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RESEARCH ARTICLE

Maternal chromium supplementation improves oxidation resistance, immunity, and intestinal morphology of goat kids injected with lipopolysaccharide

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Highlights

- Maternal chromium (Cr) supplementation can be transferred to offspring *via* both placenta and colostrum.
- Maternal Cr supplementation increased serum immunoglobulin concentrations and antioxidant capacity of goat kids.
- Maternal Cr supplementation improved the intestinal morphology of goat kids.

Abstract

This study evaluated the effects of maternal chromium (Cr), supplemented with Cr propionate (CrPro) during perinatal period of does, on antioxidant capacity, immune response, and intestinal morphology of goat kids injected with lipopolysaccharide (LPS). Forty Lezhi black does at 90 d of pregnancy were divided into 4 groups based on body weight (52.36±8.24) kg with 10 replicate pens for each treatment and one doe for each replicate pen. Treatments consisted of 0, 0.4, 1.2, or 2.0 mg of supplemental Cr per head per day (per head d^{-1}) from CrPro. After birth, the goat kids were allowed to suckle until 21 d. At 21-d-old, one male goat kid per replicate was sacrificed 2 h after LPS injection. Individual weight and litter weight of goat kids at birth and 21 d were not affected by maternal Cr supplementation. Chromium concentrations in umbilical cord, colostrum and liver of goat kids were linearly increased by maternal Cr supplementation (P<0.05). Maternal Cr supplementation quadratically increased serum total superoxide dismutase (T-SOD) activity of goat kids (P<0.05). Goat kids from maternal Cr supplementation groups had higher serum T-SOD activity than those from the control group (P<0.05). Serum malondialdehyde (MDA) concentration of goat kids was linearly decreased, whereas serum glutathione peroxidase (GSH-Px) activity was linearly increased as maternal Cr increased (P<0.05). Maternal Cr supplementation linearly increased colostrum immunoglobulin A (IgA), immunoglobulin G (IgG) and immunoglobulin M (IgM) concentrations (P<0.05), and quadratically increased serum IgG and IgM concentrations of goat kids with the greatest response detected at 0.4 mg per head d^{-1} maternal Cr supplementation group (P<0.05). The villus height (VH) and the ratio of VH to crypt depth (CD) (V/C) in the duodenum of goat kids increased quadratically as maternal Cr increased, and both reached the highest values in the 1.2 mg per head d^{-1} maternal Cr supplementation group. Maternal Cr supplementation linearly decreased ileal CD of goat kids. The results indicate that 0.4–2.0 mg (0.47–2.41 mg by analysis) per head d^{-1} maternal Cr supplementation from CrPro could improve antioxidant capacity, immune response, and small intestinal morphology of goat kids injected with LPS.

Keywords: maternal chromium supplementation, goat kids, antioxidant capacity, immune response, intestinal morphology

1. Introduction

The perinatal period, which includes late pregnancy and early lactation, is an important transitional physiological stage for maternal pregnancy, delivery, and nursing of neonates. This is a very stressful stage because the animals with pregnancy will experience important physiological and metabolic

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adaptations, in which the resulting redox imbalances lead to the occurrence of oxidative stress (Sordillo and Aitken 2009). On the other side, the increased stress hormones such as cortisol during this stage are known to negatively affect immune function of the pregnant animals (Burdick *et al.* 2012). This situation makes the pregnant females more vulnerable to health and fertility problems (Mekuriaw 2023). Maternal nutritional condition in this stage affects not only the pregnant animals themselves but also their offspring (Khanal and Nielsen 2017). This has led to an increase in the need of practices in reducing the physiological and metabolic stresses and enhancing the antioxidant capability as well as strengthening immune system of the pregnant animals and their offspring. Nutritional prevention and interventions have been the primary means for these practices because of the safety consideration during pregnancy. Thus, supplementing antioxidant micronutrients in prepartum diets has been suggested as a strategy to counterbalance reactive oxygen species (ROS) produced in late gestation and their consequences for animals and neonates (Sordillo and Aitken 2009; Abuelo *et al.* 2019).

In last decades, chromium (Cr) supplementation in the diets of domestic animals has attracted researchers' attention due to its broad influences in nutrition metabolism. Chromium, as a micronutrient, functions in insulin-sensitive tissues for enhancing insulin action (Spears 2019) and is involved in the metabolism of carbohydrates, proteins, lipids and nucleic acids (Sands and Smith 1999; Khan *et al.* 2014). The beneficial effects of Cr are observed mostly in the animals with environmental, dietary or hormonal stresses, in which Cr can reduce the harmful effects induced by these stresses (Lien *et al.* 1999; Sahin *et al.* 2002). Some studies have shown that Cr supplementation can improve growth performance, immunological status, and intestinal structure of broilers (Lu *et al.* 2019; Hayat *et al.* 2020; Huang *et al.* 2020), and increase the immune status of pigs and calf by increasing serum immunoglobulin concentration (Moonsie-Shageer and Mowat 1993; Wang *et al.* 2012). Moreover, the role of Cr in increasing antioxidant capacity in animals cannot be overlooked. For example, supplementation of Cr to finishing lambs with 3 mg of Cr kg^{-1} DM in the form of Cr methionine (CrMet) increased erythrocyte glutathione peroxidase (GSH-Px) and superoxide dismutase (SOD) activity, and decreased serum malondialdehyde (MDA) (Seifalinasab *et al.* 2022). Addition of 0.8 mg Cr kg^{-1} in the form of Cr propionate (CrPro) to heat-stressed ducks increased the serum SOD and GSH-Px activity and decreased serum MDA (Chen *et al.* 2021). The increased total antioxidant capacity (T-AOC) level and GSH-Px activity were also observed in broilers fed diet supplemented with 0.2 mg Cr kg^{-1} from CrPro (Zhang *et al.* 2024). These results clearly demonstrated that Cr plays an important role in increasing the antioxidant capacity of animals.

Female animals are under stress during gestation, which may result in Cr deficiency as stress has been shown to increase urinary Cr excretion (Anderson *et al.* 1988; Pechova and Pavlata 2007). Even if dietary Cr concentrations can meet normal production need, animals may still become Cr-deficient in the critical situations such as advanced pregnancy, parturition, onset of lactation, weaning, and transport (Lashkari *et al.* 2018). Therefore, it is particularly important to replenish Cr in diets of animals during these critical periods. Indeed, it has been noticed that addition of Cr to maternal diets increased the litter size in swine (Lindemann *et al.* 2004; Real *et al.* 2008) and offspring birth weight in lambs (Mousaie *et al.* 2017). Supplementing Cr in the form of CrPro to ewes' diets in the last 50 d of gestation and first 70 d of lactation increased lamb weaning weights at 70 d of age (Brochine *et al.* 2023). Although the beneficial effects of supplementing Cr to different animals on their growth performance, antioxidant capacity and immunity have been widely reported in the literature, the potential effects of maternal Cr supplementation on immune response, antioxidant capacity and intestinal morphology development of their offspring have not yet been explored. We hypothesized that maternal Cr supplementation would improve immune response, antioxidant capacity and intestinal morphology in goat kids by increasing their Cr levels *via* placenta and milk. To test our hypothesis, we examined the effects of maternal Cr supplementation during the perinatal period on umbilical cord and colostrum Cr deposition of does, and on the antioxidant capacity, immune response, and intestinal morphology of goat kids in Lezhi black goats.

2. Materials and methods

2.1. Animals, diets and experimental design

A total of 100 multiparous Lezhi black does (second or third parity) were hand-mated to a single buck following hormonally synchronized estrus and confirmed pregnancy by ultrasound examination. Forty Lezhi black does with similar body condition at 90 d of pregnancy (90±3.53) d were selected and randomly assigned to one of four treatments, based on average body weight (52.36±8.24) kg, with 10 replicate pens for each treatment and one doe for each replicate pen. Does were housed and fed individually in pens. Treatments consisted of 0, 0.4, 1.2, or 2.0 mg of supplemental Cr per head per day (per head d^{-1}) from feed grade CrPro. The CrPro used in the current study is the same as that used in our previous study (Huang *et al.* 2020). The doses of supplemental Cr were selected based on the results of the previous studies (Spears *et al.* 2019; Huang *et al.* 2020; Spears *et al.* 2020; Seifalinasab *et al.* 2022).

Does received a total-mixed ration (TMR), which was formulated to meet or exceed all nutrient requirements for does (NRC 2007). Ingredients and chemical compositions of the TMR are presented in Table 1. In addition to the TMR, does were fed ground corn-CrPro mixtures (50 g per head d^{-1}), which actually provided 0, 0.47, 1.42, or 2.41 mg Cr from CrPro, because analyzed Cr concentrations in the corn-CrPro mixtures were 0.101, 9.48, 28.4 and 48.3 mg kg^{-1} respectively. The corn-CrPro mixtures were top-dressed on the morning feeding. All does consumed the entirety of their corn-CrPro mixtures throughout the study. The TMR was delivered twice daily (08:00 and 16:00) in amounts to allow does ad libitum access to feed.

At birth, all goat kids were immediately separated from their dams. Within the first 15 min after birth, they were dried, ear

Table 1 Composition and nutrient concentrations of basal diet (%, dry matter (DM) basis)

Ingredients	Amount
Alfalfa pellets	30.00
Corn silage	15.00
Ryegrass	5.00
Corn	21.13
Beet pulp	15.00
Soybean meal	13.00
Sodium chloride	0.28
Calcium carbonate	0.50
Mineral premix[1)]	0.05
Vitamins[2)]	0.04
Total	100.00
Nutrient composition[3)]	
ME (MJ kg^{-1})	8.10
CP	14.40
Ca	0.97
P	0.33
NDF	40.6
ADF	23.5
Cr (mg kg^{-1})	0.29

[1)] Provided per kg of diet: Cu (as copper sulfate) 10 mg, Fe (as iron sulfate) 50 mg, Mn (as manganese sulfate) 20 mg, Zn (as zinc sulfate) 40 mg, I (as calcium iodate) 0.5 mg, Se (as sodium selenite) 0.10 mg, Co (as cobalt carbonate) 0.1 mg.
[2)] Provided per kg of diet: vitamin A 5,000 IU, vitamin D 700 IU, vitamin E 20 IU.
[3)] Analyzed values and each value based on triplicate determinations. ME, metabolizable energy; CP, crude protein; Ca, calcium; P, phosphorus; NDF, neutral detergent fiber; ADF, acid detergent fiber; Cr, chromium.

tagged, and weighed. After that, goat kids were allowed to suck colostrum from their dams and remained together from birth to wk 1. From wk 1 to wk 3 relative to birth, they were allocated in pens designed for goat kids (3.0 m×3.0 m), with up to 5 goat kids allocated per pen. Goat kids had free access to water and were allowed to suck milk from their dams for 30 min 3 times a day (08:00, 14:00, and 18:00). Colostrum and milk intake were estimated using the weigh-suckle-weigh method described by Nouri *et al.* (2023). Briefly, all goat kids were weighed before and after suckling, and the weight difference was registered as colostrum or milk intake. During the experimental period, goat kids had no access to any solid feed. At 21 d of age, male goat kids were weighed after food deprivation for 12 h. Lipopolysaccharide (LPS, *Escherichia coli* O111:B4; Sigma), was injected into the jugular vein of goat kids (200 ng LPS kg^{-1} of body weight) and the anal temperature was measured to determine whether they were in a state of stress. (Takeuchi *et al.* 1995; Bernhard *et al.* 2012). Goat kids were euthanized 2 h after LPS injection (He *et al.* 2014).

2.2. Sample collection

Umbilical cord samples on farrowing day were collected and stored at –20°C for Cr concentration analysis. Colostrum samples were collected within 1 h after the goat kids birth and stored at –20°C for Cr concentration analysis and immunoglobulin determinations. Blood samples of goat kids were obtained from the jugular vein in nonheparinized vacutainer tubes (Becton Dickinson, Franklin Lakes, NJ, USA), and centrifuged at 2,500×g for 10 min to separate the serum. The serum was collected and stored at –20°C for antioxidant profile and immunoglobulin determinations. After collection of blood samples, male goat kids from each treatment were euthanized as needed for welfare concerns. Liver (left lobe) samples obtained from a similar location in each goat kid were frozen in liquid nitrogen immediately and then stored at –80°C for Cr concentration and antioxidant profile analysis. The intestine was removed and divided into 3 segments of duodenum, jejunum and ileum. Duodenal, jejunal and ileal segments measuring approximately 3 cm were fixed in 4% paraformaldehyde solution for analysis of intestinal morphology.

2.3. Laboratory analyses

The concentrations of Cr in the corn-CrPro mixtures, TMR, umbilical cord, colostrum, and liver of goat kids were measured by graphite furnace atomic absorption spectroscopy (SOLAAR S2, Thermo Elemental, USA) after wet digestions with trace metal grade nitric acid (Trace Metal Grade, Fisher Scientific, USA) (Zhang *et al.* 2023). The concentrations of Ca, P and CP in the feed ingredient or TMR were determined as described by the AOAC (1990; 927.02, 988.05). Serum and colostrum immunoglobulin A (IgA), immunoglobulin G (IgG) and immunoglobulin M (IgM) concentrations were determined using double antibody sandwich commercial ELISA kits (Bethyl Laboratories, Montgomery, TX, USA) following the instructions. The activities of T-SOD and GSH-Px, and concentrations of MDA in serum and liver of the goat kids were measured using diagnostic kits (Nanjing Jiancheng Bioengineering Institute, Nanjing, China) according to the kit instructions. The histologic sections were examined with an Axioplan 2 optical microscope (Carl Zeiss Jena GmbH, Oberkochen, Germany) equipped with a refrigerated QImaging Retiga-4000R digital camera (QImaging, Surrey, Canada) coupled with a charge-coupled device detector. The images were analyzed with Motic Images Advanced 3.2. The villus height (VH) and crypt depth (CD) of 10 well-oriented villi were measured per section, and the ratio of villus height to crypt depth (V/C) was calculated.

2.4. Statistical analyses

All data were analyzed using the MIXED procedure of SAS (2008) for a randomized complete design with pen as the experimental unit. Orthogonal comparisons (unequally spaced) were applied for linear and quadratic responses when significant differences were detected (Lei *et al.* 2024). Significance was declared at $P \leq 0.05$. Differences among treatment means were determined using the LSD test.

3. Results

3.1. Growth performance

Dry matter intake of does was similar for all treatment groups, and no differences were detected in the estimated colostrum and milk intake of goat kids among treatments (data not shown). There were no effects of treatments on the average individual goat kid weight ($P>0.05$) and litter weight ($P>0.05$) at birth or 21 d after birth (Table 2). The average daily gain (ADG) ($P>0.05$) of goat kids was also not affected by maternal Cr supplementation during the 0–21 d (Table 2).

3.2. Tissue chromium concentrations

Chromium concentrations of umbilical cord (P<0.05), colostrum (P<0.0001) and liver of goat kids (P<0.05) were linearly increased with increased maternal Cr supplementation (Table 3).

3.3. Antioxidant capacity

No treatment differences were detected in liver T-SOD (P>0.05), GSH-Px (P>0.05) activities, and MDA concentration (P>0.05) of goat kids (Table 4). However, a quadratic response was detected for serum T-SOD activity (P<0.05) of goat kids as maternal Cr supplementation was increased. Goat kids from Cr supplementation groups had higher serum T-SOD activity than those from the control group (P<0.05). No differences were detected among Cr supplementation groups (P>0.05). Serum GSH-Px activity increased (P<0.05), and MDA concentration of goat kids decreased (P<0.05) linearly to increased maternal Cr supplementation (Table 4).

3.4. Serum and colostrum immunoglobulin concentrations

Colostrum IgA (P<0.05), IgG (P<0.05), and IgM (P<0.05) concentrations increased linearly as maternal Cr increased (Table 5). Compared with the control group, 1.2 mg per head d^{-1} maternal Cr supplementation group had higher IgA, IgG and IgM concentrations in colostrum. No differences were detected among Cr supplementation groups. Serum IgA (P>0.05) concentration of goat kids was not affected by maternal Cr supplementation. However, serum IgG and IgM concentrations of goat kids increased quadratically (P<0.05) with increased maternal Cr supplementation. The highest serum IgG and IgM concentrations were observed in goat kids from does fed with 0.4 mg Cr per head d^{-1} (Table 5).

3.5. Intestinal morphology

Jejunal morphology of goat kids was not affected by treatments. The duodenal VH (P<0.05) and V/C (P<0.05) of goat kids were quadratically increased with increased maternal Cr supplementation, and both reached the highest for the kids from does fed with 1.2 mg Cr per head d^{-1}. Crypt depth of ileum of goat kids (P<0.05) was linearly decreased by maternal Cr supplementation. No differences were observed in duodenal CD (P>0.05), ileal VH (P>0.05) and ileal V/C (P>0.05) of goat kids (Table 6).

4. Discussion

Maternal Cr supplementation at 0.4–2.0 mg (0.47–2.41 mg by analysis) per head d^{-1} from CrPro increased Cr concentration

Table 2 Effect of maternal chromium (Cr) supplementation on growth performance of goat kids

Items	Supplemental Cr does (mg per head d^{-1})				SEM[1)]	P-value	Linear	Quadratic
	0	0.4	1.2	2.0				
Average birth weight (kg)	3.46	3.26	3.09	3.29	0.196	0.654	–	–
Litter weight (kg)	6.51	7.15	7.09	7.05	0.668	0.924	–	–
21 d average weight (kg)	5.75	6.02	6.37	6.59	0.408	0.515	–	–
21 d litter weight (kg)	12.5	13.3	14.0	13.3	1.43	0.910	–	–
Average daily gain (g)	110	130	150	150	13.2	0.196	–	–

[1)] SEM, standard error of the mean.
Each value represents the mean of 10 replicates (n=10). –, not analyzed.

Table 3 Effect of maternal chromium (Cr) supplementation on Cr deposition in umbilical cord, colostrum, and liver of goat kids

Items	Supplemental Cr does (mg per head d^{-1})				SEM[1)]	P-value	Linear	Quadratic
	0	0.4	1.2	2.0				
Umbilical cord Cr (μg g^{-1} dry matter)	4.91 c	6.94 bc	9.05 ab	11.2 a	1.00	0.009	0.001	0.972
Colostrum Cr (ng mL^{-1})	30.2 b	35.4 b	63.7 a	70.2 a	6.15	0.0001	<0.0001	0.916
Liver Cr (μg g^{-1} dry matter)	0.25 b	0.27 b	0.40 ab	0.44 a	0.048	0.030	0.007	0.905

[1)] SEM, standard error of the mean.
Different letters in a row indicate a significant difference (P≤0.05). Each value represents the mean of 10 replicates (n=10).

Table 4 Effect of maternal chromium (Cr) supplementation on antioxidant indices of goat kids

Items[1)]	Supplemental Cr does (mg per head d^{-1})				SEM[2)]	P-value	Linear	Quadratic
	0	0.4	1.2	2.0				
Serum								
T-SOD (U mL^{-1})	137 b	151 a	158 a	150 a	3.05	0.008	0.007	0.004
GSH-Px (U mL^{-1})	99.7 b	116 b	137 ab	150 a	10.8	0.019	0.003	0.824
MDA (nmol mL^{-1})	6.39 a	6.46 a	6.48 a	5.62 b	0.220	0.018	0.037	0.055
Liver								
T-SOD (U mg/prot)	263	259	255	266	10.4	0.872	–	–
GSH-Px (U mg/prot)	14.2	12.8	17.3	14.2	1.83	0.347	–	–
MDA (nmol mg/prot)	0.61	0.67	0.59	0.63	0.076	0.900	–	–

[1)] T-SOD, total superoxide dismutase; GSH-Px, glutathione peroxidase; MDA, malondialdehyde.
[2)] SEM, standard error of the mean.
Different letters in a row indicate a significant difference (P≤0.05). Each value represents the mean of 10 replicates (n=10). –, not analyzed.

of umbilical cord and colostrum in does and liver in their goat kids. Increased serum IgG and IgM concentrations, serum T-SOD and GSH-Px activities, duodenal VH and V/C and decreased serum MDA concentration and ileal crypt depth of goat kids injected with LPS were also observed in the present study, indicating that maternal Cr supplementation had positive effects on immune response, antioxidant capacity and intestinal morphology of goat kids injected with LPS by increasing their Cr level *via* placenta and milk. Therefore, these results support our hypothesis, and provide a theoretical basis for the use of Cr during the perinatal period of does.

Lipopolysaccharide is a major component of the gram-negative bacteria cell wall. Studies have shown that LPS can induce inflammation and oxidative stress (Ranneh *et al.* 2019). In order to investigate the effect of maternal Cr on the immune response and antioxidant capacity of goat kids, LPS was used in our study to establish a stress model of goat kids. The elevated anal temperature measured indicated that the goat kids were under stress.

Chromium propionate supplementation to perinatal does did not affect goat kid weights and litter weights at birth and 21-d after birth. The ADG of goat kids was also not affected by maternal Cr supplementation in the present experiment. In previous studies, responses to maternal Cr supplementation in offsprings have been inconsistent. Supplementing does with CrPro during the last 50 d of gestation and 70 d of lactation did not affect goat kids birth weights but improved 70-d weaning weights (Brochine *et al.* 2023). In agreement with the present experiment, addition of 0.2–0.4 mg Cr kg^{-1}, from CrMet, to the diet of sows (from the prenatal period of 4 wk to the stages of re-breeding and delivery) had no effect on offspring birth weight, and litter weight at birth, or body weights at 21 d of age (Jia and Bao 2012). Maternal diet supplemented with 100 mg CrPro kg^{-1} for 21 d had no effect on the birth weight of the offspring rats (Staniek and Krejpcio 2009). However, addition of 0.1, 0.2, 0.4, or 0.8 mg Cr kg^{-1}, from Cr picolinate (CrPic), to the diet of New Zealand rabbits for consecutive 4 reproductive cycles increased offspring birth weight, litter weight and litter weaning weight (Li *et al.* 2012). Addition of 1.65 mg CrPic kg^{-1} to the diet of sows (from the d 14 of lactation to the end of the next piglet's birth) increased offspring litter weight but had no effect on offspring birth weight (Du *et al.* 2006). Many factors, such as Cr source, period and duration of Cr feeding, type of animals, and Cr concentration in the basal diet may affect animal responses to Cr supplementation. Further research is needed to explain the discrepancy among these experiments.

Consistent with the results in the present study, dietary CrPro supplementation at 0.2 mg Cr kg^{-1} or higher also increased liver Cr concentrations in turkeys (Spears *et al.* 2024), broilers (Spears *et al.* 2019) and dairy cows (Lloyd *et al.* 2010). The addition of 0.5 mg Cr kg^{-1} from CrPic also

Table 5 Effect of chromium (Cr) supplementation on immunoglobulin concentrations of colostrum and the serum of goat kids

Items[1)]	Supplemental Cr does (mg per head d^{-1})				SEM[2)]	*P*-value	Linear	Quadratic
	0	0.4	1.2	2.0				
Colostrum (mg mL^{-1})								
IgA	6.27 b	6.91 ab	7.37 a	7.62 a	0.316	0.0366	0.0049	0.9716
IgG	15.84 b	17.87 a	18.16 a	18.52 a	0.6349	0.0326	0.0081	0.5167
IgM	5.65 b	6.68 ab	6.92 a	7.47 a	0.3842	0.0242	0.0033	0.5276
Serum (mg mL^{-1})								
IgA	2.66	3.09	2.73	2.54	0.18	0.121	–	–
IgG	7.75 b	9.24 a	7.43 b	6.59 b	0.414	0.008	0.016	0.014
IgM	2.52 b	3.41 a	2.16 b	2.38 b	0.268	0.012	0.198	0.007

[1)] IgA, immunoglobulin A; IgG, immunoglobulin G; IgM, immunoglobulin M.
[2)] SEM, standard error of the mean.
Different letters in a row indicate a significant difference ($P \leq 0.05$). Each value represents the mean of 10 replicates ($n=10$). –, not analyzed.

Table 6 Effect of maternal chromium (Cr) supplementation on intestinal morphology of goat kids

Items[1)]	Supplemental Cr does (mg per head d^{-1})				SEM[2)]	*P*-value	Linear	Quadratic
	0	0.4	1.2	2.0				
Duodenum								
VH (μm)	608 bc	704 ab	721 a	606 c	32.4	0.030	0.943	0.005
CD (μm)	257	248	251	263	12.2	0.763	–	–
V/C	2.53 b	3.00 ab	3.21 a	2.48 b	0.943	0.042	0.769	0.019
Jejunum								
VH (μm)	401	517	463	509	45.0	0.350	–	–
CD (μm)	176	197	207	213	17.2	0.545	–	–
V/C	2.77	2.60	2.44	3.14	0.276	0.284	–	–
Ileum								
VH (μm)	428	416	398	402	43.4	0.966	–	–
CD (μm)	211 a	193 a	193 a	139 b	14.7	0.013	0.007	0.239
V/C	2.51	2.26	2.51	3.05	0.278	0.185	–	–

[1)] VH, villus height; CD, crypt depth; V/C, ratio of villus height to crypt depth.
[2)] SEM, standard error of the mean.
Different letters in a row indicate a significant difference ($P \leq 0.05$). Each value represents the mean of 10 replicates ($n=10$). –, not analyzed.

increased liver Cr concentration in broilers (Zha *et al.* 2009). In the present study, we found maternal Cr supplementation increased Cr concentrations in umbilical cord and colostrum of does as well as liver Cr concentration of goat kids. This suggests that Cr might enter goat kids' bodies through the placental barrier. Goat kids could obtain Cr from umbilical cord and colostrum of the does and increase liver Cr concentration.

The role of Cr in improving the antioxidant capacity of monogastric animals and ruminants is well documented (Lashkari *et al.* 2018; Chen *et al.* 2021). Sahin *et al.* (2010) reported linear decreases in concentrations of serum and liver MDA with increasing supplemental Cr as CrPic from 0 to 0.8 mg kg^{-1} in quails' diet. Chen *et al.* (2021) also reported supplementing 0.8 mg Cr kg^{-1} from CrPro increased the serum SOD and GSH-Px activities and decreased serum MDA concentration of ducks under heat stress. Similar results were reported in a study conducted in finishing lambs with the addition of 3 mg Cr kg^{-1} from CrMet (Seifalinasab *et al.* 2022). In agreement with these studies, serum SOD and GSH-Px activities of goat kids were increased, and serum MDA concentration was decreased by maternal Cr supplementation in the present study. This result may be related to the decrease of the production of ROS. Goat kids injected with LPS resulted in the production of ROS that damaged cell membranes, lipoproteins, DNA, and other components (Cecerska-Heryć *et al.* 2022). Organisms use antioxidant enzymes to neutralize ROS (Lei *et al.* 2016). The production of ROS in tissues is inversely associated with insulin sensitivity (Banse *et al.* 2015). Low insulin sensitivity elevated mitochondrial ROS production in the hippocampus of female rats (Kerr *et al.* 2024). Chromium enhances insulin sensitivity by binding to a low molecular weight oligopeptide (chromodulin) that amplifies insulin receptor tyrosine kinase activity (Vincent 2001). Therefore, we speculate Cr might decrease ROS production by enhancing insulin sensitivity, and then the reduced production of ROS might decrease the consumption of antioxidant enzymes, ultimately increasing their activity. However, no differences were detected in liver antioxidant properties of goat kids due to maternal Cr supplementation. Serum antioxidant index reflects the overall antioxidant capacity of the body (Debata *et al.* 2023; Chen *et al.* 2024), which might be one of the reasons for the different results between liver and serum.

Enhancement of the immune response of different animals including monogastric and ruminant animals receiving dietary Cr supplementation has been reported by many researchers (Sahin *et al.* 2005; Kheiri and Toghyani 2009; Lu *et al.* 2019). Gentry *et al.* (1999) reported that the cell-mediated immunity of late gestation and early lactating cows responded to Cr supplementation, indicated by higher blastogenic response of blood lymphocytes to phytohemagglutinin. Immunoglobulin M, IgA, and IgG are the dominant immunoglobulins in the serum and their concentrations are used as important indices of host humoral immune function (Ma *et al.* 2021). Supplemental 0.4 mg Cr kg^{-1} DM as Cr nicotinic acid increased total serum IgG of calves (Kegley and Spears 1995). Heat-stressed birds fed diets supplemented with 0.2 mg Cr kg^{-1} from CrPro showed increased IgG and IgM concentrations (Huang *et al.* 2020). Consistent with these results, serum IgG and IgM of goat kids responded quadratically to increasing maternal Cr in the present study. Goat kids from does supplemented with 0.4 mg Cr per head d^{-1} had the highest serum IgG and IgM concentrations. Although there are many studies have demonstrated the enhancement of the immune response in animals receiving dietary Cr supplementation, no data were available for maternal Cr supplementation on immunity of offspring. To our knowledge, this is the first study to investigate the effect of maternal Cr supplementation on immune response of goat kids.

Goat kids are born with an immature immune system. For newborn ruminants, the insufficient transfer of immune components (i.e., immunoglobulins) through the placenta makes colostrum intake almost the only way to achieve optimal passive immune transfer (Hernández-Castellano *et al.* 2015b). Almost all IgG detected in the bloodstream of lambs during the first days after birth is colostrum derived (Hernández-Castellano *et al.* 2015a). Similar results were reported by Rodríguez *et al.* (2009) in goat kids. In the present study, an increase in IgG in colostrum was detected by maternal Cr supplementation and along with the IgG increase in colostrum, an increase in the serum IgG of goat kids were also detected. Many studies have shown that the immunoglobulin concentrations of the colostrum play key roles in the healthy growth and development of offspring (Charneca *et al.* 2015; Zhang *et al.* 2021). The better immune response of goat kids may be due to increased colostrum IgG concentration and the antioxidant activity of Cr. It is the first study, to our knowledge, to explore the effect of maternal Cr supplementation on colostrum IgG concentration. The mechanism for increasing colostrum IgG concentration by maternal Cr supplementation is still unknown, and further research is needed.

Small intestinal morphology, including the VH, CD, and V/C, reflects the capacity of the small intestine for nutrient absorption to a certain extent. Villus height and V/C are good indicators of gut health and the functional capacity of the intestine (Fasina and Olowo 2013). Limited research has investigated the effect of dietary Cr on intestinal morphology of goats. In the present study, duodenal VH and V/C of goat kids were increased by maternal Cr supplementation and CD in ileum was decreased by maternal Cr supplementation. This implies that maternal Cr supplementation from CrPro is beneficial to gut health of goat kids. Consistent with this result, the addition of 0.2 mg CrPro kg^{-1} in the diet of broilers increased the VH and V/C in duodenum (Huang *et al.* 2020). Significant results with respect to VH and V/C of broilers were also observed in groups receiving Cr compared to control (Hayat *et al.* 2020). Improved intestinal morphology may result in better absorption and utilization of nutrients and improve growth performance of the animals. The mechanism behind this needs to be investigated and clarified in future studies.

5. Conclusion

Based on the data of the present study, 0.4–2.0 mg (0.47–2.41 mg by analysis) per head d^{-1} maternal Cr supplementation increased immunoglobulin concentrations in the colostrum of

does and the serum of goat kids injected with LPS. Serum antioxidant capacity and the intestinal morphology of goat kids were also improved. This suggests that, under the conditions of this experiment, 0.4–2.0 mg (0.47–2.41 mg by analysis) per head d^{-1} maternal Cr supplementation from CrPro would be beneficial for goat kids injected with LPS to improve immune response, antioxidant capacity and intestinal morphology.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that they did not use AI in the preparation and writing of this manuscript.

Ethical approval

All experimental procedures were approved by the Animal Care and Use Committee of Southwest Minzu University, China (approval no. smu-202301147).

References

Abuelo A, Hernández J, Benedito J L, Castillo C. 2019. Redox biology in transition periods of dairy cattle: Role in the health of periparturient and neonatal animals. *Antioxidants*, **8**, 20.

Anderson R A, Bryden N A, Polansky M M, Deuster P A. 1988. Exercise effects on chromium excretion of trained and untrained men consuming a constant diet. *Journal of Applied Physiology*, **64**, 249–252.

AOAC (Association of Official Analytical Chemists). 1990. *Official Methods of Analysis*. 9th ed. Association of Official Analytical Chemists, Arlington, VA, USA.

Banse H E, Frank N, Kwong G P S, McFarlane D. 2015. Relationship of oxidative stress in skeletal muscle with obesity and obesity associated hyperinsulinemia in horses. *Canadian Journal of Veterinary Research*, **79**, 329–338.

Bernhard B C, Burdick N C, Rounds W, Rathmann R J, Carroll J A, Finck D N, Jennings M A, Young T R, Johnson B J. 2012. Chromium supplementation alters the performance and health of feedlot cattle during the receiving period and enhances their metabolic response to a lipopolysaccharide challenge. *Journal of Animal Science*, **90**, 3879–3888.

Brochine L, dos Santos F F, Moreira F M, de Zoppa A L, Leme P R, Tedeschi L O, Gallo S B. 2023. The impact of fetal programming in ewe nutrition with chromium propionate or calcium salts of palm oil on the meat quality and bone of the progeny. *Biological Trace Element Research*, **201**, 2331–2340.

Burdick N C, Bernhard B C, Carroll J A, Rathmann R J, Johnson B J. 2012. Enhancement of the acute phase response to a lipopolysaccharide challenge in steers supplemented with chromium. *Innate Immunity*, **18**, 592–601.

Cecerska-Heryć E, Polikowska A, Serwin N, Roszak M, Grygorcewicz B, Heryć R, Michalczyk A, Dołęgowska B. 2022. Importance of oxidative stress in the pathogenesis, diagnosis, and monitoring of patients with neuropsychiatric disorders, a review. *Neurochemistry International*, **153**, 105269.

Charneca R, Vila-Viçosa J M, Infante P, Nunes J, Dividich L J. 2015. Colostrum production of Alentejano and Large-White×Landrace sows: Consumption, passive immunity and mortality of piglets. *Spanish Journal of Agricultural Research*, **13**, e0611.

Chen J F, Xing Y, Nie M, Xu M M, Huang H F, Xie H, Liao J H, Lin X, Duan J N, Zhang J X. 2024. Comparative effects of various dietary selenium sources on growth performance, meat quality, essential trace elements content, and antioxidant capacity in broilers. *Poultry Science*, **103**, 104057.

Chen X L, Zeng Y B, Liu L X, Song Q L, Zou Z H, Wei Q P, Song W J. 2021. Effects of dietary chromium propionate on laying performance, egg quality, serum biochemical parameters and antioxidant status of laying ducks under heat stress. *Animal*, **15**, 100081.

Debata N R, Sethy K, Swain R K, Mishra S K, Panda N, Maity S. 2023. Supplementation of nano-selenium (SeNPs) improved growth, immunity, antioxidant enzyme activity, and selenium retention in broiler chicken during summer season. *Tropical Animal Health and Production*, **55**, 260.

Du L Y, Lu J B, Cui Z J, He M Y. 2006. Effect of supplementation chromium on reproductive performance in multiparous sows. *Journal of Inner Mongolia Minzu University* (Natural Science), **21**, 53–56. (in Chinese)

Fasina Y O, Olowo Y L. 2013. Effect of a commercial yeast-based product (Maxigen®) on intestinal villi morphology and growth performance of broiler chickens. *International Journal of Poultry Science*, **12**, 9–14.

Gentry L R, Fernandez J M, Ward T L, White T W, Southern L L, Bidner T D, Thompson D L, Horohov D W, Chapa A M, Sahlu T. 1999. Dietary protein and chromium tripicolinate in Suffolk wether lambs: Effects on production characteristics, metabolic and hormonal responses, and immune status. *Journal of Animal Science*, **77**, 1284–1294.

Hayat K, Bodinga B M, Han D, Yang X, Sun Q Z, Aleya L, Abdel-Daim M M, Yang X J. 2020. Effects of dietary inclusion of chromium propionate on growth performance, intestinal health, immune response and nutrient transporter gene expression in broilers. *Science of the Total Environment*, **705**, 135869.

He Z X, Sun Z H, Yang W Z, Beauchemin K A, Tang S X, Zhou C S, Han X F, Wang M, Kang J H, Tan Z L. 2014. Effects of maternal protein or energy restriction during late gestation on immune status and responses to lipopolysaccharide challenge in postnatal young goats. *Journal of Animal Science*, **92**, 4856–4864.

Hernández-Castellano L E, Morales-delaNuez A, Sanchez-Macias D, Moreno-Indias I, Torres A, Capote J, Arguello A, Castro N. 2015a. The effect of colostrum source (goat vs. sheep) and timing of the first colostrum feeding (2h *vs*. 14h after birth) on body weight and immune status of artificially reared newborn lambs. *Journal of Dairy Science*, **98**, 204–210.

Hernández-Castellano L E, Suarez-Trujillo A, Martell-Jaizme D, Cugno G, Arguello A, Castro N. 2015b. The effect of colostrum period management on BW and immune system in lambs: From birth to weaning. *Animal*, **9**, 1672–1679.

Huang Y L, Luo Q H, Xiao F, Lin X, Spears J W. 2020. Research note: Responses of growth performance, immune traits, and small intestinal morphology to dietary supplementation of chromium propionate in heat-stressed broilers. *Poultry Science*, **99**, 5070–5073.

Jia R L, Bao H Y. 2012. Effect of chromium methionine on the reproductive performance of sows. *Feed Industry*, **33**, 57–58. (in Chinese)

Kegley E B, Spears J W. 1995. Immune response, glucose metabolism, and performance of stressed feeder calves fed inorganic or organic chromium. *Journal of Animal Science*, **73**, 2721–2726.

Kerr N R, Mossman C W, Chou C H, Bunten J M, Kelty T J, Childs T E, Rector R S, Arnold W D, Grisanti L A, Du X W, Booth F W. 2024. Hindlimb immobilization induces insulin resistance and elevates mitochondrial ROS production in the hippocampus of female rats. *Journal of Applied Physiology*, **137**, 512–526.

Khan R U, Naz S, Dhama K. 2014. Chromium: Pharmacological applications in heat stressed poultry. *International Journal of Pharmacology*, **10**, 213–217.

Khanal P, Nielsen M O. 2017. Impacts of prenatal nutrition on animal production and performance: A focus on growth and metabolic and endocrine function in sheep. *Journal of Animal Science and Biotechnology*, **8**, 1–14.

Kheiri F, Toghyani M. 2009. Effect of different levels of inorganic chromium on performance and immunity of broiler chicks. *Journal of Animal and Veterinary Advances*, **8**, 1819–1823.

Lashkari S, Habibian M, Jensen S K. 2018. A review on the role of chromium supplementation in ruminant nutrition — effects on productive performance, blood metabolites, antioxidant status,

and immunocompetence. *Biological Trace Element Research*, **186**, 305–321.
Lei K W, Wu H, Spears J W, Lin X, Wang X, Bai X, Huang Y L. 2024. Responses of growth performance, antioxidant function, small intestinal morphology and mRNA expression of jejunal tight junction protein to dietary iron in yellow-feathered broilers. *Journal of Integrative Agriculture*, **23**, 1329–1337.
Lei X G, Zhu J H, Cheng W H, Bao Y, Ho Y S, Reddi A R, Holmgren A, Arnér E S. 2016. Paradoxical roles of antioxidant enzymes: Basic mechanisms and health implications. *Physiological Reviews*, **96**, 307–364.
Li X C, Zhao W J, Zhang F F, Chen H C, Feng Q K, Huang S Wang G. 2012. Effect of chromium on the reproductive performance of SPF-rated New Zealand rabbits. *Laboratory Animal Science*, **29**, 26–28. (in Chinese)
Lien T F, Horng Y M, Yang K H. 1999. Performance, serum characteristics, carcase traits and lipid metabolism of broilers as affected by supplement of chromium picolinate. *British Poultry Science*, **40**, 357–363.
Lindemann M D, Carter S D, Chiba L I, Dove C R, LeMieux F M, Southern L L. 2004. A regional evaluation of chromium tripicolinate supplementation of diets fed to reproducing sows. *Journal of Animal Science*, **82**, 2972–2977.
Lloyd K E, Fellner V, McLeod S J, Fry R S, Krafka K, Lamptey A, Spears J W. 2010. Effects of supplementing dairy cows with chromium propionate on milk and tissue chromium concentrations. *Journal of Dairy Science*, **93**, 4774–4780.
Lu L, Zhao L L, Dong S Y, Liao X D, Dong X Y, Zhang L Y, Luo X G. 2019. Dietary supplementation of organic or inorganic chromium modulates the immune responses of broilers vaccinated with Avian influenza virus vaccine. *Animal*, **13**, 983–991.
Ma J, Mahfuz S, Wang J, Piao X. 2021. Effect of dietary supplementation with mixed organic acids on immune function, antioxidative characteristics, digestive enzymes activity, and intestinal health in broiler chickens. *Frontiers in Nutrition*, **8**, 673316.
Mekuriaw Y. 2023. Negative energy balance and its implication on productive and reproductive performance of early lactating dairy cows. *Journal of Applied Animal Research*, **51**, 220–229.
Moonsie-Shageer S, Mowat D N. 1993. Effect of level of supplemental chromium on performance, serum constituents, and immune status of stressed feeder calves. *Journal of Animal Science*, **71**, 232–238.
Mousaie A, Valizadeh R, Chamsaz M. 2017. Selenium-methionine and chromium-methionine supplementation of sheep around parturition: Impacts on dam and offspring performance. *Archives of Animal Nutrition*, **71**, 134–149.
Nouri M, Zarrin M, Ahmadpour A, Castro N, González-Cabrera M, Hernández-Castellano L E. 2023. Feed restriction around parturition does not affect colostrum immunoglobulin G concentration in dairy fat-tailed sheep but does affect performance and blood metabolites in newborn lambs. *Journal of Dairy Science*, **106**, 2980–2988.
NRC (National Research Council). 2007. *Nutrient Requirements of Goats*. 7th ed. National Academies Press, Washington, D.C.
Pechova A, Pavlata L. 2007. Chromium as an essential nutrient: A review. *Veterinarni Medicina*, **52**, 1–18.
Ranneh Y, Akim A M, Hamid H A, Khazaai H, Fadel A, Mahmoud A M. 2019. Stingless bee honey protects against lipopolysaccharide induced-chronic subclinical systemic inflammation and oxidative stress by modulating Nrf2, NF-κB and p38 MAPK. *Nutrition and Metabolism*, **16**, 1–17.
Real D E, Nelssen J L, Tokach M D, Goodband R D, Dritz S S, Woodworth J C, Owen K Q. 2008. Additive effects of L-carnitine and chromium picolinate on sow reproductive performance. *Livestock Science*, **116**, 63–69.
Rodríguez C, Castro N, Capote J, Morales-DelaNuez A, Moreno-Indias I, Sánchez-Macías D, Argüello A. 2009. Effect of colostrum immunoglobulin concentration on immunity in Majorera goat kids. *Journal of Dairy Science*, **92**, 1696–1701.
Sahin K, Ozbey O, Onderci M, Cikim G, Aysondu M H. 2002. Chromium supplementation can alleviate negative effects of heat stress on egg production, egg quality and some serum metabolites of laying Japanese quail. *The Journal of nutrition*, **132**, 1265–1268.
Sahin N, Akdemir F, Tuzcu M, Hayirli A, Smith M O, Sahin K. 2010. Effects of supplemental chromium sources and levels on performance, lipid peroxidation and proinflammatory markers in heat-stressed quails. *Animal Feed Science and Technology*, **159**, 143–149.
Sahin N, Sahin K, Onderci M, Gursu M F, Cikim G, Vijaya J, Kucuk O. 2005. Chromium picolinate, rather than biotin, alleviates performance and metabolic parameters in heat-stressed quail. *British Poultry Science*, **46**, 457–463.
Sands J S, Smith M O. 1999. Broilers in heat stress conditions: Effects of dietary manganese proteinate or chromium picolinate supplementation. *Journal of Applied Poultry Research*, **8**, 280–287
SAS (Statistical Analysis System). 2008. Institute SAS/STAT version 9.2 User's Guide. SAS Institute, Cary, NC, USA.
Seifalinasab A, Mousaie A, Doomary H. 2022. Dietary high chromium-methionine supplementation in summer-exposed finishing lambs: Impacts on feed intake, growth performance, and blood cells, antioxidants, and minerals. *Biological Trace Element Research*, **200**, 156–163.
Sordillo L M, Aitken S L. 2009. Impact of oxidative stress on the health and immune function of dairy cattle. *Veterinary Immunology and Immunopathology*, **128**, 104–109.
Spears J W. 2019. Boron, chromium, manganese, and nickel in agricultural animal production. *Biological Trace Element Research*, **188**, 35–44.
Spears J W, Lloyd K E, Krafka K, Hyda J, Grime J L. 2024. Research note: Chromium propionate for turkeys: Effect on tissue chromium concentrations and human food safety. *Poultry Science*, **103**, 103196.
Spears J W, Lloyd K E, Pickworth C A, Huang Y L, Krafka K, Hyda J, Grime J L. 2019. Chromium propionate in broilers: Human food and broiler safety. *Poultry Science*, **98**, 6579–6585.
Spears J W, Lloyd K E, Siciliano P, Pratt-Phillips S, Goertzen E W, McLeod S J, Moore J, Krafka K, Hyda J, Rounds W. 2020. Chromium propionate increases insulin sensitivity in horses following oral and intravenous carbohydrate administration. *Journal of Animal Science*, **98**, skaa095.
Staniek H, Krejpcio Z. 2009. The effects of tricentric chromium (III) propionate complex supplementation on pregnancy outcome and maternal and foetal mineral status in rat. *Food and Chemical Toxicology*, **47**, 2673–2678.
Takeuchi Y, Kikusui T, Mori Y. 1995. Changes in the behavioral parameters following the lipopolysaccharide administration in goats. *Journal of Veterinary Medical Science*, **57**, 1041–1044.
Vincent J B. 2001. The bioinorganic chemistry of chromium (III). *Polyhedron*, **20**,1–26.
Wang M Q, Wang C, Li H, Du Y J, Tao W J, Ye S S, He Y D. 2012. Effects of chromium-loaded chitosan nanoparticles on growth, blood metabolites, immune traits and tissue chromium in finishing pigs. *Biological Trace Element Research*, **149**, 197–203.
Zha L Y, Zeng J W, Chu X W, Mao L M, Luo H J. 2009. Efficacy of trivalent chromium on growth performance, carcass characteristics and tissue chromium in heat-stressed broiler chicks. *Journal of the Science of Food and Agriculture,* **89**, 1782–1786.
Zhang L L, Gu X L, Wang J, Liao S, Duan Y H, Li H, Song Z H, He X, Fan Z Y. 2021. Effects of dietary isomaltooligosaccharide levels on the gut microbiota, immune function of sows, and the diarrhea rate of their offspring. *Frontiers in Microbiology*, **11**, 588986.
Zhang Q Q, Zhang H T, Jiang Y K, Wang J P, Wu D, Wu C M, Che L Q, Lin Y, Zhuo Y, Luo Z, Nie K K, Li J. 2024. Chromium propionate supplementation to energy-and protein-reduced diets reduces feed consumption but improves feed conversion ratio of yellow feathered male broilers in the early period and improves meat quality. *Poultry Science*, **103**, 103260.
Zhang Y M, Ao D, Lei K W, Lin X, Spears J W, Shi H T, Huang Y L, Yang F L. 2023. Dietary copper supplementation modulates performance and lipid metabolism in meat goat kids. *Journal of Integrative Agriculture*, **22**, 214–221.

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