing piglets from sows fed diets supplemented with spray-dried plasma

| Item                   | Dietary treatments | SEM  | \( p \)-value |
|------------------------|-------------------|------|--------------|
| Day 3 of lactation     |                   |      |              |
| IgG (ng/mL)            | CON\(^2\)         | 242.13 | 9.95 | 0.818 |
|                        | SDP\(^2\)         | 251.47 |      |      |
| IgM (ng/mL)            | CON\(^2\)         | 89.69  | 10.16 | 0.235 |
|                        | SDP\(^2\)         | 106.97 |      |      |
| IgA (ng/mL)            | CON\(^2\)         | 30.22  | 5.38  | 0.844 |
|                        | SDP\(^2\)         | 25.71  |      |      |
| Day 7 of lactation     |                   |      |              |
| IgG (ng/mL)            | CON\(^2\)         | 219.28 | 13.62 | 0.795 |
|                        | SDP\(^2\)         | 221.83 |      |      |
| IgM (ng/mL)            | CON\(^2\)         | 58.46  | 7.79  | 0.612 |
|                        | SDP\(^2\)         | 69.95  |      |      |
| IgA (ng/mL)            | CON\(^2\)         | 22.65  | 4.40  | 0.692 |
|                        | SDP\(^2\)         | 33.69  |      |      |

\(^1\)Values are presented as the least squares mean of 6 replicates.
\(^2\)CON, control sow diet based on corn and soybean meal; SDP, CON + 1% spray-dried plasma.

### Table 6. Growth performance of weaned pigs from sows fed diets supplemented with spray-dried plasma

| Item                   | Dietary treatments | SEM  | \( p \)-value |
|------------------------|-------------------|------|--------------|
| Number of weaned pigs/pen (n) | CON\(^2\)       | 9.66 | 0.41 | 0.439 |
|                        | SDP\(^2\)        | 9.00 |      |      |
| Initial BW (kg)        | CON\(^2\)        | 5.82 | 0.41 | 0.439 |
|                        | SDP\(^2\)        | 6.35 |      |      |
| Final BW\(^3\) (kg)    | CON\(^2\)        | 23.23 | 0.96 | 0.102 |
|                        | SDP\(^2\)        | 26.11 |      |      |
| Feed intake (kg)       | CON\(^2\)        | 25.50 | 0.53 | 0.348 |
|                        | SDP\(^2\)        | 26.85 |      |      |
| ADG (g/d)              | CON\(^2\)        | 414.52 | 18.21 | < 0.10 |
|                        | SDP\(^2\)        | 470.47 |      |      |
| ADFI (g/d)             | CON\(^2\)        | 607.17 | 0.14 | 0.345 |
|                        | SDP\(^2\)        | 639.24 |      |      |
| G:F ratio (g/g)        | CON\(^2\)        | 0.682 | 0.03 | 0.773 |
|                        | SDP\(^2\)        | 0.735 |      |      |

\(^1\)Values are presented as the least squares mean of 6 replicates.
\(^2\)CON, control sow diet based on corn and soybean meal; SDP, CON + 1% spray-dried plasma.
\(^3\)The 3-phase feeding program with basal nursery diet was used to feed weaned pigs: week 1 as phase 1; week 2 as phase 2; and week 3 to 6 as phase 3. Pigs had free access to water and diets throughout the experiment.

BW, body weight; ADG, average daily gain; ADFI, average daily feed intake; G:F ratio, gain to feed ratio.
Table 7. Immune responses of weaned pigs from sows fed diets supplemented with spray-dried plasma

| Item                  | CON[^1] | SDP[^2] | SEM  | p-value |
|-----------------------|---------|---------|------|---------|
| Day 1 postweaning     |         |         |      |         |
| WBC (× 10^3/μL)       | 12.91   | 13.42   | 1.46 | 0.412   |
| TNF-α (pg/mL)         | 320.24  | 358.90  | 57.21| 0.847   |
| TGF-β1 (pg/mL)        | 1,121.44| 1,077.46| 117.21|0.765   |
| CRP (ng/mL)           | 87.53   | 76.54   | 14.94| 0.546   |
| Cortisol (ng/mL)      | 1.34    | 1.18    | 0.10 | 0.387   |
| Day 3 postweaning     |         |         |      |         |
| WBC (× 10^3/μL)       | 16.09   | 13.44   | 2.20 | 0.341   |
| TNF-α (pg/mL)         | 449.80  | 344.11  | 38.32| < 0.10  |
| TGF-β1 (pg/mL)        | 1,071.75| 1,024.15| 158.32|0.687   |
| CRP (ng/mL)           | 126.60  | 103.58  | 17.30| 0.541   |
| Cortisol (ng/mL)      | 1.88    | 1.40    | 0.16 | < 0.05  |
| Day 7 postweaning     |         |         |      |         |
| WBC (× 10^3/μL)       | 16.95   | 16.15   | 1.25 | 0.741   |
| TNF-α (pg/mL)         | 388.84  | 370.12  | 41.89| 0.601   |
| TGF-β1 (pg/mL)        | 836.48  | 718.33  | 41.89| < 0.05  |
| CRP (ng/mL)           | 112.28  | 78.41   | 15.50| < 0.10  |
| Cortisol (ng/mL)      | 1.74    | 1.56    | 0.11 | 0.230   |

[^1]Values are presented as the least squares mean of 6 replicates.
[^2]CON, control sow diet based on corn and soybean meal; SDP, CON + 1% spray-dried plasma. WBC, white blood cells; TNF-α, tumor necrosis factor-α; TGF-β1, transforming growth factor-β1; CRP, C-reactive protein.

Research is needed to elucidate the mechanisms of improved immune responses in pigs from sows supplemented with SDP.

CONCLUSION

In conclusion, supplementation of SDP during late gestation and lactating sows’ diets improved productive performance and immune responses of lactating sows and their litters.

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