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Metabolic and Reproductive Responses to Peripartum Feed Supplementation in Hyperprolific Gilts

Julia Cantin [1], Carlos Cantin [2], Olga Mitjana [1,3], Maria Teresa Tejedor [4,*], Carlos Gil-Rubio [5], Ana Maria Garrido [1] and Maria Victoria Falceto [1,3]

[1] Department of Animal Pathology, University of Zaragoza, Spain
[2] Independent consulting veterinarian, Zaragoza, Spain
[3] Agroalimentary Institute of Aragon-IA2, Department of Animal Pathology, Universidad de Zaragoza-CITA
[4] Department of Anatomy, Embryology and Animal Genetics, CIBERV, University of Zaragoza
[5] Veterinary technical service Nutega, CCPA Group
* Correspondence: ttejedor@unizar.es

Abstract

A nutritional supplement was formulated for hyperprolific gilts to support metabolic adaptation and reproductive performance during the peripartum period. A total of 126 gilts were randomly assigned to a control (C) or a treatment (T) group. Control gilts received standard commercial diets, whereas treatment gilts received the same diets supplemented during the last 35 days of gestation and the first 5 days of lactation. The multi-nutrient supplement contained calcium (Ca; 4.1%), sodium (Na; 4.0%), lysine (Lys; 1.96%), methionine (Met; 1.32%), vitamin B_{12} (0.3 mg/kg), choline chloride (600 mg/kg), betaine (475 mg/kg), and L-carnitine (500 mg/kg). The treatment group showed a reduction in stillbirth rate ($p = 0.001$), a lower incidence of neonatal diarrhea ($p < 0.001$), and a lower prevalence of postpartum hypophagia ($p = 0.014$). In addition, β-hydroxybutyrate (BHBA) and creatinine (CREA) concentrations at day 107 of gestation were significantly lower in the T group ($p < 0.001$). Higher piglet body weight at birth ($p = 0.011$) and at 15 days of lactation ($p < 0.001$), as well as greater maternal backfat thickness and longissimus muscle depth at 26 days of lactation ($p < 0.001$), were also observed in supplemented gilts. Moreover, hypophagia was associated with elevated BHBA concentrations ($p < 0.001$), whereas neonatal diarrhea was associated with higher BHBA ($p = 0.001$) and CREA ($p = 0.005$) concentrations. Overall, peripartum multi-nutrient supplementation could represent a practical nutritional strategy to support reproductive efficiency and early litter performance in hyperprolific gilts.

Keywords: feed supplementation; gilts; peripartum; reproduction; metabolism

1. Introduction

Genetic selection for hyperprolific sows has markedly increased the number of live-born piglets per litter. However, this improvement in prolificacy has also introduced challenges, including reduced piglet birth weight, greater within-litter variability, lower vitality, and slower growth during lactation, ultimately leading to reduced weaning weights [1–5]. Multiparous sows generally outperform gilts in piglet growth and weaning weights, emphasizing the need for targeted nutritional strategies for nulliparous sows [6–8].

Genetic progress in the modern sow population has primarily focused on lean meat deposition and feed efficiency, traits closely linked to reproductive physiology [9]. For nulliparous sows, appropriate nutrition is crucial to sustain ongoing body growth, maintain adequate fat and muscle reserves, and support fetal and placental development. Sufficient nutrient intake also ensures optimal colostrum synthesis, smooth farrowing, and efficient lactation, maximizing reproductive performance [10].

Over recent decades, sow milk yield has nearly doubled, reaching 10.7 kg/day along with approximately 0.75 kg/day per nursing piglet [11,12]. To achieve high lifetime productivity, hyperprolific gilts should attain a body weight of 140–160 kg and a back-fat thickness of 13–15 mm at 220–240 days of age. Although mating at heavier weights (≈170 kg) may improve immediate reproductive performance, it also increases lifetime energy requirements and reduces feed efficiency [9,13,14].

The transition period—typically encompassing the final 5–7 days of gestation and the first 3–5 days of lactation—represents a critical window for both the sow and her litter. During this stage, sows experience abrupt physiological and behavioral shifts, including relocation from group gestation pens to individual farrowing crates, major hormonal changes that prepare the uterus and mammary glands for parturition and lactation, and marked fluctuations in feed intake [9,15]. Concurrently, piglets undergo dramatic metabolic and environmental transitions from intra- to extrauterine life, making this period crucial for neonatal survival. Notably, nulliparous sows exhibit lower voluntary feed intake than multiparous animals, further increasing their risk of negative energy balance [6,16,17].

In hyperprolific gilts, the metabolic burden of large litters promotes extensive mobilization of protein reserves from skeletal muscle, intestinal tissue, and reproductive organs, which may adversely affect farrowing and offspring development [13,18,19]. During the peripartum phase, nutrient imbalances frequently occur due to the simultaneous demands for mammary growth, colostrum synthesis, rapid fetal development, uterine contractions, and milk production. These processes induce profound endocrine and metabolic alterations, such as gestational hyperglycemia and transient hypophagia, which complicate nutritional management [20–27].

Oxidative stress also plays a central role during this transition. Replacement gilts display higher oxidative stress markers than multiparous sows [28]. Sodium (Na) contributes to the synthesis of glutathione, a tripeptide crucial for detoxification, immune modulation, and antioxidant defense. Glutathione neutralizes reactive oxygen species and preserves cellular integrity [29–32]. Calcium (Ca) is another key mineral during farrowing, supporting uterine contractility and milk production. Hypocalcemia at parturition impairs myometrial contractions, prolongs farrowing duration, and increases stillbirth incidence [33].

Amino acid balance also becomes critical during late gestation. Lysine (Lys) and methionine (Met) requirements increase substantially to sustain fetal growth, placental expansion, and mammary tissue development. Dietary lysine deficiency compromises milk yield and reduces piglet daily weight gain [9,34].

Several vitamins and metabolic cofactors further modulate peripartum metabolism and reproductive success. L-carnitine enhances mitochondrial fatty acid oxidation and adenosine triphosphate (ATP) production, reducing oxidative stress and supporting reproductive efficiency. It also limits ketosis, promotes protein synthesis, and stabilizes mitochondrial membranes, contributing to improved piglet survival and milk output [35]. Importantly, studies have demonstrated that L-carnitine supplementation during late gestation and early lactation can increase colostrum yield and immunoglobulin content, improving passive immune transfer and early piglet growth [36–39]. This enhancement of colostrum quality may represent a key mechanism linking maternal metabolic support to improved neonatal performance, particularly in hyperprolific nulliparous sows. Betaine, a derivative of sugar beet, functions as an osmolyte and methyl-group donor, conserving cellular energy and supporting osmotic balance. It enhances nutrient absorption by thickening the intestinal mucosa and contributes to protein metabolism through its role in transmethylation cycles in muscle, liver, and kidney tissues [40–42]. Vitamin B_{12} (cobalamin) is essential for erythropoiesis, nervous system integrity, and amino acid metabolism. Plasma vitamin B_{12} concentrations are often lower in gilts than in multiparous sows, indicating competition between somatic growth and reproduction for this micronutrient. Supplementation enhances placental angiogenesis, increases piglet birth weight, and prevents hyperhomocysteinemia, which may impair neonatal growth and immunity [43–46]. Choline, a precursor of acetylcholine and a key methyl donor, is indispensable for cell membrane integrity, lipid transport, and fetal growth. Through its role in very-low-density lipoprotein (VLDL) formation, choline prevents hepatic lipid accumulation and inflammation, thereby supporting maternal metabolic homeostasis [47,48]. Choline deficiency, conversely, can lead to hepatic injury and impaired fetal growth [49]. Collectively, these nutrients act synergistically to stabilize energy metabolism, enhance antioxidant capacity, and support efficient nutrient transfer from the sow to the litter. Yet, despite evidence supporting individual nutrient roles, the combined effects of multi-nutrient peripartum supplementation in hyperprolific nulliparous sows remain poorly characterized [8,17,50].

Therefore, the present study aimed to evaluate the effects of a tailored peripartum dietary supplement containing essential minerals, amino acids, and vitamins on metabolic status, reproductive performance, and litter growth in hyperprolific nulliparous sows. We hypothesized that optimizing nutrient supply during this critical transition would mitigate metabolic and oxidative stress, enhance farrowing performance and colostrum quality, and ultimately improve neonatal survival and early growth—an approach consistent with comprehensive service-to-weaning feeding regimens, which has been shown to improve sow and litter outcomes [8]. Addressing these challenges is essential to support the long-term productivity, welfare, and sustainability of modern hyperprolific sow herds.

2. Materials and Methods

The authors declare that they have not used any type of GenAI in any way for the performance of this work (generation of text, data, or graphics, or assistance in study design, data collection, analysis, or interpretation).

All protocols used in this study were approved by the Animal Ethics Committee of the University of Zaragoza (reference number: PI37/23). The procedure was carried out on a commercial farm in north-eastern Spain. Expert veterinarians supervised the care and handling of the animals, ensuring their welfare throughout the experiment.

2.1. Experimental Design, Housing, and Management

This study included 127 nulliparous sows (DanBred Landrace × DanBred Large White) divided into control (C, 64 sows) and treatment (T, 63 sows) groups. Sows were randomly assigned to groups and housed in pens during gestation, transitioning to individual farrowing crates from day 110 of gestation to 28 days postpartum. Conducted over seven months (April–October 2021) on a farm with 620 reproductive sows, the study ensured that all sows belonged to the same contemporary group.

Estrus was monitored daily, and sows were inseminated with a commercial semen dose (2×10^9 sperm cells) and reinseminated after 24 h if still in estrus. The T group received a nutritional additive supplement starting at day 80 of gestation until five days postpartum, in addition to the basal diet. Control sows were fed only the basal diet, which was formulated according to the National Research Council recommendations [51].

Gilts entered the farm at five months of age (approximately 100 kg body weight) and were acclimated in pens of 25 gilts for 8 weeks with ad libitum feeding. Subsequently, the largest gilts were allocated to weekly batches of six animals and fed a commercial lactation diet with flushing and altrenogest treatment for estrus synchronization. Pregnancy was confirmed by ultrasonography 24 days after insemination.

Gestating sows were housed in pens of 55 animals with partially slatted floors, providing 3 m^2 per sow, and were fed using semi-stall-feeding systems. Feeding commenced at 2.5 kg/day of the basal diet and continued until farrowing, with individual confinement for 30 min daily from day 80 of gestation to allow controlled feeding. Farrowing crates (1.80 × 2.65 m) were equipped with individual drinkers (water flow rate of 3 L/min), creep areas with heated floors, and infrared lamps for piglets. Farrowing occurred naturally, with obstetrical assistance provided when birth intervals

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exceeded 20 min. Litters were standardized within 24 h postpartum to 13–14 piglets per sow, matched for piglet size and litter number across experimental groups.

2.2. Dietary Treatments, Feeding, and Feeding Systems

Two feeding diets were designed and randomly assigned to the control group (C) and the treatment group (T) in this experiment.

2.2.1. Control Group (C):

The control group was fed a commercial diet formulated according to the recommendations of the Spanish Foundation for the Development of Animal Nutrition (FEDNA) nutritional tables for production sows [52], based on established nutrient requirement guidelines for swine [53]. Table 1 illustrates that the feeding program consisted of a gestation diet administered from weaning until day 110 of gestation and a lactation diet provided from day 110 of gestation until 28 days postpartum. Feeding followed a “flat” curve of 2.5 kg/day from mating until day 110 of gestation, after which the feeding strategy was adjusted to match that of multiparous sows, as described by Cantin et al. [8].

2.2.2. Treatment Group (T):

The T group was fed the same commercial diet as the C group, formulated according to the FEDNA recommendations for swine nutrition [53]. Table 1 illustrates that the feeding program consisted of a gestation diet administered from weaning until day 110 of gestation and a lactation diet provided from day 110 of gestation until 28 days postpartum. However, the treatment diet was supplemented during the last 35 days of gestation and the first 5 days of lactation. The supplement was administered at 300 g per sow per day during the final 35 days of gestation, as part of a single daily feeding regimen, and during the first 5 days of lactation in the morning feeding, following the protocol described by Cantin et al. [8].

Table 1. Composition of the diets, gestation standard, and lactation standard of groups C and T.

	Items (units)	**Gestation Standard (Group C)**	**Lactation Standard (Group C)**
Ingredients			
	Barley (%)	48.410	22.030
	Maize (%)	0.000	19.440
	Wheat (%)	0.000	0.000
	Soybean meal (47% crude protein)	0.000	18.900
	Animal blended fat (%)	0.000	0.000
	Beet pulp (%)	0.000	0.000
	Full fat soya (%)	0.000	0.000
	Rice cylinder(%)	10.000	5.000
	By-product biscuit(%)	0.000	7.000
	Zootechnical meal(%)	7.430	10.000
	Sodium bicarbonate(%)	0.100	0.310
	Monocalcium phosphate(%)	0.090	0.580
	Dicalcium phosphate(%)	0.000	0.000
	Salt(%)	0.400	0.150
	L-Lisine 50(%)	0.330	0.270
	L-Threonine (%)	0.040	0.050
	L-Methionine (%)	0.000	0.000

Choline chloride (%)	0.050	0.040
Soybean oil (%)	0.500	1.480
Calcium carbonate (%)	1.620	1.720
Sunflower meal (36% crude protein)	10.000	2.700
Wheat bran (%)	18.980	10.000
Alfalfa (%)	0.480	0.000
Sepiolite (%)	1.320	0.000
Glucogenic precursor (%)	0.000	0.000
Others (%, additives)[1]	0.240	0.300
Nutrients [2]		
Metabolizable energy (Kcal/kg)	2.844.879	3.174.143
Fat Matter (%)	4.106	5.008
Crude protein (%)	12.500	17.000
Crude fiber (%)	8.000	5.000
Neutral detergent fiber (%)	23.460	15.953
Arginine (%)	0.812	1.108
Digestible Arginine (%)	0.672	0.978
Lysine (%)	0.650	0.973
Digestible Lysine (%)	0.508	0.811
Methionine (%)	0.215	0.284
Digestive methionine (%)	0.176	0.243
Methionine + cystein (%)	0.479	0.587
Methionine + cysteine Digestive (%)	0.358	0.463
Calcium (%)	0.900	1.000
Phosphorus, Total (%)	0.616	0.613
Phosphorus, Digestive (%)	0.230	0.340

The supplement composition was carefully designed to optimize maternal and fetal health:

- Electrolyte Balance: The electrolyte balance was adjusted to approximately 200 mEq/kg using Mogin's formula:

Balance = mEq/kg Na + mEq/kg K - mEq/kg Cl = Na × 434.97 + K × 255.74 - Cl × 282.06.

Sodium was added to achieve the desired balance.

- Calcium: Calcium was included in sufficient amounts to mitigate hypocalcemia during the peripartum period, caused by demineralization in late gestation. Phosphorus levels were also balanced.

- Lysine and Methionine: These amino acids were included to meet the needs for muscle growth in sows and the development of fetal and placental tissues, thereby helping to prevent muscle loss and ketosis.

- Vitamins and Provitamins: Vitamin B_{12}, choline chloride, betaine, and L-carnitine were incorporated for their hepatoprotective effects.

- Ingredients: The supplement contained extruded wheat, dehulled soybean meal (genetically modified organism), calcium carbonate, and powdered whey.

- Analytical Components: Calcium, 4.1%; Sodium, 4%; Phosphorus, 0.3%; Lysine, 1.96%; Methionine, 1.32%.

- Additives per Kilogram of Supplement:
  - Vitamins: Vitamin B_{12} (0.3 mg), choline chloride (600 mg), betaine anhydrous (475 mg), L-carnitine (500 mg).
  - Trace Elements: Selenomethionine (from Saccharomyces cerevisiae) (1.1 mg).

- Preservatives: Citric acid (E330) (209.5 mg), sodium propionate (E282) (150,000 mg).
- Antioxidants: Butylated hydroxytoluene (BHT, E321) (166.5 mg), propyl gallate (E310) (166.5 mg).
- Anti-Caking Agents: Sepiolite (E562) (100 g), precipitated and dried silica (E551a) (7.8 g).
- Flavoring Agents: Flavoring mix (1.053 mg).

2.3. Data Collection and Chemical Analysis

2.3.1. Body Condition

Body condition was assessed by measuring backfat thickness (BFT) and longissimus muscle depth (LMD) at the P2 reference point, 6 cm from the midline and behind the last rib, using a wireless ultrasound scanner (Backfat & Loin Depth Scanner SF-1, SonicVet, China) with a 5 MHz linear digital probe connected to an iPad via Wi-Fi. These measurements were carried out on all animals in both groups on days 80 and 112 of gestation, as well as on days 15 and 26 of lactation.

2.3.2. Sow Plasma Metabolites

To determine the presence of ketone bodies in blood, β-hydroxybutyrate (BHBA; mmol/L) was measured using the Freestyle Precision Beta-Ketone e system with B-ketone test strips (Abbott Laboratories, Chicago, USA). This measurement was performed in both groups at 107 days of gestation and 2 days postpartum, with a value of 0 indicating negative sows and values greater than 0 indicating positive sows.

To determine muscle damage and sow catabolism and correlate these findings with BHBA levels, blood creatinine (CREA) concentrations were analyzed at 107 days of gestation. Blood samples were collected from sows and sent to a laboratory for biochemical analysis.

2.3.3. Clinical Hypophagia

Clinical hypophagia (HP) was visually observed during the first week of lactation. Sows were considered positive for HP if they failed to consume their ration for two consecutive feedings; they were considered negative if they consumed their ration.

2.3.4. Litter and Piglet Production Parameters

Farrowing was strictly monitored from start to finish to record the total number of piglets born (TB), including those born alive (BA) and stillborn (SB).

Individual piglet weights were recorded at birth (before colostrum intake) and at 15 days of age in 50 litters from the C group and 50 litters from the T group.

Litters presenting diarrhea during the first week of lactation were visually assessed and recorded. A litter was considered positive when clinical signs of diarrhea were observed in at least one piglet, whereas litters without any observable diarrheal symptoms were classified as negative [54].

2.4. Statistical Methods

Statistical analyses were performed using SPSS version 29 software (IBM, Chicago, IL, USA). For continuous variables with a single measurement per individual, a one-way analysis of variance (ANOVA) was used to compare means, with the group serving as the factor. This technique was also used to determine the relationship between a continuous and a categorical variable. For quantitative variables with marked discontinuities, the Mann-Whitney U test (a non-parametric test) was applied. When a variable was measured repeatedly in the same individual at different times, a two-way mixed ANOVA was used, considering the group, time, and group × time interaction as factors. The relationships between two continuous variables were studied using Pearson's correlation coefficient (r); for categorical variables, Pearson's chi-squared test or Fisher's exact test were used. In all cases, p-values < 0.050 were considered statistically significant. When significant differences were detected in more than two variables, the Bonferroni correction for multiple comparisons was applied.

3. Results

3.1. Litter Characteristics

Table 2 shows litter characteristics. Regarding the percentage of SB piglets in TB/litter, highly significant differences were observed between the groups, with a higher mean in group C (p = 0.001). For the percentage of piglets weighing less than 1 kg at birth in BA/litter, no significant differences were observed between the groups (p = 0.275). The mean piglet birth weight/litter significantly differed between the groups, with a higher mean in group T (p = 0.011). At 15 days of lactation, highly significant differences in mean piglet weight/litter were observed between the groups, with a higher mean in group T (p < 0.001). The number of piglets at 15 days after birth/litter showed significant differences between groups (p = 0.001); values were higher in group T.

In terms of neonatal diarrhea in piglets during the first week of lactation, highly significant differences were detected between the groups, with a lower frequency of diarrhea per litter observed in group T (p < 0.001).

Table 2. Results for litter characteristics in both groups. Data are count/n (percentage) or mean ±SD (standard deviation).

Variable	Group C		Group T		p- value
	n	Mean±SD; Count/n (%)	n	Mean±SD; Count/n (%)	
Stillborn piglets/litter (%)	64	4.63±5.512	63	1.80±4.013	0.001
Piglets weighing less than 1 kg at birth/litter	64	13.02±10.861	63	11.43± 11.739	0.275
Mean piglet birth weight/litter (Kg)	60	1.19±0.151	54	1.27±0.174	0.011
Mean piglet weight at 15 days of lactation/litter (Kg)	60	3.25±0.486	54	3.62±0.542	<0.001
Piglets at 15 days after birth/litter	60	11.90±2.129	54	12.59±1.108	0.001
Neonatal diarrhea in piglets during the first week of lactation /litter		39/64(60.9%)		8/63(12.7%)	<0.001

3.2. Sow Performance

Results for sow performance are shown in Table 3.

Table 3. Results for sow performance in both groups. Data are count/n (percentage) or mean ±SD (standard deviation) .^{a,b,c,d}: Different letters indicate significant differences between moments within group (column).

Variable	Group C		Group T		Effect (p- value)	
	n	Mean ± SD; Count /n (%)	n	Mean ± SD; Count /n (%)	Group x Moment	Group
BFT (mm) 80 days of gestation	64	14.06±3.576^{a}	63	13.87±3.177^{a}	<0.001	0.744

BFT (mm) 112 days of gestation	64	13.60±3.265^a	63	13.50±2.673^a		0.848
BFT (mm) 15 days of lactation	64	11.92±3.078^b	63	12.40±2.227^b		0.315
BFT (mm) 26 days of lactation	64	10.02±2.322^c	63	11.46±2.069^c		<0.001
Moment Effect (p-value)		<0.001		<0.001		
LMD (mm) 80 days of gestation	64	49.21±5.668^a	63	49.15±4.382^a	0.145	0.108
LMD (mm) 112 days of gestation	64	47.35±5.647^b	63	48.53±5.368^b		
LMD (mm) 15 days of lactation	64	45.41±6.173^c	63	47.03±5.017^c		
LMD (mm) 26 days of lactation	64	44.09±6.381^d	63	46.28±4.492^d		
Moment Effect (p-value)		<0.001				
Hypophagia in sows during the first week of lactation (%)		15/64 (23.4%)		4/63 (6.3%)		0.014

For BFT measurements at 80 and 112 days of gestation and at 15 days of lactation, no significant differences were detected between groups. However, at 26 days of lactation, highly significant differences were observed, with higher mean values in group T ($p < 0.001$) (Table 3).

For LMD, no significant differences were found between groups at any moment ($p = 0.108$)

Regarding BFT measurements, both group C and group T showed highly significant differences across time points ($p < 0.001$). No significant differences in BFT were detected between 80 and 112 days of gestation, but from this point onwards, a significant decline in BFT values was observed at 15 and 26 days of lactation.

Regarding the measurement of LMD, significant differences were detected between time points ($p < 0.001$); a significant decline in LMD values was observed in both groups from the first measurement to the last.

Regarding hypophagia in sows during the first week of lactation, significant differences were observed between the groups, with a lower frequency of hypophagia in group T ($p = 0.014$).

3.3. Sow Plasma Metabolites

Table 4 shows the results for plasma metabolites in the studied sows.

Table 4. Results for sow plasma metabolites in both groups. Data are count/n (percentage) or mean ±SD (standard deviation). .

Variable	**Group C**		**Group T**		**p-value**
	n	**Mean±SD**	**n**	**Mean±SD**	

BHBA 107 days of gestation (mmol/L)	64	0.131±0.1283	63	0.040±0.0636	<0.001
CREA 107 days of gestation (mmol/L)	64	2.794±1.4283	63	2.071±0.6917	<0.001

Regarding BHBA, highly significant differences were detected between groups at 107 days of gestation, with higher mean values observed in group C ($p < 0.001$).

Similarly, for CREA levels at 107 days of gestation, highly significant differences were also found between groups, with group C showing higher mean values ($p < 0.001$).

3.4. Correlations

The correlation coefficients for BHBA and CREA at 107 days of gestation, in relation to sow performance and litter characteristics, are shown in Table 5. At 107 days of gestation, blood BHBA levels showed highly significant negative correlations with BFT at 15 days ($p = 0.005$) and 26 days of lactation ($p < 0.001$), as well as with LMD at 112 days of gestation ($p = 0.014$). BHBA also exhibited significant negative correlations with the number of piglets per litter at 15 days ($p < 0.001$) and with mean piglet weight per litter at 15 days of lactation ($p = 0.001$). Conversely, BHBA levels were significantly and positively correlated with the percentage of SB piglets per litter ($p = 0.005$) and with blood CREA levels at 107 days of gestation ($p = 0.010$). In all cases, the magnitude of these correlations was low, indicating weak but statistically significant associations between BHBA and the evaluated parameters.

For CREA levels at 107 days of gestation, a significant positive correlation was observed with the percentage of SB piglets per litter ($p = 0.013$) and a significant negative correlation with LMD at 112 days of gestation ($p = 0.023$). As with BHBA, the correlation coefficients for CREA were low, suggesting a limited strength of association despite statistical significance.

Table 5. Correlation coefficients for the concentration of BHBA and CREA at 107 days of gestation with sow performance and litter characteristics.

Variable 1	**Variable 2**											
	CREA 107 days of gestation (mmol/L)	**BFT 112 days of gestation**	**BFT 15 days of lactation**	**BFT 26 days of lactation**	**LMD 112 days of gestation**	**LMD 15 days of lactation**	**LMD 26 days of lactation**	**Piglets weighing less than 1 kg at birth/litter**	**Stillborn piglets/litter (%)**	**Mean piglet birth weight/litter (Kg)**	**Piglets at 15 days after birth**	**Mean piglet weight at 15 days of lactation/litter (kg)**
	r p-value n	r p-value n	r p-value n	r p-value n	r p-value n	r p-value n	r p-value n	r p-value n	r p-value n	r p-value n	r p-value n	r p-value n
BHBA 107 days of gestation (mmol/L)	0.228	-0.130	-0.246	-0.305	-0.218	-0.041	0.013	0.023	0.249	-0.086	-0.360	-0.298
	0.010	0.147	0.005	<0.001	0.014	0.645	0.880	0.800	0.005	0.339	<0.001	0.001
	127	127	127	127	127	127	127	127	127	127	114	114
CREA 107 days of gestation (mmol/L)		-0.010	-0.076	-0.004	-0.201	-0.076	-0.004	0.058	0.220	-0.105	-0.119	-0.123
		0.908	0.393	0.962	0.023	0.393	0.962	0.516	0.013	0.24	0.209	0.194
		127	127	127	127	127	127	127	127	127	114	114

When correcting for the effect of CREA levels at 107 days of gestation, a small but significant negative correlation was still detected between LMD at 112 days of gestation and BHBA concentrations at 107 days of gestation ($p = 0.043$). However, when correcting for the effect of BHBA levels at 107 days of gestation, no significant correlation was found between LMD at 112 days of gestation and CREA concentrations at 107 days of gestation ($p = 0.074$).

The detected correlation between LMD at 112 days of gestation and CREA levels at 107 days of gestation may be driven by the interrelationship between CREA and BHBA values at 107 days of gestation.

Table 6 shows the relationships between (a) metabolite concentration at 107 days of gestation and LMD at 112 days of gestation and (b) the presence or absence of hypophagia and neonatal diarrhea.

A significant difference was detected between the presence or absence of hypophagia; hypophagia was associated with higher BHBA levels ($p < 0.001$). An association was also identified between BHBA levels and neonatal diarrhea; neonatal diarrhea was associated with higher BHBA levels ($p = 0.001$). CREA was only associated with neonatal diarrhea ($p = 0.005$). In the presence of neonatal diarrhea, higher values of CREA were found.

Additionally, significant associations were detected between LMD and the presence of both hypophagia and neonatal diarrhea ($p < 0.05$); lower LMD values were found in the presence of both problems.

Table 6. Relationships of metabolite concentration at 107 days of gestation and LMD at 112 days of gestation with the absence /presence of hypophagia and neonatal diarrhea.

4. Discussion

The present study reports on the effects of a nutritional supplement administered during the peripartum period on reproductive performance and metabolic adaptation in hyperprolific gilts under commercial conditions.

First, significant differences in stillbirth rates were observed between groups, with higher values in the control group. This finding is consistent with previous studies indicating that inadequate nutritional and metabolic status during late gestation is associated with prolonged farrowing, increased perinatal mortality, and reduced piglet vitality [55–59]. Among the nutrients involved, calcium plays a central role in farrowing physiology by regulating uterine contractility through calcium–calmodulin–dependent actomyosin interactions, which enable effective ATP-dependent contraction cycles [60,61]. In addition, postpartum hypocalcemia, accentuated by elevated calcitonin concentrations during gestation, may impair intestinal calcium absorption and increase renal calcium excretion, thereby prolonging farrowing and increasing the risk of SB piglets [24].

Moreover, adequate energy availability is equally critical for efficient parturition. Beyond mineral balance, the lower stillbirth rate observed in the treatment group likely reflects a more favorable metabolic adaptation during farrowing. In this context, L-carnitine supplementation has been associated with enhanced mitochondrial fatty acid oxidation and increased ATP production, which supports sustained uterine contractility during labor [62–65]. Consequently, a faster and more energetically efficient farrowing process may improve oxygen delivery to piglets, reducing perinatal hypoxia and increasing neonatal viability.

Piglet birth weight was significantly higher in the treatment group, reinforcing the well-established relationship between maternal nutrition and fetal growth [14,19]. Calcium also contributes to fetal and placental function by promoting skeletal mineralization and facilitating umbilical calcium transport, thereby supporting adequate mineral homeostasis in both the sow and the fetus [33,66]. In parallel, amino acids such as lysine and methionine play a key role in placental development. Increased placental angiogenesis stimulated by these amino acids enhances fetal nutrient and oxygen supply, resulting in heavier piglets at birth [67–70]. Together, these mechanisms provide a physiological framework linking optimized peripartum nutrition with improved fetal growth.

At 15 days of lactation, piglets from the treatment group maintained a higher body weight. This sustained growth advantage likely reflects increased maternal milk yield and improved nutrient composition during the early stages of lactation. Calcium directly contributes to milk mineral content and supports neonatal skeletal development [13,33], while methionine promotes skeletal muscle growth in suckling piglets [71]. In addition, increased maternal lysine intake during lactation enhances milk synthesis and composition, contributing to greater litter growth and reduced pre-weaning mortality [6,10,72]. These effects are consistent with more efficient nutrient partitioning toward lactation in supplemented gilts.

Regarding neonatal health, the incidence of diarrhea was significantly lower in the treatment group. Heavier piglets generally show improved thermoregulation and higher colostrum intake, which enhances passive immune transfer and early survival [73–76]. Maternal nutrition during gestation has also been shown to influence neonatal immune competence and intestinal health, while methionine supplementation supports intestinal epithelial integrity and limits pathogenic bacterial colonization [71]. Although colostrum composition was not assessed in the present study, previous research indicates that peripartum supplementation with amino acids, vitamins, and metabolic cofactors can improve colostrum yield and immunological quality, thereby enhancing early piglet immunity and growth [77–81]. Consequently, improved colostrum-mediated immune transfer may partially explain the lower incidence of diarrhea observed in the supplemented group.

Maternal body condition did not differ between groups during gestation but diverged significantly toward the end of lactation, with higher BFT and LBT observed in supplemented gilts. Late gestation and lactation are characterized by intense nutrient mobilization to support fetal development and milk synthesis [9,13]. The reduced loss of body reserves observed in the treatment group suggests more efficient nutrient partitioning and lower catabolic stress [16,27]. Adequate lysine supply is particularly critical in gilts, which must simultaneously sustain body growth and lactation, as lysine deficiency accelerates tissue mobilization and compromises milk production [17,82]. These results highlight the importance of optimized amino acid nutrition during the peripartum period in preserving maternal body condition and long-term reproductive performance [14,83].

A significantly lower frequency of postpartum hypophagia was observed in the treatment group. Hypophagia during early lactation reflects insufficient energy intake and is commonly associated with elevated BHBA concentrations, indicative of negative energy balance and increased lipid mobilization [13,16,84]. In the present study, BHBA concentrations at 107 days of gestation were significantly higher in the control group, suggesting impaired metabolic adaptation prior to farrowing [5,50].

CREA concentrations were also higher in control gilts at the end of gestation, reflecting increased muscle protein mobilization under conditions of energy or amino acid insufficiency [6,10]. CREA was positively associated with stillbirth rate and negatively correlated with muscle depth, supporting its role as a marker of protein catabolism and body reserve mobilization [13,15]. Importantly, CREA concentrations were not associated with hypophagia, indicating that energy and protein catabolism represent partially distinct aspects of metabolic stress during the peripartum period.

The positive association between BHBA and CREA highlights the close coupling between energy deficit and protein mobilization during late gestation. In addition, elevated BHBA concentrations were associated with the presence of neonatal diarrhea, reinforcing the link between maternal metabolic imbalance, compromised immune transfer, and early piglet health [17,50,76,84].

The current results highlight dynamic relationships among metabolic markers—particularly CREA, BHBA, and LMD—reflecting the intricate balance between energy and protein metabolism in pregnant sows. The significant positive correlation between CREA and BHBA suggests that both indicators respond to similar metabolic stresses. CREA increases with muscle protein degradation [10,15], whereas BHBA rises under conditions of hypophagia and negative energy balance [50,84].

Their interdependence underscores the coupling of muscle and energy metabolism during gestation and lactation.

Furthermore, the negative correlation between LMD at 112 days and BHBA at 107 days confirms the link between reduced feed intake, elevated ketone production, and diminished muscle development [3,16]. Reduced nutrient intake during gestation promotes BHBA accumulation and protein mobilization, resulting in diminished muscle mass and lower LMD values [3,27]. These findings support the use of BHBA as a dual indicator of energy balance and lean tissue status [17,84].

Overall, these results illustrate the intricate relationship between maternal nutrition, metabolic adaptation, and reproductive performance in hyperprolific gilts. The integrated evaluation of metabolic indicators, such as BHBA and CREA, provides valuable insight into the physiological mechanisms linking peripartum nutritional management with farrowing outcomes, maternal body condition, and early piglet survival in modern production systems.

5. Conclusions

This study highlights the importance of precise nutritional management during the peripartum period in supporting performance in modern hyperprolific gilts, whose metabolic demands may exceed traditional nutrient recommendations [51,85]. The peripartum dietary supplement evaluated in this study was associated with improved reproductive outcomes, a more favorable metabolic profile, and enhanced early piglet performance under commercial conditions.

The evaluated peripartum dietary supplement, containing lysine, methionine, calcium, L-carnitine, and essential vitamins, significantly improved reproductive performance, metabolic stability, and early piglet growth. Supplementation reduced stillbirth rates, likely through enhanced calcium availability and the role of L-carnitine in supporting energy metabolism during farrowing. In addition, supplementation increased piglet birth weight and early litter growth and reduced the incidence of neonatal diarrhea, indicating improved immune status and overall neonatal health. The results further suggest that optimized methionine-to-lysine ratios contribute to improved fetal development and metabolic adaptation during the peripartum period.

In conclusion, targeted nutritional supplementation during the peripartum period enhances farrowing efficiency, stabilizes maternal metabolism, preserves body condition, and improves piglet health. These findings support the implementation of tailored nutritional strategies as a practical and effective approach to improve productivity, resilience, and long-term sustainability in hyperprolific gilt herds.

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Abbreviations

The following abbreviations are used in this manuscript:
ANOVA: analysis of variance
BA: born alive
BFT: backfat thickness
BHBA: b-hydroxybutyrate
BHT**:** Butylated hydroxytoluene
C: Control
CREA: creatinine
FDNA: Development of Animal Nutrition
HP: hypophagia
LMD: longissimus muscle depth
mEq: milliequivalents
SB: stillborn
SD: standard deviation
T: Treatment
TB: total born

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