

RESEARCH ARTICLE

Determinants of extremely low birth weight piglets per litter in Landrace × Yorkshire sows under commercial conditions in Vietnam



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ABSTRACT

Background and Aim: Extremely low birth weight piglets (LBP) contribute disproportionately to preweaning mortality and reduced production efficiency. However, large-scale commercial evidence regarding piglets weighing <750 g remains limited, particularly in Southeast Asia. This study aimed to quantify extremely LBP per litter and identify their major determinants in Landrace × Yorkshire sows under commercial conditions in Vietnam.

Materials and Methods: This retrospective cohort study used commercial farm records collected from 2018 to October 2025. Descriptive analysis included 17,712 farrowing records from 4,476 sows, representing 211,720 piglets. Two cleaned datasets were analyzed: Model 1 comprised 7,985 records, whereas Model 2 comprised 6,336 records and additionally incorporated the weaning-to-service interval (WSI). Factors associated with LBP were evaluated using zero-inflated Poisson generalized linear mixed models, with sow and boar included as random effects.

Results: The overall incidence of LBP was 4.30%, corresponding to 0.51 LBP per litter, and 31.39% of litters contained at least one LBP. Litter size was the strongest determinant; each additional piglet was associated with an approximately 31%–32% increase in the expected LBP count. LBP exhibited a non-linear relationship with parity, increasing through intermediate parities, peaking at parity 5, and declining thereafter. A parity × litter size interaction indicated a stronger adverse association between increasing litter size and LBP in older sows, with a significant interaction at parity 6 in Model 2. WSI >20 days was associated with increased LBP, whereas gestation length >116 days was associated with lower LBP.

Conclusion: Litter size is the primary determinant of extremely LBP under the studied commercial conditions, highlighting the trade-off between prolificacy and piglet viability. Parity-specific effects, prolonged WSI, and gestation length further influence LBP occurrence. Management strategies emphasizing appropriate litter size management, particularly in older sows, together with reproductive management that avoids prolonged WSI and shortened gestation, may help reduce extremely LBP and improve herd productivity.

Keywords: commercial swine production, extremely low birth weight piglets, gestation length, litter size, parity, piglet viability, Vietnam, weaning-to-service interval.

INTRODUCTION

Low birth weight piglets (LBP) remain a major constraint in modern swine production because they are strongly associated with increased preweaning mortality, impaired thermoregulation, and reduced growth performance [1]. Numerous studies have demonstrated markedly lower survival among piglets with lower birth weights. Mortality rates have been reported to reach 28% in piglets weighing <1.2 kg compared with 7% in heavier piglets [2] and 32% in piglets weighing <1.1 kg compared with 10% in those above this threshold [3]. Similarly, piglets with birth weights <1.11 kg have approximately fourfold higher preweaning mortality than those weighing ≥1.11 kg (34.4% vs. 8.2%) [4]. Piglets weighing 410–990 g also exhibit substantially higher mortality than heavier categories (27.5% vs. 11.77%–13.05%) [5]. This reduced survival is partly attributable to limited energy reserves and impaired thermoregulatory capacity, as heavier piglets have been shown to maintain higher body

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temperatures and greater physiological stability shortly after birth [6]. Consequently, even a relatively small proportion of extremely LBP can have a disproportionate effect on overall litter performance.

The reported incidence of LBP varies considerably according to the threshold used. When broader definitions are applied (<1.0–1.11 kg), the proportion of affected piglets can exceed 13%–21% [2, 4, 7]. In contrast, studies using stricter thresholds, such as <750–800 g, generally report lower incidences of approximately 4%–7% [8–10]. Despite these differences in classification, the biological and economic consequences remain important because extremely LBP contribute disproportionately to mortality and impaired productive performance.

Among the factors influencing the occurrence of LBP, litter size has consistently been identified as an important determinant. Larger litters are associated with lower individual birth weights and greater within-litter variation [7, 11]. Each additional piglet has been associated with a reduction in average birth weight of approximately 19.5–21.7 g [12]. The incidence of LBP also increases with increasing litter size [8], reflecting constraints in uterine capacity and nutrient availability per fetus. Furthermore, increased litter size has been associated with higher preweaning mortality at the herd level [13], highlighting the trade-off between prolificacy and individual piglet viability.

Parity is another potentially important determinant, although findings have been inconsistent. Some studies have reported that birth weight is lowest in first-parity sows and increases in subsequent parities [14, 15], whereas others have demonstrated an increasing proportion of LBP with advancing parity [9] or no significant association between parity and low birth weight [7]. These inconsistencies indicate that the relationship between parity and low birth weight may depend on differences in population characteristics, birth weight thresholds, litter size, and production conditions.

Reproductive management factors, including the weaning-to-service interval (WSI) and gestation length, may also influence fetal development. Some studies have reported no clear effect of WSI on birth weight distribution [15], whereas others have demonstrated an association between prolonged WSI and reduced birth weight, with each additional day of WSI associated with an approximately 25.8-g reduction in birth weight [12]. Shorter gestation length has also been associated with reduced birth weight and an increased incidence of LBP [7], potentially reflecting the shorter period available for fetal growth during late gestation.

Most previous studies have investigated LBP using relatively broad thresholds of approximately 800–1,110 g [2–4, 7–9]. In contrast, evidence specifically addressing piglets weighing ≤ 750 g remains limited [10]. Piglets weighing <750 g represent an extreme subgroup with markedly reduced viability and may be culled shortly after birth under commercial conditions because of their limited survival and growth potential [5, 16, 17]. Under such production systems, the loss of these piglets reduces the number of potentially marketable animals while the maintenance costs associated with the sow remain, thereby affecting herd productivity and economic efficiency. Despite their biological and production relevance, quantitative evidence regarding the incidence and determinants of extremely LBP remains substantially more limited than that available for broader low birth weight categories.

This evidence gap is particularly important in tropical Asian commercial production systems, where environmental conditions, including heat stress, together with farm-specific reproductive and management practices, may influence fetal development and piglet viability. Although studies conducted under tropical conditions have demonstrated associations among litter size, parity, birth weight, and piglet survival [6, 18, 19], evidence specifically characterizing extremely LBP under large-scale commercial conditions remains scarce. Furthermore, most previous investigations have evaluated low birth weight as an individual piglet trait or categorical outcome rather than as the number of affected piglets within a litter [2, 4, 7, 9, 12]. Consequently, there is limited evidence from hierarchical count-based analyses that simultaneously account for repeated farrowings within individual sows, paternal variation attributable to boars, and biologically plausible interactions among reproductive and litter level determinants. Addressing these methodological and geographical gaps is necessary to better characterize factors associated with extremely LBP under commercial tropical production conditions.

Therefore, this study aimed to quantify the number of extremely LBP per litter, defined as live-born piglets weighing <750 g, and to identify the major reproductive and litter level determinants associated with this outcome in Landrace $\times$ Yorkshire sows under commercial conditions in Vietnam. Particular emphasis was placed on evaluating the associations of litter size, parity, gestation length, and WSI with the number of extremely LBP per litter while accounting for the hierarchical structure of commercial production data. The study further evaluated biologically plausible interactions among major determinants to determine whether their associations with

extremely low birth weight varied across reproductive conditions. The <750-g threshold was selected because it represents the operational cutoff used by the study farm for management decisions and identifies a subgroup of piglets with limited survival potential.

MATERIALS AND METHODS

Ethical approval

This retrospective cohort study was conducted exclusively using pre-existing production records obtained from a commercial swine farm and did not involve prospective animal enrollment, experimental manipulation, direct animal handling, collection of biological samples, or alteration of routine farm management. Therefore, formal ethical approval was not required according to the applicable institutional guidelines. All study procedures involving the use and analysis of farm records were conducted in accordance with the relevant institutional and national guidelines for animal research ethics of Vietnam National University of Agriculture. The data were anonymized before analysis, and identifiers that could disclose the identity of the farm were not available to the researchers. The study therefore involved secondary analysis of routinely collected production data without additional interventions involving animals.

Study period and location

Farm production records covered farrowings occurring from 2018 to October 2025. The records were extracted between June and October 2025 following a request by the principal investigator based on predefined study objectives. The study was conducted using data from a commercial swine farm with approximately 1,200 sows located in central Vietnam. The records were provided by the herd veterinarian in Microsoft Excel format.

Regional average monthly minimum temperatures ranged from approximately 15°C to 27°C, whereas average monthly maximum temperatures ranged from approximately 20°C to 35°C. The highest average monthly maximum temperatures occurred between June and August and reached approximately 35°C, while mean relative humidity was approximately 85%–86%. During the hot season, the farm implemented heat-mitigation measures, including cooling pads, mechanical ventilation to remove hot air from the barns, and misting systems. On extremely hot days, sows were additionally showered in the afternoon to reduce heat stress.

Study design

This retrospective cohort study evaluated routinely collected sow- and litter level production records to quantify the number of extremely LBP per litter and identify associated reproductive and litter level factors. The original dataset comprised 17,712 farrowing records from 4,476 sows, representing 211,720 piglets born. All available records were included in the descriptive analysis. Following predefined data cleaning and eligibility procedures, two complementary analytical datasets were constructed to accommodate the absence of WSI information for parity 1 sows. Model 1 retained parity 1 but excluded WSI, whereas Model 2 excluded parity 1 and incorporated WSI. This complementary modeling strategy allowed evaluation across the full parity range while separately assessing the association of WSI with the study outcome.

Herd description

The animals included in the study were commercial maternal-line sows derived from Landrace and Yorkshire genetics and originating from a grandparent herd maintained within the same region of Vietnam. The foundation grandparent stock was originally imported from Europe. Replacement gilts were routinely vaccinated against major swine pathogens, including porcine reproductive and respiratory syndrome virus, porcine circovirus type 2 (PCV2), classical swine fever virus, foot-and-mouth disease virus, Aujeszky's disease virus (ADV), porcine parvovirus (PPV), *Mycoplasma hyopneumoniae*, and *Escherichia coli*. Booster vaccinations were administered during gestation and at regular intervals in breeding sows.

Gilts and sows were artificially inseminated multiple times during each estrus, with gilts and sows inseminated four and three times, respectively, according to standard farm protocols. Pregnant sows were housed individually in gestation crates and transferred to farrowing crates approximately 1 week before parturition. Piglets were provided with a heated creep area after birth.

During gestation, sows received commercial diets according to gestational stage, with approximately 3.0, 2.5, and 3.3 kg/day provided during weeks 1–4, 5–12, and 13–16 of gestation, respectively. Feed allowance was reduced during the 5 days preceding the expected farrowing date. After farrowing, feed intake was gradually increased to *ad libitum* throughout lactation until weaning. Diets provided approximately 2,900 kcal/kg metabolizable energy and 16% crude protein during the first 12 weeks of gestation and approximately 3,100

kcal/kg metabolizable energy and 17% crude protein during late gestation and lactation. Sow body condition was routinely evaluated by farm personnel, and feed allowance was adjusted according to nutritional status. However, individual body condition scores were unavailable in the retrospective dataset and were therefore not included in the statistical analyses.

Data collection

The dataset contained sow- and litter level information, including sow identification, date of birth, parity, service number associated with each farrowing, boar identification, dates of insemination, farrowing, and weaning, and litter performance traits. Recorded litter traits included total number of piglets born, number born alive, and numbers of stillborn, mummified, deformed, and LBP per litter.

The farm records contained only the number of piglets weighing <750 g within each litter; exact individual birth weights of these piglets were unavailable. Individual piglet birth weight, average litter birth weight, total litter birth weight, preweaning mortality, sow culling rate, and herd health status were also unavailable in the dataset.

Data definitions

Gestation length was calculated as the interval between insemination and farrowing. Litter size was defined as the total number of piglets born per litter. WSI was calculated as the interval between weaning and subsequent insemination.

For this study, extremely LBP were defined as live-born piglets weighing <750 g [10]. The <750-g threshold represented the operational cutoff used by the study farm for immediate culling decisions and was used to identify piglets considered to have extremely poor survival prospects. According to routine farm procedures, total litter weight was recorded after farrowing. Piglets identified as noticeably smaller than their littermates were subsequently weighed individually using an electronic scale, and those weighing <750 g were recorded as LBP.

Stillborn and mummified piglets were recorded as separate outcomes and were not classified as LBP, irrespective of body weight. Stillborn piglets were defined as fully developed piglets born dead at farrowing without signs of tissue degeneration. Mummified piglets were defined as fetuses that died during gestation and had undergone tissue degeneration characterized by dark discoloration [20].

Data cleaning and construction of analytical datasets

The initial dataset comprised 17,712 farrowing records from 4,476 sows, representing 211,720 piglets born. Before analysis, records with missing gestation length data ($n = 470$), WSI data ($n = 4,559$), or boar information ($n = 9,566$) were identified for exclusion as applicable to the analytical dataset. First-parity records ($n = 3,540$) did not have WSI information and therefore could not be included in analyses requiring this variable.

Additional exclusions comprised records in which gestation length was erroneously entered as a date ($n = 23$), gestation lengths <109 days ($n = 2$), biologically implausible WSI values <0 days ($n = 4$), WSI >180 days ($n = 15$), and boars represented by only one farrowing record ($n = 17$). Gestation lengths <109 days were considered premature farrowing or abortion cases. Eligible records had gestation lengths of 109–120 days, WSI values of 0–180 days, and litter sizes of 2–22 piglets.

After data cleaning, two complementary analytical datasets were constructed. Model 1 included parity 1 and comprised 7,985 records from 3,105 sows serviced by 137 boars. WSI was excluded from Model 1 because this information was unavailable for parity 1, thereby allowing parity 1 to be retained and the complete parity range to be evaluated. Model 2 excluded parity 1 and incorporated WSI, comprising 6,336 records from 2,427 sows serviced by 130 boars. Consequently, results for parity 1 were available only from Model 1.

Compared with the original dataset, which had a mean litter size of 11.95 ± 2.20 piglets, the analytical datasets had slightly larger mean litter sizes of 12.45 ± 2.23 and 12.56 ± 2.23 piglets for Models 1 and 2, respectively. Mean LBP values were 0.51 ± 0.89 , 0.54 ± 0.91 , and 0.56 ± 0.91 piglets per litter in the original dataset, Model 1, and Model 2, respectively.

The original dataset contained 3,540, 3,763, 3,061, 2,444, 1,827, 1,308, and 1,769 records for parities 1, 2, 3, 4, 5, 6, and >6, respectively. Model 1 contained 1,304, 1,928, 1,581, 1,319, 933, 631, and 289 records for the corresponding parity groups. Model 2 contained 1,813, 1,483, 1,245, 908, 604, and 283 records for parities 2, 3, 4, 5, 6, and >6, respectively.

For gestation length, Model 1 contained 1,330, 5,948, and 707 records for <114, 114–116, and >116 days, respectively, whereas Model 2 contained 1,011, 4,796, and 529 records for the same categories. For WSI, Model 2 contained 5,181, 297, 197, and 661 records for 0–6, 7–10, 11–20, and >20 days, respectively.

The proportion of litters containing at least one LBP was 31.39% (5,559/17,712) in the complete dataset, compared with 33.34% (2,662/7,985) in Model 1 and 34.39% (2,179/6,336) in Model 2. No imputation was performed for missing WSI or boar information because these variables could not be reliably reconstructed from the available farm records. Records with missing values were therefore excluded according to the eligibility requirements of the respective analytical dataset.

Statistical analysis

Data were analyzed using R software (version 4.6.1; R Core Team). Parity was categorized into seven groups (1, 2, 3, 4, 5, 6, and >6), WSI into four categories (0–6, 7–10, 11–20, and >20 days), gestation length into three categories (<114, 114–116, and >116 days), and service number into two categories (1 and ≥2). Litter size was analyzed as a continuous variable and mean-centered before modeling to reduce multicollinearity.

All available records were included in the descriptive analysis. The number of LBP per litter was summarized as the mean ± standard deviation.

A generalized linear mixed model (GLMM) with a Poisson distribution and log-link function was initially fitted using the `glmer` function of the `lme4` package to identify factors associated with the number of LBP per litter. Sow and boar were included as random intercepts to account for repeated observations within sows, persistent sow-level variation, and paternal effects. Random slopes were not included.

Fixed effects comprised parity, gestation length, WSI when available, and centered litter size. Three biologically plausible two-way interactions were evaluated: parity × litter size, parity × gestation length, and gestation length × litter size. Service number was excluded from the multivariable models because of substantial category imbalance. Service number 2 accounted for 6.55% ($n = 1,160$) of records in the original dataset, 4.45% ($n = 355$) in Model 1, and only 0.11% ($n = 7$) in Model 2. In a descriptive sensitivity analysis, mean LBP per litter for service numbers 1 and 2 was 0.52 and 0.46, respectively, in the original dataset; 0.55 and 0.49 in Model 1; and 0.56 and 1.14 in Model 2. Given the very small number of observations for service number 2, particularly in Model 2, reliable estimation of this effect within the GLMM framework was not considered feasible.

Because all records originated from a single commercial farm, spatial autocorrelation was not applicable. Temporal effects of year and month of farrowing were initially explored as fixed and random effects but were not retained in the final models because of model instability and lack of improvement in model fit. Although mean LBP varied among farrowing months (0.278–0.729 piglets per litter), descriptive evaluation did not reveal an obvious or consistent seasonal pattern. Model convergence was achieved using the `bobyqa` optimizer with the maximum number of function evaluations increased to 200,000.

Model diagnostics were evaluated using simulation-based residual diagnostics implemented in the `DHARMA` package (version 0.5.0). Dispersion and zero inflation were assessed using simulation-based tests. The initial Poisson GLMM showed no evidence of problematic dispersion but indicated excess zeros. Therefore, two alternative zero-inflated models were evaluated: a zero-inflated Poisson (ZIP) GLMM and a zero-inflated negative binomial (ZINB) GLMM. All three models were fitted using the same fixed- and random-effect structure to permit direct comparison of model fit and diagnostic performance.

The competing Poisson, ZIP, and ZINB GLMMs were compared using Akaike's information criterion (AIC), marginal and conditional R^2 , and zero inflation and dispersion diagnostics. The model providing the most favorable overall combination of model fit and diagnostic performance was selected for final inference.

Model estimates were expressed as incidence rate ratios (IRRs) with 95% confidence intervals (CIs), obtained by exponentiating the model coefficients. For zero-inflated models, IRRs were derived by exponentiating coefficients from the conditional count component. Marginal and conditional R^2 values were calculated using the Nakagawa–Schielzeth method with the delta approximation implemented in the `r.squaredGLMM` function of the `MuMIn` package. Marginal R^2 represented variance explained by the fixed effects, whereas conditional R^2 represented variance explained by the complete model, including fixed and random effects. Multicollinearity was assessed using generalized variance inflation factors (GVIFs) from the `car` package.

To facilitate interpretation of the parity × litter size interaction, model-based predicted LBP values were estimated on the response scale using the `emmeans` package. Predictions were obtained at representative litter sizes of 10, 12, 14, and 16 piglets for parities 2, 5, 6, and >6. For Model 2, WSI was fixed at the reference category of 0–6 days, whereas predictions were averaged across gestation length categories. Predicted LBP values per litter were presented with 95% CIs and plotted to illustrate the magnitude of the parity × litter size interaction. Statistical significance was defined as $p < 0.05$.

RESULTS

Descriptive statistics

The mean WSI, gestation length, and litter size of the herd were 9.9 ± 16.8 days, 114.7 ± 11.5 days, and 11.95 ± 2.20 piglets, respectively. The mean number of piglets born alive was 10.90 ± 1.98 per litter. The mean numbers of stillborn, mummified, and deformed piglets were 0.39 ± 1.05 , 0.07 ± 0.44 , and 0.08 ± 0.33 piglets per litter, respectively. Mean litter size varied across parity groups, increasing from 11.56 ± 2.14 piglets at parity 1 to a maximum of 12.30 ± 2.21 piglets at parity 4, followed by a gradual decline in later parities, with the lowest mean observed at parity >6 (11.69 ± 2.01 piglets). Overall, 4.30% (9,100/211,720) of piglets weighed <750 g, corresponding to a mean of 0.51 LBP per litter (9,100/17,712).

Across parity groups, the mean number of LBP per litter exhibited a non-linear pattern, increasing from the early parities to a maximum of 0.75 at parity 5 and subsequently declining at higher parities. The proportion of litters containing at least one LBP followed a similar pattern, reaching a maximum of 46.2% at parity 5 and a minimum of 23.6% at parity 2.

Across WSI categories, the mean number of LBP per litter was lowest in the 0–6-day group (0.51 ± 0.85) and was 0.65 ± 1.02 , 0.62 ± 1.14 , and 0.59 ± 0.97 in the 7–10-, 11–20-, and >20 -day groups, respectively. The proportion of litters containing at least one LBP ranged from 32.2% to 35.7%, with no consistent descriptive trend across increasing WSI categories.

The mean number of LBP increased progressively with litter size, from 0.12 in litters containing ≤ 10 piglets to 1.47 in litters containing >15 piglets. Similarly, the proportion of litters containing at least one LBP increased from 7.6%–8.2% in the smallest litter size categories to 64.5% in litters containing >15 piglets.

The mean number of LBP per litter decreased across gestation length categories, from 0.60 in sows with gestation lengths <114 days to 0.39 in those with gestation lengths >116 days. The corresponding proportion of litters containing at least one LBP decreased from 35.6% to 23.1%.

Service number showed comparatively small descriptive differences. The mean number of LBP per litter was 0.52 among first-service sows and 0.46 among sows with service number ≥ 2 , whereas the corresponding proportions of litters containing at least one LBP were 31.7% and 26.6%, respectively (Table 1).

Table 1: Descriptive statistics of low birth weight piglets per litter according to reproductive and litter characteristics

Factors	LBP per litter, mean $\pm$ SD; median (IQR)	Litters with at least one LBP (%)
Parity (n = 17,712)		
1 (n = 3,540)	0.46 ± 0.87 ; 0 (0–1)	27.5
2 (n = 3,763)	0.39 ± 0.82 ; 0 (0–0)	23.6
3 (n = 3,061)	0.45 ± 0.86 ; 0 (0–1)	27.0
4 (n = 2,444)	0.63 ± 0.95 ; 0 (0–1)	37.6
5 (n = 1,827)	0.75 ± 0.99 ; 0 (0–1)	46.2
6 (n = 1,308)	0.62 ± 0.87 ; 0 (0–1)	41.7
>6 (n = 1,769)	0.51 ± 0.84 ; 0 (0–1)	31.9
WSI (n = 13,153)		
0–6 days (n = 10,239)	0.51 ± 0.85 ; 0 (0–1)	32.2
7–10 days (n = 774)	0.65 ± 1.02 ; 0 (0–1)	35.7
11–20 days (n = 459)	0.62 ± 1.14 ; 0 (0–1)	33.3
>20 days (n = 1,681)	0.59 ± 0.97 ; 0 (0–1)	33.6
Litter size (n = 17,712)		
<10 (n = 1,482)	0.12 ± 0.46 ; 0 (0–0)	8.2
10 (n = 2,969)	0.12 ± 0.53 ; 0 (0–0)	7.6
11 (n = 3,162)	0.22 ± 0.59 ; 0 (0–0)	16.0
12 (n = 3,553)	0.46 ± 0.74 ; 0 (0–1)	33.7
13 (n = 2,517)	0.69 ± 0.86 ; 0 (0–1)	46.9
14 (n = 1,843)	0.96 ± 1.03 ; 1 (0–2)	55.3
15 (n = 1,265)	1.09 ± 1.13 ; 1 (0–2)	56.3
>15 (n = 921)	1.47 ± 1.37 ; 2 (0–2)	64.5
Gestation length (n = 17,219)		
<114 days (n = 3,173)	0.60 ± 0.95 ; 0 (0–1)	35.6
114–116 days (n = 12,718)	0.50 ± 0.87 ; 0 (0–1)	30.9
>116 days (n = 1,328)	0.39 ± 0.84 ; 0 (0–0)	23.1
Service number (n = 17,712)		
1 (n = 16,552)	0.52 ± 0.89 ; 0 (0–1)	31.7

Factors	LBP per litter, mean $\pm$ SD; median (IQR)	Litters with at least one LBP (%)
≥ 2 (n = 1,160)	0.46 $\pm$ 0.88; 0 (0–1)	26.6

IQR = interquartile range; LBP = low birth weight piglets; SD = standard deviation; WSI = weaning-to-service interval. LBP values are presented as mean $\pm$ SD and median (IQR), with IQR representing the 25th–75th percentile and calculated from all available records. Incidence represents the percentage of litters containing at least one LBP (<750 g).

Model comparison and selection

Model 1 included 7,985 farrowing records from 3,105 sows serviced by 137 boars and did not incorporate WSI, whereas Model 2 included 6,336 records from 2,427 sows serviced by 130 boars and incorporated WSI. Among the candidate distributions, the ZIP model had the lowest AIC in both Model 1 (13,510.80) and Model 2 (10,731.96), compared with the corresponding Poisson (13,520.23 and 10,736.82) and ZINB (13,512.80 and 10,733.96) models. The ZIP and ZINB models yielded identical marginal and conditional R^2 values, which were higher than those obtained with the Poisson models. Marginal R^2 values were 0.222 and 0.235 for the ZIP and ZINB models compared with 0.174 and 0.183 for the Poisson models in Models 1 and 2, respectively. Conditional R^2 values were 0.524 and 0.516 for the ZIP and ZINB models compared with 0.438 and 0.422 for the corresponding Poisson models.

The ZIP models had dispersion statistics close to 1, with values of 1.038 and 1.042 for Models 1 and 2, respectively ($p = 0.238$ and $p = 0.194$), indicating no evidence of problematic dispersion. Although the zero inflation tests remained statistically significant for the ZIP models ($p = 0.006$ and $p = 0.026$), the observed-to-simulated zero ratios were 1.021 and 1.019, respectively, compared with 1.031 and 1.022 for the corresponding Poisson models. Thus, the observed number of zeros was closer to that expected under the ZIP models than under the Poisson models, although residual evidence of zero inflation remained.

Overall, the ZIP model provided the most favorable combination of model fit and residual diagnostic performance among the three candidate distributions and was therefore selected for final inference despite the remaining zero inflation signal. Random-effect variance components were broadly consistent between the two analytical datasets. Multicollinearity was low, with maximum GVIF values of 2.23 for Model 1 and 2.16 for Model 2 (Table 2).

Table 2: Model fit, random effects, and diagnostic statistics for the candidate models

Parameter	Poisson GLMM	ZIP GLMM	ZINB GLMM
Model 1			
AIC	13,520.23	13,510.80	13,512.80
Marginal R^2	0.174	0.222	0.222
Conditional R^2	0.438	0.524	0.524
Sow variance (SD)	0.124 (0.352)	0.067 (0.259)	0.067 (0.259)
Boar variance (SD)	0.543 (0.737)	0.546 (0.739)	0.546 (0.739)
Dispersion (p)	1.044 (0.128)	1.038 (0.238)	1.039 (0.220)
RatioObsSim (p)	1.031 (<0.001)	1.021 (0.006)	1.021 (0.004)
Maximum GVIF	2.23	2.23	2.23
Model 2			
AIC	10,736.82	10,731.96	10,733.96
Marginal R^2	0.183	0.235	0.235
Conditional R^2	0.422	0.516	0.516
Sow variance (SD)	0.086 (0.293)	0.053 (0.230)	0.053 (0.230)
Boar variance (SD)	0.503 (0.709)	0.507 (0.712)	0.507 (0.712)
Dispersion (p)	1.008 (0.796)	1.042 (0.194)	1.041 (0.240)
RatioObsSim (p)	1.022 (0.004)	1.019 (0.026)	1.018 (0.028)
Maximum GVIF	2.16	2.16	2.16

AIC = Akaike information criterion; GLMM = generalized linear mixed model; GVIF = generalized variance inflation factor; SD = standard deviation; ZINB = zero-inflated negative binomial; ZIP = zero-inflated Poisson. RatioObsSim = observed-to-simulated zero ratio. Dispersion and RatioObsSim are DHARMA diagnostic statistics.

Fixed effects

The fixed effect estimates from both models are presented in Table 3. Overall, the direction and magnitude of the associations were generally consistent across the two analytical datasets.

Compared with parity 2, parities 4, 5, and 6 were consistently associated with higher expected LBP counts in both models. The largest association was observed at parity 5, with IRRs of 2.29 (95% CI = 2.01–2.61, $p < 0.001$) in Model 1 and 2.30 (95% CI = 2.01–2.63, $p < 0.001$) in Model 2. Parity 3 was associated with a higher expected LBP count in Model 1 (IRR = 1.16, 95% CI = 1.01–1.33, $p = 0.041$), whereas the corresponding estimate was not

statistically significant in Model 2 (IRR = 1.15, 95% CI = 0.99–1.33, $p = 0.061$). For parity >6, the estimates were IRR = 1.22 (95% CI = 0.98–1.53, $p = 0.075$) in Model 1 and IRR = 1.25 (95% CI = 1.00–1.56, $p = 0.055$) in Model 2. In Model 1, parity 1 was also associated with a higher expected LBP count than parity 2 (IRR = 1.35, 95% CI = 1.18–1.54, $p < 0.001$).

Litter size showed the strongest positive association with LBP in both models. Each one-unit increase in centered litter size was associated with an approximately 31%–32% increase in the expected LBP count (Model 1: IRR = 1.32, 95% CI = 1.27–1.37; Model 2: IRR = 1.31, 95% CI = 1.27–1.36; both $p < 0.001$).

Gestation length >116 days was consistently associated with a lower expected LBP count than gestation length <114 days (Model 1: IRR = 0.72, 95% CI = 0.62–0.84; Model 2: IRR = 0.70, 95% CI = 0.59–0.84; both $p < 0.001$).

In Model 2, WSI >20 days was associated with a higher expected LBP count than the reference category of 0–6 days (IRR = 1.20, 95% CI = 1.08–1.34, $p < 0.001$). No statistically significant differences were observed for WSI of 7–10 or 11–20 days.

Table 3: Incidence rate ratios from two zero-inflated Poisson generalized linear mixed models evaluating factors associated with low birth weight piglets per litter.

Variable	Model 1: IRR (95% CI), p-value	Model 2: IRR (95% CI), p-value
Intercept	0.33 (0.27–0.40), <0.001	0.32 (0.26–0.39), <0.001
Parity 1	1.35 (1.18–1.54), <0.001	Not applicable
Parity 2	Reference category	Reference category
Parity 3	1.16 (1.01–1.33), 0.041	1.15 (0.99–1.33), 0.061
Parity 4	1.62 (1.42–1.85), <0.001	1.61 (1.40–1.85), <0.001
Parity 5	2.29 (2.01–2.61), <0.001	2.30 (2.01–2.63), <0.001
Parity 6	1.71 (1.46–1.99), <0.001	1.70 (1.45–1.99), <0.001
Parity >6	1.22 (0.98–1.53), 0.075	1.25 (1.00–1.56), 0.055
Litter size	1.32 (1.27–1.37), <0.001	1.31 (1.27–1.36), <0.001
Gestation length <114 days	Reference category	Reference category
Gestation length 114–116 days	0.95 (0.87–1.03), 0.217	0.95 (0.87–1.04), 0.264
Gestation length >116 days	0.72 (0.62–0.84), <0.001	0.70 (0.59–0.84), <0.001
WSI 0–6 days	Not applicable	Reference category
WSI 7–10 days	Not applicable	0.95 (0.79–1.13), 0.555
WSI 11–20 days	Not applicable	1.07 (0.87–1.32), 0.541
WSI >20 days	Not applicable	1.20 (1.08–1.34), <0.001
Parity 1 × litter size	1.00 (0.95–1.05), 0.897	Not applicable
Parity 2 × litter size	Reference category	Reference category
Parity 3 × litter size	0.98 (0.93–1.03), 0.357	0.99 (0.94–1.04), 0.585
Parity 4 × litter size	0.98 (0.94–1.03), 0.484	0.98 (0.93–1.03), 0.422
Parity 5 × litter size	0.97 (0.92–1.01), 0.175	0.97 (0.93–1.02), 0.224
Parity 6 × litter size	1.05 (0.99–1.12), 0.080	1.06 (1.00–1.13), 0.039
Parity >6 × litter size	1.10 (0.99–1.23), 0.087	1.11 (0.99–1.25), 0.062

CI = confidence interval; IRR = incidence rate ratio; WSI = weaning-to-service interval. p-value represents the Wald z-test p-value. “Not applicable” indicates variables or interactions not included in the respective model because of the dataset structure. Estimates were obtained from zero-inflated Poisson generalized linear mixed models and represent effects from the conditional count component.

Interaction effects

The parity × litter size interaction indicated that the association between increasing litter size and the expected LBP count differed across parity groups. In Model 2, the interaction for parity 6 was statistically significant (IRR = 1.06, 95% CI = 1.00–1.13, $p = 0.039$), indicating a steeper litter size association at parity 6 than at the reference parity 2. The corresponding interaction in Model 1 was in the same direction but was not statistically significant (IRR = 1.05, 95% CI = 0.99–1.12, $p = 0.080$). For parity >6, the interaction estimates were also >1 but did not reach statistical significance in either Model 1 (IRR = 1.10, 95% CI = 0.99–1.23, $p = 0.087$) or Model 2 (IRR = 1.11, 95% CI = 0.99–1.25, $p = 0.062$). Thus, the results provide evidence of a stronger litter size association at parity 6 in Model 2, whereas the corresponding estimates for the other higher parity comparisons were less conclusive.

Predicted LBP per litter across litter size and parity

To illustrate the parity × litter size interaction, predicted LBP counts per litter were estimated at litter sizes of 10, 12, 14, and 16 piglets for parities 2, 5, 6, and >6 (Figure 1). In Model 1, as litter size increased from 10 to 16 piglets, predicted LBP increased from 0.146 (95% CI = 0.116–0.185) to 0.770 (95% CI = 0.631–0.940) piglets per

litter in parity-2 sows; from 0.363 (95% CI = 0.293–0.451) to 1.566 (95% CI = 1.298–1.889) in parity-5 sows; from 0.220 (95% CI = 0.173–0.281) to 1.581 (95% CI = 1.263–1.979) in parity-6 sows; and from 0.142 (95% CI = 0.098–0.206) to 1.324 (95% CI = 0.866–2.024) in sows with parity >6.

Predictions from Model 2 were similar. As litter size increased from 10 to 16 piglets, predicted LBP increased from 0.151 (95% CI = 0.118–0.192) to 0.771 (95% CI = 0.627–0.949) piglets per litter in parity-2 sows; from 0.373 (95% CI = 0.299–0.466) to 1.598 (95% CI = 1.309–1.951) in parity-5 sows; from 0.220 (95% CI = 0.171–0.284) to 1.633 (95% CI = 1.288–2.071) in parity-6 sows; and from 0.144 (95% CI = 0.099–0.211) to 1.411 (95% CI = 0.900–2.212) in sows with parity >6. At a litter size of 16 piglets, parity-6 sows were predicted to have 0.81 and 0.86 more LBP per litter than parity-2 sows in Models 1 and 2, respectively.

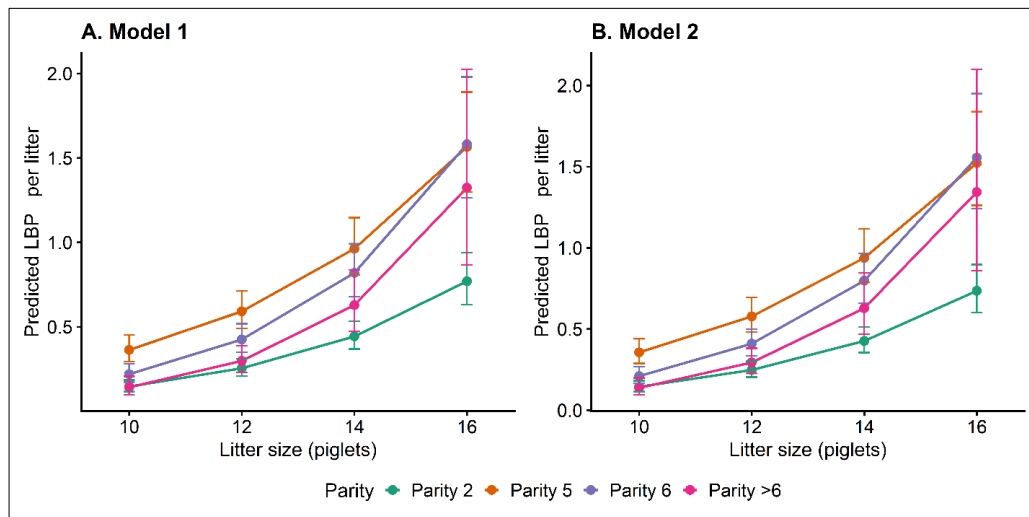


Figure 1: Predicted LBP per litter according to parity and litter size from zero-inflated Poisson mixed-effects models. Predictions are shown for parities 2, 5, 6, and >6 at litter sizes of 10, 12, 14, and 16 piglets. LBP = low birth weight piglets.

DISCUSSION

Principal findings

This study provides one of the first large-scale evaluations of extremely LBP (<750 g) at the litter level in tropical commercial swine production. Unlike most previous studies, which applied broader birth weight thresholds of approximately 0.8–1.11 kg or focused primarily on individual piglet birth weight, the present study quantified the number of extremely LBP per litter using hierarchical mixed-effects count models that accounted for repeated farrowings within sows and clustering attributable to boars. Litter size emerged as the strongest determinant of LBP, while parity, WSI, and gestation length were also associated with the outcome. In addition, the parity × litter size interaction indicated that the association between litter size and LBP differed across parity groups, with the strongest statistical evidence observed at parity 6 in Model 2. These findings provide additional evidence from a tropical commercial swine production system, for which comparable large-scale data remain limited.

Incidence of extremely LBP

The mean number of LBP per litter and the overall incidence of piglets weighing <750 g were 0.51 and 4.30%, respectively. These values were very similar to the 0.48 LBP per litter and 4.22% incidence reported for piglets weighing ≤750 g by Beaulieu *et al.* [10], with an absolute difference of only 0.08 percentage points in incidence. Comparable estimates have also been reported using similar low birth weight thresholds. For example, an incidence of 6.53% was reported for piglets weighing <800 g [8], which was 2.23 percentage points higher than that observed in the present study, whereas incidences of 5.7%–12.3% have been reported across parity groups [9], corresponding to approximately 1.3–2.9 times the present estimate.

In contrast, considerably higher incidences have been reported when broader definitions of low birth weight were applied, including 13.1% for piglets weighing <1.0 kg [2], 14.7% for piglets weighing <1.0 kg and 21.3% for those weighing <1.11 kg [7], and 15.2% for piglets weighing <1.11 kg [4]. These differences emphasize the importance of the selected birth weight threshold when comparing prevalence estimates among studies. The <750-g threshold used in the present study represents a particularly severe low birth weight category and therefore identifies a smaller, but potentially more vulnerable, subgroup of piglets.

Parity and its interaction with litter size

LBP exhibited a non-linear association with parity, with the lowest values observed at parity 2, followed by an increase to a maximum at parity 5 and a subsequent decline in older sows. A broadly similar increase with advancing parity has been reported previously, with the proportion of piglets weighing ≤ 800 g increasing from 5.7% in parity-2 sows to 10.4% in parity-3–4 sows and 12.3% in sows of parity >4 [9]. In contrast, another study found no significant association between parity and the incidence of runt piglets weighing <1.11 kg [7]. These differing findings suggest that the relationship between parity and low birth weight may vary according to the birth weight threshold, litter characteristics, genetic background, and production environment.

The relatively low LBP count at parity 2 compared with parity 1 may reflect differences in maternal maturity and reproductive performance, whereas the increase through parities 3–5 may partly coincide with changes in litter size. Larger litters have been associated with increased within-litter variation in birth weight and a higher frequency of LBP [7]. This interpretation is also consistent with evidence that increasing litter size adversely affects individual piglet birth weight [12, 24]. However, because the present study was observational and did not directly measure all maternal physiological characteristics, these mechanisms should be interpreted as plausible explanations rather than established causal pathways. The decline in LBP after parity 5 may likewise be related to changes in litter size and selective retention of reproductively successful sows, but these possibilities could not be directly evaluated using the available data.

The parity $\times$ litter size interaction further indicated that the relationship between litter size and LBP varied across parity groups. In Model 2, the interaction at parity 6 was statistically significant, whereas the corresponding estimate in Model 1 and the estimates for parity >6 did not reach statistical significance. Therefore, the evidence supports a stronger litter size association at parity 6 in Model 2, while the pattern among the oldest sows remains suggestive rather than conclusive. Previous studies have rarely evaluated parity $\times$ litter size interactions directly, with parity more commonly assessed as an independent main effect [7, 12]. The present findings therefore add evidence that the effect of increasing litter size may not be uniform across parity groups.

This interaction is biologically plausible because uterine and placental capacity are important determinants of fetal growth and litter uniformity. As litter size increases, competition among fetuses for available uterine space and nutrients may intensify, resulting in reduced fetal growth and greater within-litter variation in birth weight [21–23]. If older sows have less capacity to accommodate additional reproductive demands, the effect of large litters on fetal growth could become more pronounced. Nevertheless, the wider CIs around interaction estimates in higher parity groups indicate lower precision. Larger datasets with greater representation of older sows are therefore required to confirm the magnitude and consistency of these interactions.

Litter size as the major determinant of LBP

Litter size showed the strongest positive association with LBP in both analytical models. Each additional piglet was associated with an approximately 31%–32% increase in the expected LBP count. This finding is consistent with previous studies demonstrating an inverse association between litter size and individual birth weight [12, 24–26]. Each additional piglet has been reported to reduce average birth weight by approximately 19.5–21.7 g [12], while the incidence of LBP has also been shown to increase with increasing litter size [8].

Larger litter size has additionally been associated with increased within-litter birth weight variation [7]. The biological basis for this relationship is supported by the finite uterine capacity and placental surface area available to support fetal development, which may reduce nutrient availability per fetus as litter size increases [27]. Increased litter size is also associated with greater heterogeneity in fetal growth [28] and greater within-litter birth weight variation [25], thereby increasing the probability that some piglets fall below a predefined low birth weight threshold [29].

The magnitude and consistency of the association observed across both models support litter size as the principal determinant of LBP in this population and illustrate the trade-off between prolificacy and individual piglet viability. Although increased prolificacy can increase the number of piglets born, larger litters may also increase the number of extremely LBP with reduced survival potential. Previous studies have consistently associated low birth weight with impaired thermoregulation, reduced growth performance, and increased preweaning mortality [1–4]. From a practical perspective, the present findings suggest that sows with large litters, particularly those in higher parity groups, may warrant closer monitoring. Nutritional and body condition management during gestation could potentially contribute to maintaining maternal condition and supporting fetal development; however, intervention studies are needed before specific management strategies can be

considered effective for reducing LBP.

WSI

Compared with litter size, WSI showed a more modest association with LBP. In Model 2, WSI >20 days was associated with a higher expected LBP count than the reference interval of 0–6 days, whereas WSI categories of 7–10 and 11–20 days were not significantly associated with LBP. Previous studies have reported no significant effect of WSI on mean birth weight or on the proportions of piglets weighing <1.0 kg or >1.8 kg [15]. In contrast, another study reported an inverse association between WSI and subsequent piglet birth weight, with each additional day of WSI associated with an approximately 25.8-g reduction in birth weight [12].

A short WSI is generally associated with adequate reproductive recovery after weaning [30], whereas a prolonged WSI may reflect poorer recovery following lactation, potentially in association with excessive body weight or backfat loss [31]. Maternal energy status may subsequently influence reproductive performance and fetal development, and adverse maternal energy balance has been associated with greater within-litter variation in piglet birth weight [15]. Nevertheless, body condition, backfat thickness, feed intake, and energy balance were not available in the present dataset. Therefore, the mechanisms underlying the association between prolonged WSI and LBP could not be directly examined and should not be inferred from the present observational findings.

Gestation length

Gestation length >116 days was associated with a lower expected LBP count than gestation length <114 days. This finding is consistent with previous studies showing that shorter gestation is associated with lower birth weight and a higher incidence of piglets weighing <1.11 kg [7]. Fetal growth accelerates during late gestation [32], and a shorter gestational period may therefore reduce the time available for continued tissue growth and nutrient deposition before birth.

Accordingly, piglets born after shorter gestation may be more likely to fall below the predefined low birth weight threshold, whereas longer gestation within the normal physiological range allows additional time for fetal growth. However, the present study was observational and gestation length was not experimentally manipulated. The findings therefore demonstrate an association between gestation length and LBP rather than establishing that prolonging gestation would directly reduce the occurrence of extremely LBP.

Strengths and limitations

A major strength of this study was the large commercial dataset, comprising 17,712 farrowing records from 4,476 sows and 211,720 piglets in the descriptive population. The use of hierarchical mixed-effects models also allowed repeated farrowings within sows and variation associated with boars to be incorporated into the analysis. In addition, the study focused specifically on the litter level count of extremely LBP using a strict <750-g threshold, a category for which large-scale commercial data remain limited.

Several limitations should nevertheless be considered when interpreting the findings. First, the retrospective observational design and reliance on commercial production records introduce the possibility of selection bias. A substantial proportion of records were excluded because of incomplete data. Specifically, 9,727 records (54.9%) were excluded from Model 1 and 11,376 records (64.3%) from Model 2, leaving 7,985 (45.1%) and 6,336 (35.7%) records, respectively, from the original 17,712 observations. Consequently, the analytical datasets may not fully represent the characteristics of the original population.

Second, although multivariable mixed-effects models accounted for the measured factors and hierarchical structure of the data, residual confounding by unmeasured variables cannot be excluded. Sow body condition and feed intake may influence reproductive performance and fetal growth, whereas thermal stress may affect feed intake, reproductive recovery, and fetal development under tropical production conditions. Health events occurring during gestation were also unavailable and may have influenced both litter characteristics and piglet birth weight. Because the study was conducted within a single herd with a specific genetic background, the available data could not disentangle the relative contributions of genetic, nutritional, environmental, and management factors to the observed associations.

Third, routinely collected farm records may be subject to recording errors and inconsistencies in data collection. Although piglets considered noticeably small were weighed individually and those weighing <750 g were recorded as LBP, individual birth weights were not available for all piglets. Consequently, the analysis was restricted to the litter level count of piglets below the operational <750-g threshold and could not evaluate the complete birth weight distribution, mean litter birth weight, or within-litter variation directly.

Finally, the study population consisted of Landrace × Yorkshire sows managed under the tropical commercial conditions of central Vietnam. Therefore, the magnitude of the observed associations, particularly the parity × litter size interaction, may not be directly generalizable to other genetic backgrounds, climates, herd health conditions, or management systems. Further multicenter studies involving diverse genetic populations and production environments are warranted to validate these findings and determine whether the observed relationships remain consistent across commercial swine production systems.

CONCLUSION

This study demonstrated that LBP in Landrace × Yorkshire sows under commercial conditions in Vietnam was primarily associated with litter size, with each additional piglet corresponding to an approximately 31%–32% increase in the expected LBP count. Parity showed a non-linear relationship with LBP, with the highest counts observed around parity 5. The parity × litter size interaction indicated that the association between litter size and LBP varied across parity groups, with the strongest statistical evidence observed at parity 6 in Model 2. In addition, WSI >20 days was associated with a higher expected LBP count, whereas gestation length >116 days was associated with a lower expected LBP count.

The findings highlight an important production trade-off between increased prolificacy and piglet viability. Under commercial conditions, greater attention may be warranted for sows producing large litters, particularly those in higher parity groups. Monitoring reproductive characteristics, including WSI and gestation length, may also assist in identifying sows or litters at greater risk of LBP. However, because this was a retrospective observational study, the identified associations should not be interpreted as evidence that directly modifying these factors will necessarily reduce LBP.

Further multicenter studies involving different genetic backgrounds, climatic conditions, and management systems are required to determine the generalizability of these findings. Future investigations should incorporate individual piglet birth weights, sow body condition, feed intake, health status, and environmental measurements to better characterize factors associated with LBP. Prospective and intervention-based studies are also warranted to determine whether targeted reproductive, nutritional, and litter-management strategies can reduce LBP while maintaining overall reproductive performance.

The present study provides large-scale commercial evidence that the occurrence of extremely LBP is closely associated with reproductive and litter characteristics, with litter size emerging as the predominant determinant. The findings further indicate that the relationship between litter size and LBP may vary with parity and that prolonged WSI and gestation length are additional factors associated with LBP occurrence. Collectively, these results provide a basis for identifying higher-risk litters and refining reproductive management under commercial swine production conditions. Strategies that balance prolificacy with piglet viability, supported by further prospective validation, may contribute to reducing extremely LBP and improving overall herd productivity.

DATA AVAILABILITY

The de-identified data can be made available from the corresponding author upon request.

GENERATIVE AI DECLARATION

The authors used ChatGPT during the preparation of this manuscript solely for grammar, spelling, sentence structure, and language clarity. ChatGPT was not used for the creation of scientific content, data analysis, interpretation of results, conclusions, or the production of figures and tables. The authors remain fully responsible for the content of the manuscript and reviewed and approved the final version, including the accuracy and integrity of the scientific content.

AUTHORS' CONTRIBUTIONS

NHN, LTKD, TVN, DVB, TDN, and PS: Conceptualization and study design. NHN: Data collection. NHN and PS: Data analysis, interpretation of results, and drafting and revision of the manuscript. All authors contributed to scientific discussions, critically reviewed the manuscript, and read and approved the final manuscript.

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COMPETING INTERESTS

The authors declare that they have no competing interests.

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REFERENCES

1. Mbuthia JM, Kasper C, Zenk M, Bee G, Metges CC, Daş G. Predicting piglet survival until weaning using birth weight and within-litter birth weight variation as easily measured proxy predictors. *Animal*. 2025;19(4):101479.
2. Quiniou N, Dagorn J, Gaudré D. Variation of piglets' birth weight and consequences on subsequent performance. *Livest Prod Sci*. 2002;78(1):63–70.
3. Romero M, Calvo L, Morales JI, Rodríguez AI, Escudero RM, Olivares Á, *et al*. Short- and long-term effects of birth weight and neonatal care in pigs. *Animals (Basel)*. 2022;12(21):2936.
4. Feldpausch JA, Jourquin J, Bergstrom JR, Borgen JL, Bokenkroger CD, Davis DL, *et al*. Birth weight threshold for identifying piglets at risk for preweaning mortality. *Transl Anim Sci*. 2019;3(2):633–40.
5. Magnabosco D, Pereira Cunha EC, Bernardi ML, Wentz I, Bortolozzo FP. Impact of the birth weight of Landrace x Large white dam line gilts on mortality, culling and growth performance until selection for breeding herd. *Acta Sci Vet*. 2015;43:1–8.
6. Nuntapaitoon M, Muns R, Tummaruk P. Newborn traits associated with pre-weaning growth and survival in piglets. *Asian-Australas J Anim Sci*. 2018;31(2):237–44.
7. Nam NH, Sukon P. Factors influencing within-litter variation of birth weight and the incidence of runt piglets. *S Afr J Anim Sci*. 2022;52(1):1–6.
8. Stange K, Miersch C, Sponder G, Röntgen M. Low birth weight influences the postnatal abundance and characteristics of satellite cell subpopulations in pigs. *Sci Rep*. 2020;10(1):6149.
9. Wientjes JGM, Soede NM, van der Peet-Schwering CMC, van den Brand H, Kemp B. Piglet uniformity and mortality in large organic litters: effects of parity and pre-mating diet composition. *Livest Sci*. 2012;144(3):218–29.
10. Beaulieu AD, Aalhus JL, Williams NH, Patience JF. Impact of piglet birth weight, birth order, and litter size on subsequent growth performance, carcass quality, muscle composition, and eating quality of pork. *J Anim Sci*. 2010;88(8):2767–78.
11. Miles JR, Lents CA, Cushman RA, Rohrer GA, Rempel LA. Relationship of early pregnancy maternal plasma progesterone concentrations on piglet birth weight, within-litter birth weight variation, and piglet mortality from crossbred Landrace or Yorkshire dams bred with purebred Landrace or Yorkshire sires. *J Anim Sci*. 2025;103:skaf415.
12. Riddersholm KV, Bahnsen I, Bruun TS, de Knecht LV, Amdi C. Identifying risk factors for low piglet birth weight, high within-litter variation and occurrence of intrauterine growth-restricted piglets in hyperprolific sows. *Animals (Basel)*. 2021;11:2731.
13. Koketsu Y, Iida R, Piñeiro C. A 10-year trend in piglet pre-weaning mortality in breeding herds associated with sow herd size and number of piglets born alive. *Porcine Health Manag*. 2021;7(4).
14. Nam NH, Khoudphaithoune T, Lanh DTK, Thanh NV, Truong ND, Toan NC, *et al*. Effects of parity number on some reproductive parameters in Landrace x Yorkshire sows. *Int J Vet Sci*. 2024;13(5):712–716.
15. Wientjes JG, Soede NM, Knol EF, van den Brand H, Kemp B. Piglet birth weight and litter uniformity: effects of weaning-to-pregnancy interval and body condition changes in sows of different parities and crossbred lines. *J Anim Sci*. 2013;91(5):2099–107.
16. Akuru EA, Nel C, Steyn WJ, van Rensburg CJ. Piglet birth weight predicts grow–finish performance despite dietary lysine adjustment. *Livest Sci*. 2026:105954.
17. Magnabosco D, Bernardi ML, Wentz I, Cunha ECP, Bortolozzo FP. Low birth weight affects lifetime productive performance and longevity of female swine. *Livest Sci*. 2016;184:119–25.
18. Adi YK, Kirkwood RN, Tummaruk P. Newborn traits influencing piglet mortality within the first day and

between days 1 and 7 after birth in highly prolific sows in tropical environments. *Theriogenology*. 2025;246:117551.

19. Kitkha S, Boonsoongnern A, Ratanavanichrojn N, Jirawattanapong P, Pinyopummin A. Effects of the higher parity and litter size on piglet birth weight and survival rate of later born piglets. *Thai J Vet Med*. 2017;47(1):79–86.
20. Lanh DTK, Nam NH. High stillbirth rate in a swine farm in Vietnam and associated risk factors. *J Adv Vet Anim Res*. 2022;9:13–8.
21. König NL, Wähner M, Seeger J, Sigmarsson HL, Kauffold J. An investigation into uterine capacity based on litter and placental characteristics in two sow lines with different prolificacy (Danish Landrace x Danish Yorkshire versus German Saddleback). *Reprod Domest Anim*. 2021;56(1):34–45.
22. Freking BA, Lents CA, Vallet JL. Selection for uterine capacity improves lifetime productivity of sows. *Anim Reprod Sci*. 2016;167:16–21.
23. Vallet JL, McNeel AK, Miles JR, Freking BA. Placental accommodations for transport and metabolism during intra-uterine crowding in pigs. *J Anim Sci Biotechnol*. 2014;5(1):55.
24. Buthelezi LN, Mtileni B, Nephawe AK, Idowu AP, Modiba CM, Mpedi H, *et al*. The impact of parity, litter size and birth weight variations within a litter on piglet pre-weaning performance. *Czech J Anim Sci*. 2024;69(7):255–68.
25. Knap PW, Knol EF, Sørensen AC, Huisman AE, van der Spek D, Zak LJ, *et al*. Genetic and phenotypic time trends of litter size, piglet mortality, and birth weight in pigs. *Front Vet Sci*. 2023;4:1–18.
26. Boonkum W, Permthongchoochai S, Chankitisakul V, Duangjinda M. Genetic strategies for enhancing litter size and birth weight uniformity in piglets. *Front Vet Sci*. 2025;12.
27. van den Bosch M, Soede N, Kemp B, van den Brand H. Sow nutrition, uterine contractions, and placental blood flow during the peri-partum period and short-term effects on offspring: a review. *Animals (Basel)*. 2023;13(5):910.
28. Che L, Niu L, Liu L, Li M, Huo W, Deng H, *et al*. Reduction in within-litter variation of piglet birth weight through dietary supplementation of 3-hydroxyisobutyric acid in sows. *Front Vet Sci*. 2025;12:1646332.
29. Lyderik KK, Østrup E, Bruun TS, Amdi C, Strathe AV. Fetal and placental development in early gestation of hyper-prolific sows. *Theriogenology*. 2023;197:259–66.
30. Liu M, Zhang J, Zhou Y, Xiong S, Zhou M, Wu L, *et al*. Gut microbiota affects the estrus return of sows by regulating the metabolism of sex steroid hormones. *J Anim Sci Biotechnol*. 2023;14(1):155.
31. Pearodwong P, Tretipskul C, Soede NM, Tummaruk P. Factors affecting estrus and ovulation time in weaned sows with induced ovulation by GnRH administration in different seasons. *J Vet Med Sci*. 2019;81(11):1567–74.
32. Theil PK, Farmer C, Feyera T. Review: physiology and nutrition of late gestating and transition sows. *J Anim Sci*. 2022;100(6):skac176.
