



Increasing selenium supply for heat-stressed or actively cooled sows improves piglet preweaning survival, colostrum and milk composition, as well as maternal selenium, antioxidant status and immunoglobulin transfer

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ABSTRACT

This study aimed to evaluate the effects of increasing selenium (Se) supply for heat-stressed or actively cooled sows on sow productivity, colostrum and milk composition, as well as the selenium and antioxidant status and immunoglobulin levels of sows and nursing piglets. The study was a 2 × 2 factorial design, where the first factor was farrowing environment [heat stress vs. actively cooling, temperature: 29.61 ± 0.19 °C (27.70–31.60 °C) vs. 27.90 ± 0.15 °C (26.90–30.20 °C); temperature-humidity index: 72.91 ± 0.26 (70.30–75.70) vs. 70.81 ± 0.22 (69.30–73.80)], and the second factor was dietary Se level during late gestation and lactation [(0.3 vs. 1.2 mg/kg Se as Se-yeast, the basal diet was corn-soybean meal diet formulated according to NRC (2012) except for Se level]. Forty multiparous sows (Landrace × Yorkshire) were randomly allotted to 1 of 4 treatments (10 sows and following 90 piglets per treatment, respectively). The results show that: (1) There were no interactions of farrowing environment with Se treatments with the exceptions of nutrient content of 7-d milk; (2) As for zootechnical measures, piglets of sows receiving increasing Se tended to have greater preweaning survival compared with those of sows receiving control diet without interactions of environment and Se treatments; (3) As to colostrum and milk composition, greater concentrations of protein, lactose, solids-not-fat in colostrum, and greater fat concentration in 7-d and 14-d milk were found for sows fed increasing Se; (4) Regarding Se and antioxidant status, increasing Se supply for sows increased Se content in colostrum and 21-d milk, as well as in plasma of 1-day-old and 21-day-old piglets. Meanwhile, increasing Se supply for sows improved antioxidant status in colostrum (MDA content) and 21-d milk (T-AOC and MDA content), as well as in plasma of 1-day-old and 21-day-old piglets (GSH-Px activity and MDA content); (5) With regard to immunoglobulins, sows fed increasing Se had higher IgM levels in colostrum, and higher IgA in 21-d milk. Also, piglets from sows fed increasing Se had higher plasma IgA at 1 d of age, and higher IgA and IgG levels at 21 d of age. Collectively, increasing selenium supply for heat-stressed or actively cooled sows improved piglet preweaning survival, colostrum and milk composition, as well as maternal selenium, antioxidant status and immunoglobulin transfer irrespective of the climatic conditions, which indicates that Se requirements for sows should be urgently reassessed.

1. Introduction

Heat stress impairs the compensatory capacity of sows, and leads to an insufficient nutrient supply for sows [1], which becomes especially true for micronutrients with central roles in redox metabolism (e.g. Se)

[2]. Colostrum and milk are of great importance for the growth and development of piglets during and after lactation [3], because colostrum and milk supply newborns with nutrients and immune agents, as well as antioxidant protection [4–6]. It's reported that Se play an important role in regulating the composition [2], immunoglobulins [7–11],

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and antioxidant capacity of colostrum and milk [12].

In sows, our previous study demonstrated that dietary supplementation of organic Se during the entirety of the reproductive cycle increased solids-not-fat, protein, and lactose in sow milk compared with inorganic Se [2]. It was also reported that increasing Se supplementation was beneficial for mammary gland vascularity development [7], and increased colostrum IgG level [8], maternal transfer of IgG [9], and IgG absorption of newborn [10] in cattle or ewe. In sows, Hayek et al. (1989) reported injection of Se in sows during late gestation improved the transfer of immunoglobulins from sow to piglet [11].

Compared with formula-fed children, breast-fed children had greater antioxidant defense, and lesser oxidative stress status [13], and breast milk had a suppressive effect on oxidative DNA damage in infants with very low birth weight [14]. Oxidative stress may be transferred from mother to newborn via maternal milk [15], which is very important in newborn piglets because they suffer from oxidative stress due to naive antioxidant systems [16], and mainly depend on colostrum and milk for antioxidant protection [4]. To date, little is known about the effects of increasing dietary Se supply under varying climatic conditions.

Hence, the objective of this study was to investigate the effects of increasing dietary Se supply to heat-stressed and actively cooled sows on sow productivity, colostrum and milk composition, the Se and antioxidant status and immunoglobulin levels of sows and nursing piglets.

2. Materials and methods

All animal protocols used in this study were approved by the South China Agricultural University Institutional Animal Care and Use Committee (SCAU-AEC-2010-0416).

2.1. Animals and experimental design

Forty multiparous crossbred sows (Landrace × Yorkshire, average parity = 5.45 ± 0.30) on day 85 of gestation were randomly allotted by parity, body condition and historical reproductive performance to 2 dietary treatments with 20 sows per treatment (4 treatments with 10 sows per treatment for following 4 treatments). The assignment information for 4 treatments was as follows: parity (5.44 ± 0.40, 5.43 ± 0.30, 5.46 ± 0.40 and 5.46 ± 0.39, respectively), body condition score (3.00 ± 0.04, 3.01 ± 0.03, 2.99 ± 0.03 and 3.0 ± 0.04, respectively), historical reproductive performance [total born per litter (11.01 ± 0.198, 11.00 ± 0.150, 11.02 ± 0.200 and 11.01 ± 0.180, respectively), born alive per litter (10.50 ± 0.19, 10.70 ± 0.20, 10.45 ± 0.18 and 10.60 ± 0.17, respectively)]. The diet was supplemented with 0.3 or 1.2 mg/kg Se in the form of Se-enriched yeast (Se-yeast with 2000 mg/kg Se; Sel-Plex™ 2000, Alltech Inc. USA). From day 85 to 109 of gestation, all sows were managed in the same gestation facility, which was a semi-open building with natural ventilation. After day 109 of gestation, sows within each dietary treatment were equally assigned to a traditional farrowing house (heat stress, HS) or a pad-fan cooling farrowing house (actively cooling, AC). During the entire experimental period, sows within each dietary treatment were fed the same experimental diet in both late gestation and lactation. Therefore, sows were allotted to 4 groups (2 × 2 factorial arrangement of treatments, Fig. S1) with 10 sows per group: HS + 0.3 mg/kg Se, HS + 1.2 mg/kg Se, AC + 0.3 mg/kg Se, and AC + 1.2 mg/kg Se. Heat stress conditions: temperature: 29.61 ± 0.19°C (27.70–31.60 °C), temperature-humidity index: 72.91 ± 0.26 (70.30–75.70); Actively cooling conditions: temperature: 27.90 ± 0.15 °C (26.90–30.20 °C), temperature-humidity index: 70.81 ± 0.22 (69.30–73.80). The feeding trial was conducted from day 85 of gestation until day 21 of lactation (at weaning) at a 2000-sow commercial pig farm in a subtropical climate area (113.20 °E, 22.24 °N, Zhuhai City, Guangdong Province, China) between July and August, 2017. In a previous study, we reported results from research evaluating

Table 1

Composition and nutrient content of the experimental diets (as-fed basis).

Item	0.3 mg/kg Se diet	1.2 mg/kg Se diet
Ingredient, %		
Corn	52.25	52.25
Wheat bran, 15.7% CP	6.00	6.00
Wheat flour, 15.3% CP	7.50	7.50
Soybean meal, 43.0% CP	24.00	24.00
Fish meal, 62.5% CP	2.50	2.50
Soybean oil	4.00	4.00
Dicalcium phosphate	1.20	1.20
Limestone	0.90	0.90
Salt	0.30	0.30
Sodium bicarbonate	0.20	0.20
Sodium sulfate	0.40	0.40
Vitamin and mineral premix ¹	0.30	0.30
Choline chloride (50%)	0.20	0.20
Mold inhibitor (Product name: Fungicap N CH, Industrial Tecnica Pecuaria, S.A., Spain)	0.15	0.15
Mycotoxin decontaminating agent (Product name: Alquerfeed Antitox Plus, Biovet, S.A., Spain)	0.10	0.10
Total	100.00	100.00
Nutrient composition, unit		
ME, MJ/kg ²	13.10	13.10
DM, % ³	89.92	89.95
CP, % ³	18.12	18.13
CF, % ³	3.20	3.22
EE, % ³	6.50	6.49
Starch, % ³	39.01	39.21
Ca, % ³	0.79	0.78
P, % ³	0.64	0.65
Se, mg/kg ³	0.37	1.27
Cu, mg/kg ³	29.0	28.9
Fe, mg/kg ³	222.1	223.0
Zn, mg/kg ³	132.0	132.4
Mn, mg/kg ³	48.1	47.9
Digestible Lys, % ²	0.86	0.86
Digestible Met + Cys, % ²	0.51	0.51
Digestible Thr, % ²	0.60	0.60
Digestible Trp, % ²	0.18	0.18

¹ Vitamin and mineral premix supplied per kilogram of complete diet: 100 mg Zn (ZnSO₄·H₂O), 80 mg Fe (FeSO₄·H₂O), 25 mg Mn (MnSO₄·H₂O), 20 mg Cu (CuSO₄·5H₂O), 0.14 mg I (CaI₂O₆), 0.3 or 1.2 mg Se (Se-yeast), 13000 IU vitamin A, 4000 IU vitamin D₃, 30 IU vitamin E, 4 mg vitamin K₃, 4 mg vitamin B₁, 10 mg vitamin B₂, 4.8 mg vitamin B₆, 0.034 mg vitamin B₁₂, 40 mg niacin, 20 mg D-pantothenate, 2 mg folic acid and 0.16 mg D-biotin.

² Estimated values according to Chinese Feed Database [20].

³ Analyzed values.

a pad-fan cooling system for late gestating and lactating sows. We found that this cooling system was beneficial in farrowing houses, but not in gestating houses because sows reared in pad-fan cooled gestation houses farrowed more stillbirths, probably due to the higher humidity [17]. Therefore, in this study, we used the pad-fan cooling system only in farrowing houses to relieve the effect of heat stress on sows, since farrowing environment has an impact on sow metabolic status and piglet colostrum intake during lactation [18].

2.2. Diets and management

Table 1 shows the diet compositions and nutrient levels, which meet or exceed the nutrient requirements of sows during late gestation and lactation [19,20]. The experimental diet was supplemented with 0.3 (this level is industry level, above recommendation level) or 1.2 mg/kg Se as Se-enriched yeast (Se-yeast with 2000 mg/kg Se; Sel-Plex™ 2000, Alltech Inc. USA).

The traditional gestation house or farrowing house is a semi-open building with natural ventilation. The pad-fan cooling system uses a pad curtain with running water on one end of the completely closed pig house and large fans on the opposite end wall to form negative

pressure, under which the cycling water vapor from the pad will be carried through the pig house and remove heat via the fan-side wall which will lower the temperature of the farrowing house [17].

From day 85–109 of gestation, sows were housed in individual crates (0.6 × 2.0 m) in the gestation facility, and were fed 3.0 kg/d (7:00 am and 2:30 pm) with *ad libitum* access to water (3.0 kg/d diet was limited for sows during late gestation, so sows can eat up 3.0 kg/d diet). At day 110 of gestation, sows within each dietary treatment were equally transferred to a traditional farrowing facility (heat stress) or pad-fan cooling farrowing facility (actively cooling). Sows were housed in individual farrowing crates (2.4 × 2.4 m). The diets were supplied four times a day (7:00 am, 11:00 am, 5:00 pm and 9 pm) to ensure sows *ad libitum* access to feed. Sows had *ad libitum* access to water and their respective experimental diets until weaning at day 21 of lactation.

Within 48 h postpartum, litter size was standardized to 9 ± 1 piglets per litter by cross-fostering within same treatment (a total of 90 piglets per treatment), and standard practices were applied: injecting iron (200 mg Fe as gleptoferron), clipping needle teeth and tails.

2.3. Data and sample collection

2.3.1. Environmental conditions

During the experimental period, ambient real-time temperature and humidity were recorded every half-hour via an automated temperature and humidity recorder (W-series, Wangyunshan, Fujian, China). After temperature and humidity data in the entire experimental period was collected, the average half-hour temperature and temperature-humidity index (THI) within a day were calculated for the gestation facility (July) or farrowing facility (August). THI was calculated using the formula of Wegner et al. (2014) [21]: $THI = [(1.8T) + 32 - [0.55(RH/100)] \times [(1.8T) + 32] - 58]$, where T is the air temperature in °C and RH is the relative humidity in %.

2.3.2. Diet collection

Weekly subsamples of the experimental diets were collected and pooled for analysis [22].

2.3.3. Sow and litter performance

Sow backfat thickness was measured at the P2 position (at the last rib and 65 mm away from spine) using a digital backfat indicator (Renco Lean-Meater®, Renco Corporation, Minneapolis, MN, USA) at day of 85 and 110 of gestation, and day 21 of lactation. During farrowing, the birth times and individual birth weights of each piglet were recorded, and the birth order was written in the back of each piglet using a marker pen. At 24 h after onset of farrowing (the birth time of first piglet), all piglets were weighed individually to calculate colostrum yield [23]. The duration of farrowing was calculated according to the birth time between the first and the last-born piglet, and piglet birth interval was also calculated. Placental wet weight per sow was weighed, and placental weight per piglet was calculated. Placenta weight was divided by litter weight to calculate the placental efficiency [24]. Once farrowing was finished, the number of piglets born (total, live, stillborn, mummy), litter birth weight, and individual piglet weight were recorded. At day 2 (after-cross fostering within 48 h postpartum), 7, 14 and 21 of lactation, litter size and litter weights were recorded. Feed intakes of lactating sows were recorded.

2.3.4. Blood sampling

At farrowing and weaning, blood samples (20 mL per sow) of 6 sows per treatment were taken by ear venipuncture using heparinized vacutainer tubes, and the tubes were selenium-free according to the manufacturer instruction (Sanli medical technology development co. LTD, Hunan, China). Plasma was harvested after centrifuging at $3000 \times g$ for 10 min. At 1-day and 21-d old, blood (5 mL per piglet) was sampled from 3 randomly selected piglets per litter from 6 sows (previously sampled) per treatment by jugular venipuncture using a 5-mL

syringe, and then immediately pipetted into heparinized vacutainer tubes. After being separated, plasma was pooled within litter by adding an identical volume of plasma from each of the 3 piglets. Pooled plasma samples were necessary to obtain a sufficient amount of plasma for analyses to minimize individual variation [25].

After being harvested, plasma was divided as follows: triplicate 0.5 mL samples (pipetted into 1 mL frozen pipe, and immediately frozen in liquid nitrogen for immunoglobulins analysis) and a 2 mL sample (transferred to a 4 mL centrifuge tube, and stored at -20°C for Se analysis).

2.3.5. Colostrum and milk sampling

Colostrum was sampled by hand-expression from functional glands within 12-h postpartum without oxytocin injection. The 7-d, 14-d and 21-d milk were sampled after intramuscular injection of 20 IU oxytocin, which was selenium free according to the manufacturer instruction (Jiangxi Huiqifeng Bio-Technique Co. Ltd, Jiangxi, China). Approximately 30 mL were collected each time. After collection, colostrum or milk was divided as follows: a 4 mL sample (transferred to a 5 mL frozen pipe, and immediately frozen in liquid nitrogen for immunoglobulins analysis), a 13 mL sample (transferred to a 15 mL centrifuge tube, and stored at -20°C for the nutritional composition analysis), and a 2 mL sample (transferred to a 4 mL centrifuge tube, and stored in -20°C refrigerator for Se analysis).

2.3.6. Estimation of colostrum yield

Colostrum in sows is defined as mammary secretions from 0 to 24 h after onset of parturition [26]. The colostrum yield was estimated by calculating the sum of colostrum intake for all piglets within a litter. The colostrum intake for individual piglets was estimated according to the following method of Theil et al. (2014) [23]: Colostrum intake (g) = $-106 + 2.26 \times WG + 200 \times BWB + 0.111 \times D - 1414 \times WG/D + 0.0182 \times WG/BWB$, where WG is the piglet weight gain during the 24 h period after the first piglet was born (g), BWB is body weight at birth (kg) and D is the duration of colostrum suckling during the 24-h period measured in minutes (i.e., the time between birth and 24 h after birth of first born piglet).

2.4. Chemical analysis

2.4.1. Diets composition

The dietary dry matter (DM), crude protein (CP), crude fiber (CF), ether extracts (EE), starch, phosphorus (P), calcium (Ca), copper (Cu), iron (Fe), zinc (Zn), manganese (Mn) contents were analyzed according to Chinese standard methods (GB/T 6435–2014, GB/T 6432–1994, GB/T 6434–2006, GB/T 6433–2006, GB/T 20194–2006, GB/T 6437–2002 and GB/T 13885–2017).

2.4.2. Se content

The Se content in diets, plasma, colostrum and milk samples were analyzed using the fluorometric method as described in our previous studies [2,27]. The Se standard used for Se quantification was purchased from SCP Science with the Se concentration of 1000 µg/mL (Cat#: 140-051-340, SCP Science, Baie D'Urfe, Canada). Briefly, the elemental Se standard, diet samples were digested using complex acids of nitric acid and perchloric acid so that Se complex in sample was oxidized to be Se^{4+} , and under acidic medium conditions, Se^{4+} act with 2,3-diaminonaphthalene (DAN) to form 4,5-benzo piaselenol, and then was extracted by cyclohexane. The organic phase (cyclohexane) is analyzed for fluorescence degree in a spectro-fluorometer (RF-5301, shimadzu corporation, kyoto, Japan) using an excitation wavelength of 376 nm and an emission wavelength of 520 nm, and fluorescence degree has linear relationship with the Se content when sample Se content is less than 0.5 µg. All samples were analyzed in duplicate.

2.4.3. Colostrum and milk composition

The colostrum and milk samples were tested for solids-not-fat, fat, protein, lactose and ash using a fully automated milk analyzer (ULT-RAMILER-UL40AC, Hangzhou Ultrason Technologies Co., Ltd., Zhejiang, China).

2.4.4. Antioxidant status

The antioxidant status, including total antioxidant capacity (T-AOC), superoxide dismutase (SOD), glutathione peroxidase (GSH-Px), glutathione (GSH) and malonaldehyde (MDA) levels in plasma, colostrum and milk were measured as described in our previous studies [2,17,27] using commercially available kits (Nanjing Jiancheng Bioengineering Institute, Nanjing, China). Prior to analysis, lipids were extracted from colostrum and milk using the method of Zanello et al. (2013) [28]: centrifuge at $3000 \times g$, 4°C for 20 min. The results were expressed as units per milliliter plasma or milk.

2.4.5. Immunoglobulins concentration

The IgA, IgG and IgM in plasma of sows and piglets, and in colostrum and milk were analyzed by ELISA using pig immunoglobulin-specific kits (CUSABIO Biotech Company, Wuhan, China). Prior to analysis, lipids in colostrum and milk were removed using the method of Zanello et al. (2013) [28], i.e., centrifugation at $3000 \times g$, 4°C for 20 min.

2.5. Statistical analysis

Statistical analyses were conducted using the General Linear Model procedure of SPSS 22.0 software (SPSS, INC., Chicago, IL, USA), arranged as a 2×2 factorial in a completely randomized design with the environment condition and dietary Se level being the main factors. In case of a significant interaction, the significance of differences among treatments was detected using Duncan's test. Each individual sow and her litter were used as the repeated experimental unit. Results are expressed as means and a pooled SEM. Probabilities less than 0.05 were considered to be significant and probabilities less than 0.10 were considered to represent tendencies among treatments.

3. Results

3.1. Se content in diets

Composition and nutrient content of the basal diet is given in Table 1. The 2 experimental diets were analyzed for Se content, with analyzed values of 0.37 and 1.27 mg/kg in the 0.3 mg/kg and 1.2 mg/kg groups, respectively.

3.2. Environmental conditions

During lactation, sows housed in the actively cooled farrowing facility had lower environmental temperatures ($27.90 \pm 0.15^\circ\text{C}$ vs. $29.61 \pm 0.19^\circ\text{C}$) and THI (70.81 ± 0.22 vs. 72.91 ± 0.26) during both day and night compared with sows housed in the heat-stressed farrowing facility ($P < 0.05$) (Fig. S4 and Fig. S5 in Supplemental Material).

3.3. Reproductive performance

As shown in Table 2, total born, stillborn, mummies, born alive, litter birth weight, and individual piglet weight at birth were unaffected by treatments ($P > 0.05$). Additionally, farrowing duration and piglet birth interval were similar in both treatment groups ($P > 0.05$). No significant treatment differences were observed for placental weight, placental weight per piglet, or placental efficiency ($P > 0.05$).

3.4. Lactation performance

The effects of increasing the dietary selenium supply for heat-stressed or actively cooled sows on lactation performance of sows is shown in Table 3. There was no difference in colostrum yield among treatments ($P > 0.05$). Greater mean ADG during first week was observed in piglets from actively cooled sows compared with piglets from heat-stressed sows ($P < 0.05$). Litter weight and average weight at day 14 of lactation tended to be higher for actively cooled sows compared to heat-stressed sows. Additionally, piglet preweaning survival tended to be improved when sows were fed increasing Se supply vs. the control diet. No interaction effects of environment \times Se level were observed on lactation performance of sows ($P > 0.05$).

3.5. Lactation feed intake and backfat thickness

Average daily feed intake during the 2nd, 3rd, and 1st to 3rd week of lactation were greater for actively cooled sows compared with heat-stressed sows ($P < 0.05$) (Table 4). However, ADFI was not impacted by dietary Se level or environment \times Se level interaction ($P > 0.05$). Sow backfat thickness at day 110 of gestation and day 21 of lactation, and backfat thickness loss during lactation were unaffected by experimental treatments ($P > 0.05$).

3.6. Colostrum and milk composition

The effects of increasing the dietary selenium supply for heat-stressed or actively cooled sows on the composition of colostrum and milk of sows is given in Table 5. Higher protein, lactose, solids-not-fat, and ash percentage in 14-d milk were found for actively cooled sows compared with heat-stressed sows ($P < 0.05$). Greater concentrations of protein, lactose and solids-not-fat in colostrum were observed when sows were fed increasing Se supply vs. the control diet ($P < 0.05$). Elevated fat percentage in 7-d and 14-d milk were also found for sows fed increasing Se supply diet compared to the control diet ($P < 0.05$). There were numerical trends for environment \times Se interactions in protein, lactose, and solids-not-fat in colostrum with increasing dietary Se benefiting sows in the heat stress environment, but not in the actively cooled environment. The composition of 7-d milk was similarly affected by environment \times Se level interactions ($P < 0.05$) with increasing dietary Se benefiting sows in the heat stress environment, but not in the actively cooled environment.

3.7. Se status

Compared to sows fed the control diet, sows fed increasing Se diet had greater Se content in plasma at farrowing and 21-d post-partum ($P < 0.05$) (Table 6), and in colostrum and 21-d milk (Table 7). Similarly, Se content was greater in the plasma of their nursing piglets at 1-day-old and 21-day-old ($P < 0.05$) (Table 8). The Se content in sow plasma, colostrum and 21-d milk, and nursing piglet plasma were not influenced by environment or environment \times dietary Se level interaction ($P > 0.05$).

3.8. Antioxidant status

As summarized in Table 6, compared with heat-stressed sows, actively cooled sows in the farrowing house tended to have greater plasma GSH-Px activity ($P = 0.054$) at farrowing. Compared to sows fed the control diet, sows fed increasing Se diet had greater plasma GSH-Px activity, and lesser MDA content at farrowing and 21-d post-partum ($P < 0.05$).

The effects of increasing the dietary selenium supply for heat-stressed or actively cooled sows on antioxidant status in colostrum and milk is presented in Table 7. Compared to sows fed the control diet, sows fed the increasing Se diet had lesser MDA content in colostrum (P

Table 2
Effects of increasing the dietary selenium supply for heat-stressed or actively cooled sows on reproductive performance of sows.

Item	Heat stress		Actively cooling		S.E.M.	P-value		
	0.3 mg/kg Se	1.2 mg/kg Se	0.3 mg/kg Se	1.2 mg/kg Se		Environment	Se	Interaction
No. of sows	10	10	10	10				
Parity	5.44	5.43	5.46	5.46	0.30	0.969	0.990	0.990
Total born	10.83	11.00	11.13	11.00	0.46	0.884	0.983	0.884
Stillborn	0.33	0.25	0.62	0.29	0.13	0.742	0.954	0.846
Mummies	0.17	0.13	0.13	0.57	0.11	0.566	0.459	0.653
Born alive	10.50	10.63	10.38	10.14	0.43	0.407	0.407	0.319
Litter birth weight, kg	15.48	15.57	15.77	15.11	0.63	0.953	0.832	0.782
Individual piglet weight, kg	1.41	1.45	1.46	1.50	0.04	0.575	0.636	0.972
Duration of farrowing, min	143	138	133	133	10	0.754	0.924	0.924
Piglet birth interval, min	15.58	15.45	13.35	12.64	1.67	0.498	0.910	0.937
Placental weight, kg	2.63	2.61	2.55	2.60	0.18	0.911	0.975	0.923
Placental weight per piglet, kg	0.24	0.24	0.25	0.24	0.02	0.926	0.995	0.926
Placental efficiency	6.60	6.92	7.26	6.86	0.63	0.829	0.979	0.796

Heat stress conditions: temperature: 29.61 ± 0.19°C (27.70–31.60 °C), temperature-humidity index: 72.91 ± 0.26 (70.30–75.70); Actively cooling conditions: temperature: 27.90 ± 0.15 °C (26.90–30.20 °C), temperature-humidity index: 70.81 ± 0.22 (69.30–73.80). Placenta weight was divided by litter weight to calculate the placental efficiency. When P-threshold is less than 0.05, it means statistically different among treatments.

Table 3
Effects of increasing the dietary selenium supply for heat-stressed or actively cooled sows on lactation performance of sows.

Item	Heat stress		Actively cooling		S.E.M.	P-value		
	0.3 mg/kg Se	1.2 mg/kg Se	0.3 mg/kg Se	1.2 mg/kg Se		Environment	Se	Interaction
No. of sows	10	10	10	10				
Colostrum yield, kg/sow	4.5	4.5	4.6	4.6	0.2	0.744	0.930	0.949
No. of piglets per litter								
After cross-foster	9.00	9.00	9.00	9.00	0.08	0.837	0.837	0.837
7-d piglet	8.78	8.86	8.85	8.92	0.11	0.768	0.731	0.996
14-d piglet	8.43	8.78	8.85	8.77	0.12	0.401	0.571	0.401
21-d piglet (weaned)	8.14	8.67	8.56	8.67	0.12	0.406	0.204	0.406
Preweaning survival, %	90.4	96.3	94.1	96.4	0.01	0.418	0.080	0.446
Litter weight, kg								
After cross-foster	15.05	15.29	14.91	15.73	0.31	0.821	0.424	0.656
7-d piglet	21.33	21.29	22.65	23.95	0.63	0.134	0.630	0.607
14-d piglet	32.40	34.81	36.52	37.20	1.00	0.079	0.342	0.820
21-d piglet	42.07	46.42	47.38	47.86	1.11	0.138	0.284	0.388
Average pig weight, kg								
After cross-foster	1.67	1.70	1.65	1.74	0.03	0.913	0.387	0.643
7-d piglet	2.44	2.40	2.54	2.68	0.06	0.127	0.666	0.476
14-d piglet	3.84	3.96	4.09	4.34	0.09	0.102	0.337	0.743
21-d piglet	5.15	5.35	5.54	5.56	0.12	0.230	0.663	0.712
Piglet mean ADG, g/d								
1st week of lactation	153.0	140.9	178.2	188.5	7.7	0.024	0.953	0.472
2nd week of lactation	214.0	218.3	222.5	235.6	9.2	0.518	0.664	0.826
3rd week of lactation	187.7	199.3	206.8	198.7	10.9	0.693	0.939	0.673
Mean of 1st to 3rd week	179.4	187.3	201.5	201.6	6.3	0.173	0.762	0.770

Heat stress conditions: temperature: 29.61 ± 0.19°C (27.70–31.60 °C), temperature-humidity index: 72.91 ± 0.26 (70.30–75.70); Actively cooling conditions: temperature: 27.90 ± 0.15 °C (26.90–30.20 °C), temperature-humidity index: 70.81 ± 0.22 (69.30–73.80). When P-threshold is less than 0.05, it means statistically different among treatments.

<0.05), and tended to have greater T-AOC ($P = 0.109$), and lesser MDA content ($P = 0.108$) in 21-d milk. The antioxidant status in colostrum and 21-d milk was not influenced by environment × dietary Se level interaction ($P > 0.05$).

The effects of increasing the dietary selenium supply for heat-stressed or actively cooled sows on antioxidant status in plasma of nursing piglets is shown in Table 8. Compared with nursing piglets from heat-stressed sows, nursing piglets from actively cooled sows had greater plasma GSH-Px activity ($P < 0.05$) and greater GSH content ($P = 0.062$) at 1-day of age, while they had greater T-AOC ($P = 0.072$) and GSH content ($P = 0.053$), and greater SOD activity ($P < 0.05$), but lesser MDA content ($P < 0.05$) in plasma at 21-day of age. Compared to nursing piglets from sows fed the control diet, nursing piglets from sows fed increasing Se had improved plasma antioxidant status including GSH-Px activity and MDA content both at 1-day and 21-days of age ($P < 0.05$). However, the antioxidant status of plasma in nursing piglets was

unaffected by environment × dietary Se level interaction ($P > 0.05$).

3.9. Immunoglobulin levels

The effects of increasing the dietary selenium supply for heat-stressed or actively cooled sows on immunoglobulin levels in plasma of sows are shown in Table 9. No differences between treatments were observed for immunoglobulin levels in sow plasma at farrowing ($P > 0.05$). However, sows fed increasing Se supply diet had higher plasma IgA at day 21 of lactation ($P < 0.05$). The immunoglobulin levels in plasma of sows were not influenced by environment or environment × Se level interaction ($P > 0.05$).

The effects of increasing the dietary selenium supply for heat-stressed or actively cooled sows on immunoglobulin levels in colostrum and milk are displayed in Table 10. Higher IgM levels in colostrum were observed for sows fed increasing Se supply diet compared with sows fed

Table 4

Effects of increasing the dietary selenium supply for heat-stressed or actively cooled sows on feed intake during lactation and backfat thickness of sows.

Item	Heat stress		Actively cooling		S.E.M.	P-value		
	0.3 mg/kg Se	1.2 mg/kg Se	0.3 mg/kg Se	1.2 mg/kg Se		Environment	Se	Interaction
No. of sows	10	10	10	10				
Average daily feed intake, kg								
1st week of lactation	2.70	2.67	2.76	2.74	0.05	0.521	0.784	0.945
2nd week of lactation	3.45	3.42	3.89	3.99	0.12	0.038	0.893	0.788
3rd week of lactation	3.62	3.62	4.37	4.42	0.15	0.008	0.928	0.920
Mean of 1st to 3th week	3.26	3.23	3.52	3.69	0.07	0.016	0.592	0.485
Sow backfat thickness, mm								
Day 110 of gestation	19.22	19.00	19.33	19.22	0.44	0.860	0.860	0.953
Day 21 of lactation (weaning)	16.33	16.14	16.44	16.33	0.89	0.874	0.874	0.967
Loss during lactation	2.89	2.86	2.89	2.88	0.17	0.960	0.905	0.965

Heat stress conditions: temperature: 29.61 ± 0.19°C (27.70–31.60 °C), temperature-humidity index: 72.91 ± 0.26 (70.30–75.70); Actively cooling conditions: temperature: 27.90 ± 0.15 °C (26.90–30.20 °C), temperature-humidity index: 70.81 ± 0.22 (69.30–73.80). When P-threshold is less than 0.05, it means statistically different among treatments.

the control diet ($P < 0.05$). Greater IgA in 21-d milk were found for sows fed increasing Se supply diet compared to sows fed the control diet ($P < 0.05$). The immunoglobulin levels in colostrum and milk were unaffected by environment and environment × Se level interaction ($P > 0.05$).

The effects of increasing the dietary selenium supply for heat-stressed or actively cooled sows on immunoglobulin levels in plasma of nursing piglets is presented in Table 11. Greater plasma IgA was observed in 1-day piglets from sows fed increasing Se supply diet vs. the control diet ($P < 0.05$). Greater IgA and IgG levels were found in plasma of 21-day piglets from sows fed increasing Se supply diet compared to the control diet ($P < 0.05$). The immunoglobulin levels in plasma of 1-day and 21-day piglets were unaffected by environment and environment × Se level interaction ($P > 0.05$).

Table 5

Effects of increasing the dietary selenium supply for heat-stressed or actively cooled sows on the nutrient composition of colostrum and milk.

Item	Heat stress		Actively cooling		S.E.M.	P-value		
	0.3 mg/kg Se	1.2 mg/kg Se	0.3 mg/kg Se	1.2 mg/kg Se		Environment	Se	Interaction
No. of sows	10	10	10	10				
Colostrum, g/kg								
Fat	43.4	42.1	43.9	44.8	2.8	0.801	0.981	0.866
Protein	78.3	89.7	85.3	87.2	1.4	0.420	0.021	0.088
Lactose	112.6	126.5	121.0	123.5	1.7	0.427	0.019	0.094
Solids-not-fat	207.6	235.3	224.9	229.2	3.4	0.412	0.022	0.088
Ash	16.9	18.4	17.2	17.4	0.2	0.446	0.074	0.208
7-d milk, g/kg								
Fat	55.2 ^b	73.3 ^a	59.6 ^b	60.7 ^b	1.7	0.176	0.003	0.007
Protein	39.9 ^b	41.2 ^{ab}	41.6 ^a	40.0 ^b	0.3	0.542	0.692	0.003
Lactose	60.6 ^b	62.2 ^{ab}	63.1 ^a	61.1 ^b	0.4	0.348	0.781	0.022
Solids-not-fat	107.9 ^b	112.0 ^{ab}	113.3 ^a	108.8 ^b	0.7	0.408	0.871	0.002
Ash	8.5 ^b	8.8 ^b	8.9 ^a	8.5 ^b	0.1	0.588	0.837	0.003
14-d milk, g/kg								
Fat	55.9	65.4	57.2	64.8	1.8	0.925	0.023	0.798
Protein	37.8	38.9	40.5	40.1	0.4	0.011	0.593	0.317
Lactose	57.5	58.9	61.5	60.8	0.5	0.009	0.726	0.324
Solids-not-fat	103.0	105.8	110.2	109.4	1.0	0.008	0.603	0.361
Ash	8.1	8.3	8.6	8.6	0.1	0.009	0.559	0.343
21-d milk, g/kg								
Fat	65.5	67.2	64.5	70.7	2.6	0.822	0.475	0.684
Protein	41.0	40.7	40.3	40.7	0.2	0.445	0.902	0.441
Lactose	62.1	61.5	61.0	61.4	0.4	0.425	0.940	0.494
Solids-not-fat	111.6	110.9	109.6	110.5	0.6	0.396	0.914	0.534
Ash	8.8	8.7	8.6	8.7	0.1	0.427	0.993	0.476

Heat stress conditions: temperature: 29.61 ± 0.19°C (27.70–31.60 °C), temperature-humidity index: 72.91 ± 0.26 (70.30–75.70); Actively cooling conditions: temperature: 27.90 ± 0.15 °C (26.90–30.20 °C), temperature-humidity index: 70.81 ± 0.22 (69.30–73.80). When P–threshold is less than 0.05, it means statistically different among treatments. In the same row, values with different letter superscripts indicates significant difference ($P < 0.05$).

Table 6
Effects of increasing the dietary selenium supply for heat-stressed or actively cooled sows on selenium and antioxidant status in plasma of sows.

Item	Heat stress		Active cooling		S.E.M	P-value		
	0.3 mg/kg Se	1.2 mg/kg Se	0.3 mg/kg Se	1.2 mg/kg Se		Environment	Se level	Interaction
No. of sows	6	6	6	6				
0 d								
Se, µg/g	0.168	0.202	0.163	0.226	0.009	0.240	< 0.001	0.064
T-AOC, mmol/L	0.60	0.69	0.61	0.63	0.02	0.545	0.219	0.473
SOD, U/mL	33.62	35.43	35.67	36.99	0.57	0.117	0.171	0.823
GSH-Px, U/mL	614.06	653.44	633.75	703.13	10.49	0.054	0.004	0.386
GSH, µmol/L	7.01	7.62	9.75	9.75	1.11	0.106	0.758	0.759
MDA, nmol/mL	3.28	2.84	3.28	2.49	0.13	0.456	0.014	0.456
21 d								
Se, µg/g	0.265	0.330	0.253	0.340	0.010	0.914	< 0.001	0.382
T-AOC, mmol/L	0.55	0.58	0.61	0.71	0.03	0.113	0.246	0.491
SOD, U/mL	28.53	29.58	27.36	29.33	0.72	0.641	0.326	0.761
GSH-Px, U/mL	1125.47	1334.70	1219.83	1308.72	22.63	0.294	< 0.001	0.072
GSH, µmol/L	3.11	2.99	4.05	5.03	0.52	0.171	0.688	0.609
MDA, nmol/mL	3.61	3.27	3.36	3.10	0.08	0.146	0.043	0.744

Heat stress conditions: temperature: 29.61 ± 0.19°C (27.70–31.60 °C), temperature-humidity index: 72.91 ± 0.26 (70.30–75.70); Actively cooling conditions: temperature: 27.90 ± 0.15 °C (26.90–30.20 °C), temperature-humidity index: 70.81 ± 0.22 (69.30–73.80). Abbreviations: MDA, malondialdehyde; Se, selenium; SOD, superoxide dismutase, T-AOC, total antioxidant capacity; GSH, glutathione; GSH-Px, glutathione peroxidase. When P-threshold is less than 0.05, it means statistically different among treatments.

reported a significant role for Se in antioxidant system of fetal pig during early pregnancy [30,31]. Although those literatures demonstrated that maternal supplementation of different Se source exert important role in fetal development and growth during whole gestation or early gestation, our study indicates that short-term increasing Se supply during late gestation did not affect fetal growth regardless of environmental conditions.

4.2. Lactation performance

In the present study, without interactions of the environments and dietary Se supply, colostrum yield and litter performance were not affected by increasing dietary Se supply diet, but preweaning survival was improved by increasing dietary Se supply in the diet. To our knowledge, there was no literature available about the effect of increasing dietary Se supply on lactation performance in sows. Selenium was reported to improve milk yield in cows [32,33] and sheep [34] when selenium and vitamin E were injected during late gestation. Increasing dietary Se supply enhanced milk yield in ewes after lambing

when supplemented in late gestation [35] or during lactation [36]. Lactation is one of the most challenging biological performance situations, and it is a highly oxygen dependent process. Peptide synthesis is producing reactive oxygen species that must be detoxified, whereas this biofunction is blocked by reducing cellular antioxidant capacity due to Se deficiency, hence, resulting in lower synthesis potential. These results indicate that increasing dietary Se supply elevated preweaning survival of nursing piglets regardless of environmental conditions. Our results may also indicate that there was an ongoing Se deficiency for late gestating and lactating sows of modern genotypes under currently-used requirement threshold and feeding recommendations.

4.3. Colostrum and milk composition

The percentage of protein, lactose, and solids-not-fat in colostrum were improved when sows were fed increasing dietary Se supply diet in the present study. The synthesis of milk compound is very challenging for the redox system, hence, limited Se supply may have significant adverse effects on the overall milk yield and composition. In human,

Table 7
Effects of increasing the dietary selenium supply for heat-stressed or actively cooled sows on selenium and antioxidant status in colostrum and milk.

Item	Heat stress		Active cooling		S.E.M	P-value		
	0.3 mg/kg Se	1.2 mg/kg Se	0.3 mg/kg Se	1.2 mg/kg Se		Environment	Se level	Interaction
No. of sows	6	6	6	6				
0 d								
Selenium, µg/g	0.107	0.215	0.101	0.224	0.016	0.932	< 0.001	0.728
T-AOC, mmol/L	1.23	1.22	1.21	1.40	0.06	0.487	0.446	0.392
SOD, U/mL	80.27	81.48	98.88	93.17	4.85	0.137	0.821	0.728
GSH-Px, U/mL	97.71	122.62	122.95	129.18	7.82	0.329	0.339	0.563
GSH, µmol/L	2.71	3.41	3.20	4.24	0.35	0.365	0.234	0.817
MDA, nmol/mL	14.13	9.78	12.16	8.96	0.80	0.351	0.018	0.699
21 d								
Selenium, µg/g	0.313	0.453	0.338	0.459	0.040	0.715	0.005	0.817
T-AOC, mmol/L	0.81	0.96	0.83	0.98	0.04	0.825	0.109	0.956
SOD, U/mL	20.80	24.99	22.98	24.97	1.42	0.718	0.308	0.712
GSH-Px, U/mL	78.96	80.69	77.59	87.59	3.01	0.662	0.357	0.513
GSH, µmol/L	7.69	8.49	9.17	9.04	0.28	0.077	0.547	0.406
MDA, nmol/mL	10.21	8.13	8.29	6.04	0.67	0.135	0.108	0.950

Heat stress conditions: temperature: 29.61 ± 0.19°C (27.70–31.60 °C), temperature-humidity index: 72.91 ± 0.26 (70.30–75.70); Actively cooling conditions: temperature: 27.90 ± 0.15 °C (26.90–30.20 °C), temperature-humidity index: 70.81 ± 0.22 (69.30–73.80). Abbreviations: MDA, malondialdehyde; Se, selenium; SOD, superoxide dismutase, T-AOC, total antioxidant capacity; GSH, glutathione; GSH-Px, glutathione peroxidase. When P-threshold is less than 0.05, it means statistically different among treatments.

Table 8

Effects of increasing the dietary selenium supply for heat-stressed or actively cooled sows on selenium and antioxidant status in plasma of nursing piglets.

Item	Heat stress		Active cooling		S.E.M	P-value		
	0.3 mg/kg Se	1.2 mg/kg Se	0.3 mg/kg Se	1.2 mg/kg Se		Environment	Se level	Interaction
No. of litters	6	6	6	6				
1 d								
Selenium, µg/g	0.108	0.129	0.104	0.159	0.008	0.352	0.010	0.205
T-AOC, mmol/L	0.54	0.61	0.59	0.66	0.03	0.464	0.339	1.000
SOD, U/mL	38.42	38.08	38.26	39.45	0.98	0.776	0.839	0.718
GSH-Px, U/mL	285.25	335.41	361.97	422.95	17.41	0.013	0.079	0.859
GSH, µmol/L	17.46	24.35	29.34	33.15	2.73	0.062	0.318	0.771
MDA, nmol/mL	21.74	14.23	20.37	14.88	1.62	0.911	0.052	0.753
21 d								
Selenium, µg/g	0.113	0.181	0.126	0.188	0.011	0.567	0.001	0.855
T-AOC, mmol/L	0.56	0.55	0.67	0.77	0.05	0.072	0.607	0.542
SOD, U/mL	16.40	17.82	22.10	20.00	0.86	0.021	0.830	0.276
GSH-Px, U/mL	760.68	798.64	748.47	900.34	26.91	0.392	0.078	0.279
GSH, µmol/L	18.29	19.57	21.76	22.86	0.85	0.053	0.480	0.956
MDA, nmol/mL	6.56	5.39	5.56	4.65	0.20	0.008	0.002	0.663

Heat stress conditions: temperature: 29.61 ± 0.19°C (27.70–31.60 °C), temperature-humidity index: 72.91 ± 0.26 (70.30–75.70); Actively cooling conditions: temperature: 27.90 ± 0.15 °C (26.90–30.20 °C), temperature-humidity index: 70.81 ± 0.22 (69.30–73.80). Abbreviations: MDA, malondialdehyde; Se, selenium; SOD, superoxide dismutase, T-AOC, total antioxidant capacity; GSH, glutathione; GSH-Px, glutathione peroxidase. When P-threshold is less than 0.05, it means statistically different among treatments.

lactating women had higher Se reference value due to the need of breast milk compared with non-lactating women [37]. In the present study, we also found that fat percentage in 7-d and 14-d milk was improved when sows were fed increasing dietary Se supply diet vs. the control diet. When nursing piglets received milk with higher fat content, they got more energy. Besides, nursing piglets received the colostrum and milk with higher Se content, which contribute to their improved Se and antioxidant status. Those may partly explain higher preweaning survival of nursing piglets. Many studies suggested that Se can increase milk fat and protein in ewes by increasing dietary Se supply during late gestation [35] or lactation [36]. Pappas et al. (2012) reported that feeding 0, 0.15, 0.3 and 3.0 mg/kg Se as Se-yeast to broilers had a linear effect on intramuscular fat content ($P < 0.001$), and affected meat fatty acid profiles, which implies that Se may play an important role in fat synthesis and metabolism [38]. Speckmann et al. (2017) demonstrated Se-dependent effects on lipogenesis that involve epigenetic mechanisms [39]. Zhao et al. (2016) also found that high dietary Se intake alters lipid metabolism in the liver and muscle of piglets [40]. Therefore, our results indicating that increasing dietary Se supply improved fat in 7 and 14-d milk are consistent with reports in the literature.

4.4. Se status

In the present study, regardless of environment, sows fed increasing Se (1.2 mg/kg) had greater plasma Se content than the 0.3 mg/kg Se

group sows at farrowing and 21 d post-partum. Similar to our results, Horkey et al. (2013) reported that Se content in erythrocytes increased with increasing dietary Se levels (0, 0.25 and 0.50 mg/kg) [41]. Kim and Mahan (2001) found that, regardless of Se source, with increasing dietary Se level, Se content in the serum of sows increased markedly and, for organic Se, gilts fed 3 mg/kg Se had an over 2-fold serum Se content at 110 d post-breeding, and 14 d post-partum compared with 0.3 mg/kg supplemental Se [42]. Along with increased Se in blood, more Se will be transferred to the mammary gland and produce colostrum and milk with greater Se content [12,43]. In the current study, sows fed increasing Se had greater Se content in both colostrum and 21-d milk, which is consistent with previous studies reporting feeding increasing Se to domestic animals, such as dairy cows [9,44]. The Se element can be maternally transferred from dam to nursing offspring via colostrum and milk [43]. Our study demonstrated that nursing piglet plasma Se content markedly responded to greater Se content in colostrum and milk from sows fed increasing Se at 1-day-old and 21-day-old. Cao et al. (2014) reported plasma Se content of weaning piglets increased along with increasing dietary Se levels [45], which is consistent with our results.

4.5. Antioxidant status

In our study, the antioxidant of sows was influenced by increasing Se diet regardless of environmental conditions. Consistent with our

Table 9

Effects of increasing the dietary selenium supply for heat-stressed or actively cooled sows on immunoglobulin levels in plasma of sows.

Item	Heat stress		Actively cooling		S.E.M.	P-value		
	0.3 mg/kg Se	1.2 mg/kg Se	0.3 mg/kg Se	1.2 mg/kg Se		Environment	Se	Interaction
No. of sows	6	6	6	6				
L0								
IgA, µg/mL	134.72	120.00	165.14	170.04	29.77	0.213	0.877	0.757
IgG, µg/mL	533.90	619.98	648.29	786.27	83.00	0.433	0.530	0.884
IgM, µg/mL	114.82	121.53	110.21	143.24	16.50	0.812	0.582	0.715
L21								
IgA, µg/mL	97.30	136.02	97.62	221.45	18.63	0.208	0.023	0.211
IgG, µg/mL	218.18	501.37	449.75	649.58	66.65	0.142	0.067	0.740
IgM, µg/mL	74.28	112.65	86.19	175.85	17.95	0.284	0.076	0.460

Heat stress conditions: temperature: 29.61 ± 0.19°C (27.70–31.60 °C), temperature-humidity index: 72.91 ± 0.26 (70.30–75.70); Actively cooling conditions: temperature: 27.90 ± 0.15 °C (26.90–30.20 °C), temperature-humidity index: 70.81 ± 0.22 (69.30–73.80). When P-threshold is less than 0.05, it means statistically different among treatments.

Table 10
Effects of increasing the dietary selenium supply for heat-stressed or actively cooled sows on immunoglobulin levels in colostrum and milk.

Item	Heat stress		Actively cooling		S.E.M.	P-value		
	0.3 mg/kg Se	1.2 mg/kg Se	0.3 mg/kg Se	1.2 mg/kg Se		Environment	Se	Interaction
No. of sows	6	6	6	6				
Colostrum								
IgA, mg/mL	1.33	1.53	1.37	1.92	0.10	0.291	0.070	0.380
IgG, mg/mL	19.78	22.76	19.68	26.27	3.35	0.822	0.531	0.812
IgM, mg/mL	0.57	1.14	0.80	1.26	0.10	0.318	0.007	0.768
21-d milk								
IgA, mg/mL	0.36	0.55	0.38	0.66	0.06	0.573	0.045	0.702
IgG, mg/mL	1.26	2.78	1.81	4.77	0.64	0.314	0.084	0.565
IgM, mg/mL	0.50	0.63	0.38	0.58	0.02	0.326	0.071	0.708

Heat stress conditions: temperature: 29.61 ± 0.19°C (27.70–31.60 °C), temperature-humidity index: 72.91 ± 0.26 (70.30–75.70); Actively cooling conditions: temperature: 27.90 ± 0.15 °C (26.90–30.20 °C), temperature-humidity index: 70.81 ± 0.22 (69.30–73.80). When P-threshold is less than 0.05, it means statistically different among treatments.

results, Horkey et al. (2014) reported that feeding 0.25 or 0.50 mg/kg Se as Se-yeast to lactating sows increased GPx activity, and reduced/oxygenated glutathione ratio in erythrocytes compared with the control diet, and the increase was greater for the 0.50 mg/kg diet [46]. Liu et al. (2016) found that increasing dietary Se and vitamin E (VE) improved oxidative stress of heat-stressed piglets in a short-term feeding trial [47]. Liu et al. (2018) further assessed the effects of a short-term increasing dietary Se on redox balance of heat-stressed growing pigs and found that increasing dietary Se tended to increase erythrocyte GPx activity [48]. It has been demonstrated that increasing dietary Se improved oxidative stress status and modulated the expression of heat shock proteins and inflammatory genes in skeletal muscle of heat-stressed sheep together with supranutritional VE supplementation [49,50]. Increasing Se itself also improved oxidative stress in heat-stressed sheep [51].

Sows fed increasing dietary Se diet had lesser MDA concentration in both colostrum and 21-d milk compared to sows fed the control diet, which indicates that increasing dietary Se improved antioxidant status of colostrum and milk. Pappas et al. (2012) found a linear decrease in MDA content in breast muscle of broilers at 1 day after slaughter associated with increased levels of Se in diets (0, 0.15, 0.3 and 3.0 mg/kg Se) [38]. The possible explanation is that Se is efficient in enhancing antioxidant defense capacity and protecting against oxidative stress.

Consistent with improved antioxidant status and Se content in colostrum, 1-day-old nursing piglets from increasing-Se-fed sows had greater GSH-Px activity and lesser MDA content. More significantly, considering that antioxidant status and Se content in 21-d milk increased, 21-day-old nursing piglets from increasing-Se-fed sows had greater T-AOC and lesser MDA content. Along with the improvement of antioxidant status in 21-milk, 21-day-old piglets from actively-cooled

sows had greater T-AOC, SOD activity, GSH content, and lesser MDA content. This indicates that, regardless of environmental conditions, dietary supplementation of increasing Se during the prenatal period can improve antioxidant status of 21-day-old nursing piglets, providing antioxidant protection against upcoming weaning stress [52,53].

4.6. Immunoglobins

In the present study, compared with the control Se level, increasing dietary Se supply did not affect IgG level in sow plasma at farrowing or in colostrum, but improved IgG levels in 1-day-old nursing piglets. However, environmental conditions did not affect immunoglobins level of sows, colostrum, milk, and piglets. Spallholz et al (1973) also reported that mice fed diets supplemented with Se produced enhanced IgG and IgM antibody titers [54]. Consistent with our results, Kamada et al. (2007) found that adding Se into colostrum with similar IgG levels increased IgG absorption in newborn calves [10], which may reflect the facts that there was an ongoing deficiency before the increase in the dietary supply level. Hall et al. (2014) reported that increasing maternal dietary Se supply increased Se level in colostrum and milk, and it increased the maternal IgG transfer from cows to calves [9]. In a different method of Se supplementation, injection of selenium in sows during late gestation improved the transfer of immunoglobulins from sows to piglets [11]. Sows injected with Se had increased colostrum concentrations of IgM compared to other treatment groups, indicating a basis for enhanced passive transfer of antibodies [11]. This result may explain our results where increasing maternal Se supply enhanced the immunoglobulin levels of nursing piglets. When nursing piglets got higher immunoglobulin levels, they had higher immunity, which may partly explain the improved preweaning survival. As for the underlying

Table 11
Effects of increasing the dietary selenium supply for heat-stressed or actively cooled sows on immunoglobulin levels in plasma of nursing piglets.

Item	Heat stress		Actively cooling		S.E.M.	P-value		
	0.3 mg/kg Se	1.2 mg/kg Se	0.3 mg/kg Se	1.2 mg/kg Se		Environment	Se	Interaction
No. of litters	6	6	6	6				
L1								
IgA, µg/mL	157.34	246.68	194.89	235.38	13.90	0.610	0.018	0.346
IgG, µg/mL	1270.26	1743.72	1673.45	3427.93	317.35	0.083	0.065	0.275
IgM, µg/mL	168.50	228.06	159.58	190.80	29.41	0.326	0.071	0.708
L21								
IgA, µg/mL	92.37	183.96	133.87	183.44	16.41	0.511	0.034	0.501
IgG, µg/mL	204.60	470.91	346.51	689.31	65.00	0.141	0.019	0.726
IgM, µg/mL	105.23	168.10	157.22	147.43	14.84	0.615	0.398	0.252

Heat stress conditions: temperature: 29.61 ± 0.19°C (27.70–31.60 °C), temperature-humidity index: 72.91 ± 0.26 (70.30–75.70); Actively cooling conditions: temperature: 27.90 ± 0.15 °C (26.90–30.20 °C), temperature-humidity index: 70.81 ± 0.22 (69.30–73.80). When P-threshold is less than 0.05, it means statistically different among treatments.

mechanisms of how Se affects immunoglobulin levels, the most likely explanation is that peptide synthesis is producing reactive oxygen species that must be detoxified, whereas this biofunction is hampered by reducing cellular antioxidant capacity due to Se deficiency, hence, resulting in lower synthesis potential. Therefore, Se supple to sows need revision as our findings suggest an increase in certain measures irrespective of the environment.

5. Conclusions

In conclusion, increasing maternal selenium supply improved piglet preweaning survival, colostrum and milk composition, as well as maternal selenium, antioxidant status and immunoglobulin transfer irrespective of the climatic conditions, which indicate that currently-used requirement thresholds and feeding recommendations of Se may be insufficient for late gestating and lactating sows of modern genotypes. However, further precise dose-response studies are needed to map the precise point of dietary gross-Se-requirements under varying conditions.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.jtmb.2018.11.010>.

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