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Effect of phosphorus and calcium precision feeding on reproductive performances and mineral status in gestating sows

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ABSTRACT

Precision feeding can enhance amino acid utilization efficiency in swine, but precision phosphorus (P) feeding on gestating sows has not yet been tested. Therefore, the aim of the study was to evaluate the effects of a P and calcium (Ca) precision feeding strategy during gestation on the phosphocalcic status and performance of sows compared with constant dietary contents over two gestation cycles. A total of 120 sows were monitored over two consecutive cycles (**C1** and **C2**) to study the effects of three dietary treatments: Canadian (**CAN**; 0.32% digestible P; 0.83% Ca), European (**EU**; 0.25% digestible P; 0.68% Ca), and precision feeding (**PR**; 0.15–0.32% digestible P; 0.46–0.83% Ca). Phosphocalcic status was studied during two cycles on days 30 (**d30**) and 90 (**d90**) or 110 postweaning (**d110**) by the 24-h total urine collection using the catheter method and blood analyses. The BW and backfat thickness were measured at mating, on d110, and at weaning. The only performance trait affected by the dietary treatments was a higher backfat thickness on d110 in sows fed PR compared to those one of EU and CAN ($P < 0.05$). Lactation performances were similar across all treatments. Dietary treatments, stage of gestation, and cycle did not influence urinary Ca excretion. A three-way interaction was observed for urinary P excretion and urinary Ca:P ratio (Treatment × Stage × Cycle, $P < 0.05$). The PR sows excreted more P in urine than the CAN sows, although the CAN sows were fed a higher P amount. High P losses were associated with a low Ca:P ratio (less than 0.5), indicating a lack of Ca supply to retained P. At d30 of C2, EU sows excreted more P than CAN sows ($P < 0.05$) and numerically more than PR sows, likely due to insufficient Ca supply to retain P. On d90 of C2, PR sows still lack Ca (urinary Ca:P ratio less than 0.5). This study highlights the importance of controlling the digestible Ca:P ratio when applying precision feeding in order to obtain maximal dietary P efficiency. This ratio was probably too low in the PR feeding treatment. Monitoring across multiple cycles is essential to validate this strategy and support its adoption on commercial farms.

Implications

Phosphorus precision feeding enables the daily adjustment of mineral supply based on the sow's requirements, which are particularly driven by the demands of fetal development during the final two-thirds of gestation. This enables a reduction in phosphorus excretion in comparison to classic one-phase feeding. This study demonstrated that phosphorus utilization and retention are strongly influenced by calcium intake and the calcium:digestible phosphorus ratio in the feed and that current models underestimate calcium requirements. Moreover, it may be possible to reduce the level of digestible phosphorus during the first two-thirds of gestation without negatively affecting the sow's performance.

Introduction

During gestation, phosphorus (P) is primarily required for the development of the conceptus (Bikker and Blok, 2017). This requirement, added to maintenance and growth requirements, constitutes the factorial calculation approach commonly used in animal farming (NRC, 2012). In Canada, sows in commercial farms are typically fed one feed with constant nutritional content during gestation that is intended to be close to the sow's requirements at the end of gestation. To ensure that there are no deficiencies—mainly in energy and amino acids, as P deficiency is unlikely—bump feeding (i.e., an increase in the quantity of feed distributed in late gestation) can be used to meet the increased nutritional

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requirements of the conceptus during late gestation (Cloutier et al., 2023). However, the benefits of bump feeding for increasing piglet weight at farrowing and improving lactation performance have been questioned (de Oliveira Araújo et al., 2020; Cloutier et al., 2023), and a feeding strategy using a unique feed also poses several concerns: (1) a linear feed intake for a requirement that turns out not to be linear, (2) requirements do not account for the individual variability in the number of fetuses and the efficiency of P and Ca use and retention (Pomar and Remus, 2019), and (3) this diet results in large nutritional excesses during the initial two-thirds of the gestation. Nutritional excesses in the diet can lead to environmental pollution through the excretion of excess P into the manure-based fertilizers applied to agricultural land (Dourmad et al., 2020), while inorganic phosphate supplementation increases feeding costs.

Today, novel feeding technologies, such as automatic feeders, can distribute several feeds, making it possible to individualize the feeding of each sow. As a result, research is moving toward precision feeding, with the aim to adjust daily nutrient intake to the pigs' nutritional requirements and thus to improve nutrient use efficiency (Hauschild et al., 2012; Pomar et al., 2015; Pomar and Remus, 2019). In practice, this involves mixing a nutrient-rich feed with a nutrient-poor feed and adjusting their proportion throughout gestation.

Precision nutritional feeding has been applied in gestating sows to regulate energy and amino acids (Stewart et al., 2021; Cloutier et al., 2024; Ribas et al., 2024). However, to our knowledge, models for predicting daily P and Ca requirements in sows have not been studied using precision feeding, i.e. following the daily requirements recommended. The hypothesis is that the actual factorial model underestimates the daily P and Ca requirements during the first third of gestation due to not accounting for the requirement to mobilize body reserves in lactation (Heurtault et al, 2024). Furthermore, these nutritional requirements depend on the body condition of the sow, commonly assessed at insemination (Dourmad et al., 2008; NRC, 2012; Gaillard et al., 2019) and on parity (Noblet et al., 1993). These factors must be considered in a precision feeding strategy. Validating the current model requires evaluating the animal's P-Ca status. To do this, blood levels of P and Ca (Maxson and Mahan, 1986), as well as active vitamin D (DeLuca, 2004), can help interpret a P-Ca response. In addition, urinary analysis can highlight an imbalance between blood Ca and P (Vipperman et al., 1974). Thus, the aim of the study was to evaluate the effects of a precision feeding strategy for Ca and P during gestation on the P and Ca status – analyzed by blood and urine samples – and performance of sows compared with fixed feeding, including bump feeding at late gestation, over two gestation cycles.

Material and methods

Animals, housing, and diets

A total of 120 Yorkshire Landrace sows were selected from the maternity unit of the Centre Développement Porc du Québec (22 in 1st parity, 10 in 2nd parity, 9 in 3rd parity, 11 in 4th parity, and 68 in 5th parity) and followed during two gestation and lactation cycles (**C1** and **C2**), with the same sows monitored across both cycles. During 30 days from weaning, the sows were individually housed in cages measuring 1.58 m^2 and equipped with an automatic feeder (Gestal Quattro, Jyga Technologies, Saint-Lambert-de-Lauzon, Canada). The first insemination was carried out over a 6-day period (from Wednesday (Weaning day) to Monday). From 30 days postweaning (**d30**) to 110 days postweaning (**d110**), the sows were housed in groups, 60 sows per pen, sharing 66.9 m^2 of solid concrete floor and 66.9 m^2 of slatted concrete floor. Each pen was equipped with 4 free–access electronic sow feeders (Gestal 3G2, Jyga Technologies, Saint-Lambert-de-Lauzon, Canada). During lactation (from d110 of gestation to weaning), the sows were individually housed in cages measuring 3.2 m^2 within pens measuring 4.9 m^2. The pens were equipped with an automatic feeder (Gestal Quattro, Jyga Technologies, Saint-Lambert-de-Lauzon, Canada). Two days after farrowing, the litters were initially set at 14 piglets. However, adjustments were made based on the previous gestation. For example, if a sow had weaned only 10 piglets in the previous cycle, her litter would be reduced to 12 piglets for this cycle. The piglets had access to a warm and covered area of 0.61 m^2. Piglets are weaned at an average of 21 days of age. The sow always had access to water.

From weaning until the start of the experimental diet, sows were fed a standard gestation diet formulated according to NRC (2012) guidelines. The sows were allocated to one of three dietary treatments on the day after the second insemination, according to parity, BW, and backfat thickness. The experimental diet (Table 1) began 2 days after the end of this insemination period, meaning

Table 1
Ingredients and chemical composition of gestation and lactation diets for sows.

Phase	Gestation		Lactation
Feed	A	B	
Item (g/kg as fed)			
Maize	526.1	514.84	601.7
Wheat			75.00
Wheat short	300.0	300.0	
Distillers dried grain	60.00	93.00	50.00
Dehydrated bread			24.80
Oat hull	81.00	58.00	
Soybean meal	10.00		200.5
Animal fat			8.800
Limestone	10.06	18.60	14.70
Salt	6.080	6.000	4.500
DL-Methionine			1.000
L-Lysine HCl	2.200	2.360	3.700
L-Threonine	0.740	0.700	1.300
Choline chloride	0.720	0.720	
L-Tryptophan			0.200
L-Valine			0.800
Monocalcium phosphate		2.580	9.200
Phytase[1]		0.100	
Premix sow[2]	2.500	2.500	
Premix gestation	0.600	0.600	
Premix lactation			3.800
Analyzed nutrient composition per kg, as fed			
DM (%)	88.9	89.8	88.8
Net energy (MJ)	9.38	9.37	10.63
CP (g)	121	124	174
Crude fiber (g)	69	64	26
SID Lysine (g)[3]	5.3	5.3	5.3
Calcium (g)	4.6	8.3	8.1
Phosphorus (g)	5.1	5.8	5.5
Digestible P (g)[4]	1.5	3.2	4.0
Ca:Digestible P	3.1	2.6	2.03

Abbreviations: A = feed with lower digestible P content; B = feed with higher digestible P content; SID = standardized ileal digestibility; FTU = phytase activity unit defined as the amount of phytase that liberates 1 mmol of inorganic phosphate per minute from 0.0051 mol/L sodium phytate at pH 5.5 and 37 °C.

[1] 0.10% of Quantum Blue 5 000 (150 g/t) corresponds to 750 FTU/kg with an equivalence of 1.58 g digestible P and 1.92 g Ca per kg of food.

[2] Supplied per kg of diet: 4 000 IU Vitamin A acetate, 600 IU Vitamin D3, 24 IU Vitamin E (dl-α-tocopheryl acetate), 1 200 mg Menadione (niacin), 8 mg Vitamin B12, 600 mg Thiamine mononitrate, 2 400 mg Riboflavin, 10 000 mg Calcium D-pantothenate, 12 000 mg Niacin/niacinamide, 1 200 mg Pyridoxine, 320 mg Biotin, 3 200 mg Folic acid, 80 mg Chromium (chromium propionate), 16 000 mg Manganese (MnSO4), 40 000 mg Iron (FeSO4), 6 000 mg Copper (CuSO4··5H2O), 50 000 mg Zinc (ZnSO4), 200 mg Iodine (EDDI C2H10I2N2), 40 mg Selenium (Na2SeO2), 80 mg Selenium (hydroxyanalogue of selenomethionine).

[3] Values calculated according to NRC (2012).

[4] Values calculated according to NRC (2012), including the contribution of phytase.

that most sows started receiving the experimental diets 3–4 days after their first insemination (i.e., those inseminated on Saturday or Sunday). Two iso-energetic feeds were formulated: one low in nutrients including P and Ca (**A**; 1.5 g digestible P; 4.6 g Ca/kg) and one high in P and Ca (**B**; 3.2 g digestible P; 8.3 g Ca/kg). With these two feeds, three diets were defined: Canadian (**CAN**; 100% of feed B), European (**EU**; 41% of feed A and 59% of feed B, aiming 2.5 g digestible P and 6.8 g Ca/kg), and precision feeding (**PR**). For the PR feed, the requirements for maintenance and growth of the conceptus were calculated according to Bikker and Blok (2017), and growth requirements were calculated according to Dourmad et al. (2021; Table 2). Sows received 2.3 kg feed/day (primiparous) and 2.4 kg/day (multiparous), which was increased to 3 kg/day from day 90 of gestation (**d90)**. For all multiparous sows, adjustments to the allocated quantity during the first 28 days of gestation were made based on the backfat thickness (12–15 mm = + 300 g/day; < 12 mm = +600 g/day). During lactation, all sows were fed *ad libitum* the same diet formulated to meet their nutritional requirements (NRC, 2012). The lactation and gestation diets were produced at Sollio feedmill (Saint-Narcisse-de-Beaurivage, Canada) and were formulated as pellets with a maximum conditioning temperature of 80 °C and a pellet diameter of 4 mm.

Sample collection and measurements

A total of eight samples of gestation feeds (A and B) were analyzed during the project, with four samples taken per feed. Measurements on sows were performed during C1 and C2. Urine was collected during 24 h from a minimum of six sows per treatment at d30 and d90 using Foley urinary catheters (size 18; 30 mL balloon; DYND11778, Illinois, United States) following the method described by Grez-Capdeville and Crenshaw (2022). Only third-parity sows or older were selected, while gilts and second-parity sows were excluded, as it is more difficult to place a urinary catheter in younger sows. During catheter placement, the perivulvar area was cleaned with soapy water followed by a chlorhexidine solution (dilution: 2%, DIN 02295253, Ilderton, Canada), and a sterile catheter coated with triple antibiotic (DIN 02246693, Brampton, Canada) was inserted into the sow's urethra using lubricant (LU 020 PC, Elgin, United States). Urine was collected in 20 L containers. After collecting the total urine, a 2 L sample was taken from each container, and after agitation, a 50 mL sample of urine was removed and stored at −20 °C until analysis. Urine samples were only collected from CAN and PR sows at d90 because the dietary digestible P and Ca of the PR and EU treatments were deemed similar at this stage. At mating, on d110, and at weaning, sows were weighed and backfat thickness was measured using ultrasound at 6.5 cm on either side of the midline at the level of the last rib. Blood samples were taken from 15 sows per treatment from the jugular vein at d30 and d110 of the two gestation cycles and stored at −20 °C (10 mL, Vacutainer® serum tubes; Vacutainer, Becton Dickinson). Blood samples were collected at the end of the morning or at midday, always at least 3 h after the last meal. Daily individual feed distribution was recorded by the feeding system during gestation. Feed leftovers are controlled and minimized by the feed delivery system with a fixed maximum rate of 500 g/min, regardless of the total feed allocation. Individual birth weights of piglets were recorded within 24 h of birth, and the overall litter weight at weaning was also taken. Average daily gain of the litter is calculated by considering the weight of the litter at birth after balancing, and the weight at weaning.

Chemical analysis

Feed samples were analyzed for dry matter (DM; Method 950.46), and the Ca and P contents in the feed were assessed using an inductively coupled plasma–optical emission spectrometer (ICP-OES) in a commercial laboratory (Activation Laboratories, Lancaster, Canada). Plasma tubes were centrifuged at 2 000 g at 4 °C for 15 min, and samples were prepared for P and total Ca analysis by ICP-OES. To prepare 1 mL plasma samples, 0.5 mL 3 N HCl, 0.5 mL 40% trichloroacetic acid, and 3 mL MilliQ water were added and mixed between each addition. Samples were centrifuged at 7 500 g for 20 min and analyzed by ICP-OES. Concentrations of $1,25(OH)_2D_3$ were assessed in serum by the sandwich ELISA method (BioVendor, Brno, Czech Republic). Urinary P and Ca were analyzed by argon plasma emission spectrometry (ICP-OES Inductively Coupled Plasma–Optical Emission Spectrometry; Irda, Québec, Canada) after digestion with nitric acid and hydrogen peroxide.

Calculations and statistical analysis

The P balance was calculated between d7 and d110 of gestation for sows in the CAN and PR feeding treatments, which had urinary catheters implanted at d30 and d90. The ingested P during gestation was calculated as the amount of feed consumed multiplied by the analyzed dietary P content. Body P retention was estimated by assuming a maximum retention and deposition rate of 5.5 g P per kg of weight gain (Bikker and Blok, 2017). Urinary P excretion was calculated by summing the P excretion (g/day) quantified on d30 for the initial 53 days, which included the 23 days prior to the first urine collection and the subsequent 30-day measurement period. This was combined with the P excretion (g/day) measured on d90 which encompasses the 30 days prior to the second urine collection and the remaining 20 days of gestation. Fecal P excretion was calculated as [Ingested P – Body P retention – Urinary P excretion]. Total P excretion was calculated as [Fecal P excretion + Urinary P excretion]. The apparent total tract digestibility of P was calculated by dividing fecal P excretion by ingested P.

Table 2
Equations used for calculating the precise P requirements for sows.

Components	Equations
Maintenance (g/d)[1]	$(7 \times \text{sow BW}) \div 1\,000$
Placenta (g)[1]	$(\exp(7.3426 - 1.4060 \exp(-0.0625\times(d-45)) + 0.000253 \times 30 \times d + 0.06339 \times LS)$ $/(23.8 \times 6.25 \times 1\,000)) \times 100 \times$ (actual/predicted litter birth weight)
Fetus (g)[1]	$[\exp(4.591 - 6.389 \times \exp(-0.02398 \times (d - 45)) + (0.0897 \times LS))] \times$ actual/predicted litter weight d115 $\times 5.97/\exp(4.591 - 6.389 \times \exp(-0.02398 \times (115 - 45)) + (0.0897 \times LS))]$
Fluids (g)[1]	$(\exp(2.3954 + 0.09807 \times d - 0.000541 \times d2 + 0.08734 \times LS)/(23.8 \times 6.25 \times 1\,000)) \times 20 \times$ (actual/predicted litter birth weight)
Mammary gland (g)[1]	$(\exp(1.43401 + 3.32153 \exp(0.00991\times(d-45)) + 0.04803 \times 30)/(23.8 \times 6.25 \times 1\,000)) \times 60$
Maternal growth (g)[2]	$8.547\ EBW - 0.00695\ EBW^2 - 19.20\ P2$

Abbreviations: d = day of gestation; EBW = empty BW (kg); LS = litter size; P2 = backfat thickness.
[1] Bikker and Blok (2017).
[2] Dourmad et al. (2021).

The statistical unit was the sow. Sow and piglet performances were analyzed by a mixed model (package lme4; lmer, R, 4.1.2; Supplementary Material S1) with treatment and parity as fixed effects and cycle as a random effect. Although sows were followed over two cycles, a fertility problem, unrelated to the experiment (results not shown), resulted in the loss of 46, 37, and 57% of sows present in C2 for the CAN, EU, and PR treatments, respectively. Therefore, the cycle effect was treated as a random effect representing a repetition, and not the impact of two consecutive cycles. Parity was well distributed between treatments and ranged from 1 to 6. Stillbirths and the number of weaning piglets were analyzed by the PROC GLIMMIX procedure (SAS Inst. Inc., Cary, NC, US). Urinary and blood P and Ca and $1,25(OH)_2D_3$ were analyzed by a linear model (package Stats; lm, R, 4.1.2) with treatment, gestation stage, and cycle as fixed effects. The P balance was analyzed with treatment as a fixed effect and cycle as a random effect (package lme4; lmer, R, 4.1.2). Data were adjusted so that $\lambda = 0$. Two by two differences were analyzed by a Tukey test and were considered significant when $P < 0.05$, and a tendency was noted when the P was between 0.05 and 0.10.

Results

The Ca and digestible P in the gestation diets are presented in Table 3. For the CAN and EU treatments, the differences between the analyzed and formulated diets were as follows: for digestible P (g/kg) in CAN, +0.3, –0.1, –0.4, and +0.1 on days 30 and 110 for C1 and C2, respectively; for Ca (g/kg) in CAN, +1.9, +0.3, –0.7, and +0.8 on days 30 and 110 for C1 and C2, respectively; for digestible P (g/kg) in EU, +0.1, –0.1, –0.2, and +0.2 on days 30 and 110 for C1 and C2, respectively; and for Ca (g/kg) in EU, +1.4, +0.6, +0.3, and +0.8 on days 30 and 110 for C1 and C2, respectively. For blood P and Ca analysis, primiparous sows were excluded as they had not yet experienced lactation, which was necessary to study the impact of previous lactation on the animal's phosphocalcic status.

BW, backfat thickness, and feed intake of sows and litter performances

Sow BW at mating, at d110, and at weaning were influenced by parity ($P < 0.001$; Table 4). At mating and at weaning, parity 1 sows weighed less than parity 2 and 3 sows, which in turn weighed less than higher parity sows. At d110, parity 1 sows weighed less than sows in parity 3 and higher. Parity 3 sows weighed less than those in parity 4 and above. Sows in parities 4, 5, and 6 had a higher BW than lower parities at each time. Sow BW at weaning tended to be higher for the EU treatment compared to PR treatment ($P = 0.07$). The backfat thickness at mating and at d110 was influenced by parity ($P < 0.05$). At mating, sows of parity 3 and 5 had a lower backfat thickness than sows of parity 1. At day 110, sows of parity 5 had a lower backfat thickness than those of parity 1. The backfat thickness tended to be influenced at weaning ($P = 0.08$) and at d110 ($P < 0.05$) by treatment, with higher backfat thickness for the PR treatment than for the CAN and EU treatments. The feed intake of gestating sows was influenced by parity ($P < 0.001$), with parity 1 sows having a lower intake than others ($P < 0.05$); however, during lactation, the feed intake tended to be higher for EU treatment compared to PR treatment ($P = 0.09$). The total number of piglets born was affected by parity ($P < 0.05$; Table 5), while birth weight by piglet and average daily gain per piglet tended to be affected by parity ($P = 0.06$ and $P = 0.05$, respectively).

Effect of dietary treatments on Ca and P urine and plasma and P balance

A three-way interaction was found for urinary excretion of P (Interaction of treatment × Stage × Cycle; $P < 0.05$; Table 6). On d30 of C2, sows in the EU treatment excreted more P than sows in the EU treatment at d90 of C1, and all-time × cycle interactions for CAN. On d90 of C2, sows in the PR treatment excreted more P than all-time × cycle interactions for CAN. Dietary treatment, stage of gestation, and cycle had no influence on urinary Ca excretion, but the 3-way interaction had an effect on the urinary Ca:P ratio ($P < 0.05$). At d30 of C1, sows in the CAN treatment had higher urinary Ca:P ratios than sows in the PR treatment at d90 of C2 ($P < 0.05$). Blood Ca and P were not influenced by dietary treatment and cycle; however, these values were higher on d110 than on d30 (Stage, $P < 0.001$). The $1,25(OH)_2D_3$ was higher in PR than in EU sows (Treatment, $P < 0.05$) and higher at d110 than at d30 (Stage, $P < 0.05$) for both cycles. Considering the P balance, the dietary P intake, fecal excretion, and total excretion were higher for CAN than for PR sows (Treatment, $P < 0.001$; Table 7), whereas urinary P excretion and apparent total tract digestibility were lower for CAN than for PR sows (Treatment, $P < 0.001$).

Discussion

Gestation and lactation performances

A first objective was to investigate the effects of a precision P and Ca feeding strategy during gestation on the productive performances of sows during gestation and lactation compared to a constant P and Ca intake level based on current Canadian recommendations (PIC recommendations) and the recent European recommendations by Bikker and Blok (2017). The performance of the sows was monitored over two reproductive cycles, which included two gestation and lactation periods. Overall, the only trait affected by the diets was the backfat thickness measured

Table 3
Analyzed calcium and phosphorus contents in sows' diets.

Cycle	First gestation cycle						Second gestation cycle					
Stage	30			110			30			110		
Treatment	CAN	EU	PR	CAN	EU	PR	CAN	EU	PR	CAN	EU	PR
Item												
Digestible P (g/kg and g/d)[1]	3.5 / 8.4	2.6 / 6.2	1.5 / 3.6	3.1 / 9.3	2.4 / 7.2	2.0 / 6.0	2.8 / 6.7	2.3 / 5.5	1.6 / 3.8	3.3 / 9.9	2.7 / 8.1	2.2 / 6.6
Ca (g/kg and g/d)[1]	10.2 / 24.5	8.1 / 19.4	5.4 / 13.0	8.6 / 25.8	7.3 / 21.9	6.5 / 19.5	7.6 / 18.2	7.0 / 16.8	6.3 / 15.1	9.1 / 27.3	7.5 / 22.5	6.5 / 19.5
Ca:Digestible P	2.9	3.1	3.6	2.8	3.0	3.3	2.7	3.0	3.9	2.8	2.8	3.0

Abbreviations: CAN = Canadian treatment (3.2 g/kg digestible phosphorus (P); 8.3 g/kg calcium (Ca)); EU = European treatment (2.5 g/kg digestible P; 6.8 g/kg Ca); PR = precision feeding treatment (1.5 g/kg to 3.2 g/kg digestible P; 4.6 g/kg to 8.3 g/kg Ca); 30 = 30 days postweaning; 110 = 110 days postweaning.
[1] The value was adjusted based on the difference between the formulated and analyzed values of total Ca and total P, the latter being attributed to digestible P. Unit in g/d represents the feeding curve of a multiparous sows.

Table 4
BW, backfat thickness (P2), and feed intake during gestation and the following lactation in sows fed different levels of dietary phosphorus and calcium during gestation.

Item Unit	Number of sows n	BW at mating kg	BW at 110 d kg	BW at weaning kg	P2 at mating mm	P2 at 110 d mm	P2 at weaning mm	Feed intake in gestation kg	Feed intake in lactation kg
Variable									
Treatment (Trt)									
CAN	66	221	259	242	12.4	13.3[b]	11.9	307	149
EU	70	223	261	244	13.0	13.5[b]	12.1	307	153
PR	54	219	259	239	13.4	14.6[a]	12.8	303	146
Parity									
1	22	171[c]	227[c]	197[c]	14.8[a]	15.4[a]	11.5	281[b]	147
2	20	194[b]	241[bc]	219[b]	13.3[ab]	14.2[ab]	12.4	310[a]	144
3	17	211[b]	256[b]	231[b]	11.4[b]	13.7[ab]	12.1	315[a]	155
4	18	244[a]	277[a]	258[a]	12.9[ab]	13.8[ab]	13.1	311[a]	151
5	73	251[a]	277[a]	254[a]	12.7[b]	12.9[b]	12.1	312[a]	154
6	40	253[a]	278[a]	261[a]	12.5[ab]	12.9[ab]	12.4	306[a]	146
SEM		1.279	1.256	1.388	0.198	0.196	0.175	0.816	1.694
P-value									
Trt		0.199	0.521	0.078	0.103	0.043	0.087	0.248	0.093
Parity		<0.001	<0.001	<0.001	0.003	0.005	0.326	<0.001	0.408
Trt × Parity		0.537	0.908	0.361	0.928	0.654	0.304	0.124	0.282

Abbreviations: CAN = Canadian treatment (3.2 g/kg digestible phosphorus (P); 8.3 g/kg calcium (Ca)); EU = European treatment (2.5 g/kg digestible P; 6.8 g/kg Ca); PR = precision feeding treatment (1.5 g/kg to 3.2 g/kg digestible P; 4.6 g/kg to 8.3 g/kg Ca); 110 d = 110 days postweaning; P2 = backfat thickness; Trt = treatment; Fixed effects: treatment, parity and treatment × parity, random effect: cycle. Letters correspond to the treatment effect or the parity effect.

Table 5
Lactation performance of sows fed different levels of dietary phosphorus and calcium during the previous gestation period.

Item Unit	Number of sows n	Total born (TB) n	Stillbirth % of TB	Born alive (BA) n	Birth weight kg/BA	Number of weaning piglets (% of stillbirth[1])	ADG g/piglet	Weaning weight kg/piglet
Variable								
Treatment								
CAN	66	15.7	10.14	13.8	1.58	92.30	234	6.26
EU	70	16.6	10.18	14.8	1.52	91.50	242	6.51
PR	54	15.4	12.06	13.4	1.53	93.44	244	6.26
Parity								
1	22	14.6	6.99	13.5	1.43	93.49	221	6.34
2	20	14.4	7.70	13.1	1.69	95.21	244	6.31
3	17	17.2	15.19	14.6	1.55	93.11	250	6.51
4	18	17.3	10.62	15.3	1.56	92.71	251	6.37
5	73	16.4	11.77	14.1	1.49	87.96	240	6.27
6	40	15.4	12.47	13.4	1.55	92.02	232	6.26
SEM		0.286	0.242	0.265	0.018	0.229	2.563	0.061
P-value								
Trt		0.277	0.869	0.395	0.101	0.990	0.407	0.276
Parity		0.017	0.117	0.146	0.069	0.125	0.051	0.918
Trt × Parity		0.526	0.600	0.505	0.265	0.696	0.738	0.511

Abbreviations: CAN = Canadian treatment (3.2 g/kg digestible phosphorus (P); 8.3 g/kg calcium (Ca)); EU = European treatment (2.5 g/kg digestible P; 6.8 g/kg Ca); PR = precision feeding treatment (1.5 g/kg to 3.2 g/kg digestible P; 4.6 g/kg to 8.3 g/kg Ca); ADG = average daily gain; Trt = treatment; Fixed effects: treatment, parity and treatment × parity, random effect: cycle.
[1] After balancing the litter.

on d110, which was higher in PR sows than in the other treatments. This result could be explained by a numerically lower backfat thickness at mating for CAN and EU sows, with a difference of 0.5–1 mm compared to PR sows. However, the backfat thickness gain over the first 110 days postweaning was similar for CAN and PR sows, with increases of +0.9 mm and +1.2 mm, respectively. This is in line with the objectives set by the existing recommendations for the herd's genetics (Large White × Landrace crossbreed, Alphagene, 2021), aiming for a backfat thickness between 14- and 18-mm. Sows in the EU treatment showed a lower backfat thickness gain of only 0.5 mm. This could be explained by a higher proportion of parity 5 and 6 sows in the EU treatment compared to the other treatments, with 45 sows in the EU treatment versus 37 and 31 in the CAN and PR treatments, respectively. The increase in live weight with parity is not necessarily accompanied by an increase in backfat thickness, as observed by Whittemore and Kyriazakis (2008) and Lavery and al. (2019), a finding that aligns with our results for parity 5 sows. Given the effect of parity, these sows had a lower backfat thickness gain over the first 110 days postweaning. The BW at mating, at d110, and at weaning was influenced by parity. Indeed, compared with the average weight gain during the first 110 days of gestation across all parities (38 kg), the deviation from the average was −10% for multiparous sows but +48% for primiparous sows. Although primiparous sows consumed less feed than older sows, this result is consistent with the findings of Lavery et al. (2019). During lactation, primiparous sows lost an average of 30 kg, while multiparous sows (parity 2–6) lost an average of 22 kg. Primiparous sows often experience the greatest loss, as their feed intake is frequently insufficient to meet the nutritional requirements for milk production (Noblet et al., 1990). Parity also seems to contribute to the observed variation in backfat thickness at mating and at d110. Primiparous sows had numerically a higher backfat thickness than other parities, due to distributed feed quantities (and thus energy) with the goal of

Table 6
Quantity of urinary and blood calcium and phosphorus excreted at 30 and 90 or 110 days postweaning during two gestation cycles in sows fed different levels of dietary phosphorus and calcium content.

Cycle	First gestation cycle						Second gestation cycle											
Stage	30			90 or 110[1]			30			90 or 110[1]								
Treatment	CAN	EU	PR	CAN	EU	PR	CAN	EU	PR	CAN	EU	PR	SEM	TRT	Stage	TRT*Cycle	Stage*Cycle	TRT*Stage*Cycle
Number of sows (n)	8	8	9	6	–	9	9	5	8	7	–	9						
Urinary P (g/d)	1.26[c]	1.53[abc]	2.06[abc]	1.19[c]	–	1.35[bc]	1.00[c]	2.97[a]	1.63[abc]	1.12[c]	–	2.60[ab]	0.090	<0.001	0.701	0.004	<0.017	0.034
Urinary Ca (g/d)	1.112	0.770	0.911	0.590	–	0.842	0.635	1.237	0.775	0.548	–	0.689	0.055	0.693	0.154	0.056	0.437	0.357
Urinary Ca:P	0.996[a]	0.505[ab]	0.457[ab]	0.486[ab]	–	0.590[ab]	0.694[ab]	0.465[ab]	0.528[ab]	0.675[ab]	–	0.270[b]	0.042	0.023	0.159	0.886	0.596	0.020
Number of sows (n)	8	9	10	7	–	7	8	8	10	6	–	7						
Blood Ca (mg/L)	105	104	103	117	–	113	105	108	103	109	–	107	0.613	0.123	<0.001	0.469	0.028	0.848
Blood P (mg/L)	59.6	55.5	56.0	69.3	–	71.5	58.5	59.8	58.2	70.7	–	69.1	0.646	0.721	<0.001	0.379	0.708	0.207
1,25OH$_2$D$_3$ (pg/mL)	75.7	74.8	78.8	76.1	–	83.7	71.4	60.0	73.7	78.6	–	86.6	0.191	0.022	0.022	0.375	0.224	0.919

Abbreviations: CAN = Canadian treatment (3.2 g/kg digestible phosphorus (P); 8.3 g/kg calcium (Ca)); EU = European treatment (2.5 g/kg digestible P; 6.8 g/kg Ca); PR = precision feeding treatment (1.5 g/kg to 3.2 g/kg digestible P; 4.6 g/kg to 8.3 g/kg Ca); TRT = treatment; 1,25OH$_2$D$_3$ = active vitamin D; Fixed effects: treatment, gestation stage, and cycle and all interactions; cycle effect and treatment × cycle effect are not significant. Letters correspond to the interaction treatment × stage × cycle.

[1] Urinary P and Urinary Ca measured at d90 postweaning and Blood Ca and Blood P measured at d110 postweaning.

achieving a specific backfat thickness (Alphagene, 2021). As Grez-Capdeville and Crenshaw (2022) previously observed, the presently used low-P diet (PR treatment), especially during early gestation, did not impair lactation performance.

Phosphocalcic status

A second objective was to study the effects of a precision P and Ca feeding strategy on the P and Ca metabolism of sows to determine if the nutritional requirement model can be implemented for precision feeding. Part of the response to this objective was provided by the study of urinary P and Ca excretion. It is important to mention that these data were collected following a 24-h urine collection. Since the sows' water consumption follows a circadian rhythm, this should not affect urinary P and Ca excretion.

Urinary Ca was not affected by dietary Ca intake, which varied between 4.6 and 8.3 g/kg during gestation. This result is consistent and confirms over the entire gestation the findings by Lee et al. (2020), who concluded that in late-gestating sows (from day 91 to day 104), increasing dietary Ca (from 1.8 to 7.1 g/kg) increased retained Ca, so not the amount of urinary Ca. This suggests that the sows retained nearly all of the absorbed Ca. Furthermore, the urinary Ca:P ratio was close to or below 0.5 for most treatment, stage, and cycle interactions. According to Grez-Capdeville and Crenshaw (2021), this level indicates that the sows were limited in Ca but not in P, which can explain the absence of a relationship between dietary Ca and urinary Ca. Urinary P excretion was influenced by the dietary treatment, stage, and cycle. Numerically, during C1, urinary P excretion was higher in PR sows than in CAN and EU sows, while Ca excretion was similar across treatments. It should be noted that the treatments were formulated based on the digestibility of P in feed ingredients. As a result, the digestible P content may be overestimated, since gestating sows have lower P digestibility compared to growing pigs (Lee et al., 2018; 2021). Nevertheless, this result confirmed a lack of dietary Ca, which may have limited the bone mineralization, because both P and Ca are stored in the form of hydroxyapatite. Additionally, 1,25(OH)$_2$D$_3$ increased numerically in PR sows. An increase in the active form of vitamin D typically results from a rise in parathormone, resulting from low plasma Ca levels (Suttle, 2010). At d30 of C2, EU sows excreted more P than CAN sows, and numerically more than PR sows. This could be explained by the lack of Ca in the feed (urinary Ca:P ratio < 0.5), potentially limiting bone mineralization; EU sows in C2 had 18% lower Ca intake during the first 30 days than EU sows in C1. On d90 of C2, PR sows also appeared to be Ca-deficient (urinary Ca:P ratio < 0.5), which highlights the importance of optimizing the Ca to digestible P ratio in feed formulation and that the current models applying one feed (EU and CAN) or daily adjustments (PR) seem to underestimate this ratio.

Pelvic organ prolapse is a significant concern in the swine industry due to its associated high mortality rates (ranging from 14–28%, Eckberg, 2021; Paiva et al., 2023). Although the causes of uterine prolapses are multiple, one of them is linked to hypocalcemia at the beginning of parturition, as mentioned in cows (Risco et al., 1984). In sows, a study by Ayliffe et al. (1984) highlighted a reduction in uterine activity associated with hypocalcemia, as calcium plays a role in muscle contraction. This decrease in uterine activity could then lead to pelvic organ prolapse. In a recent survey (Kociemba et al., 2024) conducted in the United States, Canada, and Mexico, comparing farms having low rates of pelvic organ prolapse with higher prolapse rates showed that they were more likely to use gestation diets with a higher content of distillers dried grains with solubles (14.6 vs 4.0%, SE 3.02), higher levels of standardized total tract digestible P (0.49 vs 0.39%, SE 0.014), a narrower ratio of analyzed Ca to standardized total tract digestible P (1.7 vs 2.2, SE 0.06), and lower phytase inclusion and release (0.16 vs 0.09%, SE

Table 7
Phosphorus balance of sows fed different levels of dietary phosphorus and calcium content during gestation.

Item	Treatment CAN	PR	SEM	*P-value* TRT
Number of sows	12	13		
Feed intake (kg)	291	290	5.5	0.777
Dietary P intake (g)	1 685[a]	1 551[b]	26.4	<0.001
Body P retention (g)[1]	138	147	24.1	0.711
Urinary P excretion (g)[2]	112[b]	192[a]	19.9	<0.001
Fecal P excretion (g)[3]	1 434[a]	1 214[b]	34.32	<0.001
Total P excretion (g)[4]	1 546[a]	1 406[b]	25.36	<0.001
ATTD (%)[5]	14.7[b]	21.9[a]	0.10	<0.001

Abbreviations: CAN = Canadian treatment (3.2 g/kg digestible phosphorus (P); 8.3 g/kg calcium (Ca)); PR = precision feeding treatment (1.5 g/kg to 3.2 g/kg digestible P; 4.6 g/kg to 8.3 g/kg Ca); TRT = treatment; ATTD = apparent total tract digestibility. Fixed effects: treatment, random effect: cycle. Letters correspond to the treatment effect.
[1] The body P retention was determined by assuming a retention of 5.5 g P per kg of BW gain.
[2] Urinary excretion is estimated by considering that the first 53 days of gestation present levels of urinary P that are equivalent to those observed at d30 postweaning, while the remaining 50 days of gestation are associated with levels of urinary P measured at d90 postweaning.
[3] Fecal excretion is calculated by subtracting the body P retention and the urinary P excretion from dietary P intake.
[4] Total excretion is calculated by summing the urinary and fecal P excretion.
[5] The apparent total tract digestibility of phosphorus is calculated by dividing fecal P excretion by ingested P.

0.014). Because Ca and P can interact and form insoluble complexes that preclude the absorption of both minerals (Lautrou et al., 2022), a Ca deficiency situation could have been created by high P supply combined with low Ca supply in the farms that had high prolapse rates. Therefore, the low Ca:P ratios found in urine, even in the CAN sows (average of 0.7), indicate that more research is needed to refine Ca requirements.

Regardless of the treatment and cycle, blood P and Ca levels both increased between d30 and d110. One explanation for this could be the lower apparent total tract digestibility in mid-gestation than in late-gestation sows (Kemme et al., 1997; Jongbloed et al., 2013; Lee et al., 2019). The evolution of digestibility may be because of higher demands for P and Ca for fetal development during late gestation (Bikker and Blok, 2017). Furthermore, differences in plasma estrogen levels during gestation could influence the metabolism of $25(OH)_2D_3$, the precursor to $1,25(OH)_2D_3$, which may affect Ca and P digestibility in humans (Bansal et al., 2013; Harmon et al., 2016). This result aligns with the observed increase in $1,25(OH)_2D_3$ between d30 and d110 in this study. Another explanation could be that bump feeding—the increase in feed quantity toward the end of gestation to meet the higher nutritional demands at this stage (Goodband et al., 2013)—could have also played a role.

P balance and digestibility

In the province of Quebec, the Agricultural Operations Regulation (REA, 2024) requires farmers to establish their annual phosphorus (P_2O_5) production and to define their “agro-environmental fertilization plan” accordingly. Reducing P excretion is a solution that could align manure P with crop needs. The study showed that the precision feeding strategy reduced P excretion by 10% when compared with the current Canadian strategy using fixed levels throughout gestation. This reduction could be even greater by fine-tuning Ca:P ratio in the feed as the present results showed that there was insufficient Ca to retain P, which increased urinary P excretion. The decrease in excretion is certainly a result of a lower intake of P, but it may also be linked to an increase in P digestibility. Indeed, an intake of P either below or at the animal’s requirements can trigger the establishment of Ca-P regulation mechanisms, increasing the ability of the intestinal epithelium to absorb (Heurtault et al., 2024). Beyond the aspect of P excretion, a strategy to enhance the P sustainability lies in a lower use of mineral phosphates, as this is a finite resource (Illakwahhi et al., 2024). The precision feeding strategy reduced the use of inorganic phosphates by 81% compared to CAN, representing a reduction of 603 g P per sow between d7 and d110 of gestation. On a national scale, with a breeding stock of 1 253 436 sows and gilts in Canada (Statistics Canada, 2021), this would reduce P consumption by 755 tons.

Conclusion

The study confirmed that urinary excretion of P and Ca is sensitive to mineral imbalances and, therefore, serves as a reliable indicator of P and Ca utilization and retention. Despite the imbalances observed in the study, reducing P intake during the first two-thirds of gestation appears feasible, and this will optimize P utilization and retention without compromising reproductive performance. However, implementing this strategy requires careful monitoring of the Ca to digestible P ratio, which was too low in the current study. These promising findings should be further examined over multiple gestation cycles to validate precision feeding in P and Ca and wide adoption.

Supplementary material

Supplementary Material for this article (https://doi.org/10.1016/j.animal.2025.101644) can be found at the foot of the online page, in the Appendix section.

Ethics approval

This study was carried out under the Canadian Council on Animal Care guidelines (CCAC; https://www.ccac.ca/en/certifcation/about-certifcation). The protocol was approved by the Animal Use and Care Protection Committee of Laval University (protocol number: 2022-1162).

Data and model availability statement

None of the data were deposited in an official repository. The data that support this study’s findings are available upon request from the corresponding author.

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

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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Declaration of interest

None.

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