Arch. Anim. Breed., 69, 217–225, 2026
https://doi.org/10.5194/aab-69-217-2026

Open Access
Archives Animal Breeding

Genetic and non-genetic determinants of farrowing and lactation traits in multiparous sows under intensive management

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Received: 23 September 2025 – Revised: 16 January 2026 – Accepted: 19 March 2026 – Published: 9 April 2026

Abstract. Genetic crossbreeding and advanced management have substantially improved swine productivity, yet reproductive outcomes in commercial herds remain strongly influenced by environmental and genetic factors. This study quantified these effects on key farrowing and lactation traits in multiparous sows under intensive production, identifying genetic lines that sustain high performance under variable conditions. Farrowing year (FY) and parity number (PN) significantly influenced all farrowing traits and most lactation traits ($P<0.05$). Genetic group (GG) affected total piglets born (TPBs), piglets born alive (PBAs), and total litter birth weight (TLBW) ($P<0.05$). Sow weight at farrowing (SWF) and gestation length (GL) exerted linear effects on TPBs ($\beta\mathrm{SWF} = 0.01996$ piglets per kg; $\beta\mathrm{GL} = -0.5344$ piglets per day) and PBAs ($\beta\mathrm{SWF} = 0.01560$; $\beta\mathrm{GL} = -0.5248$). Cross-fostering increased piglet weight at day 21 (LWW21) and number of piglets weaned (NPWs) ($P<0.0001$). Insemination season (IS) affected stillborn piglets (SPs) ($P = 0.0152$) and average weaning piglet birth weight (AWPW) ($P = 0.0078$), while season farrowing (SF) influenced AWPW and NPWs ($P<0.0001$ and $P = 0.0447$, respectively). Estimates of heritabilities (h^2) were low for most traits (0.00–0.07) but moderate for LWW21 (0.21) and AWPW (0.13). Farrowing year and parity number are dominant non-genetic drivers of prolificacy and litter growth in intensive systems. Integrating optimized reproductive management, cross-fostering protocols, and sow body condition control with targeted genetic selection and enhanced nutrition and climate regulation offers a strategic pathway to maximize reproductive efficiency and farm profitability.

1 Introduction

Global pork production has shown steady growth in recent years, reaching approximately 124.5 million tonnes in 2023 – an increase of 1.4 % compared with 2022 (FAO, 2024). Sustaining these volumes under intensive production systems requires optimizing sow reproductive performance, as maternal-type females are the cornerstone of herd productivity and profitability. Sow lifetime reproductive efficiency strongly influences production economics, with key indicators including total piglets born; live-born counts; stillborn counts; litter birth weight; number of weaned piglets; and, during lactation, total and average piglet weaning weights (Segura-Correa et al., 2023). Monitoring these traits allows early detection of reproductive bottlenecks and supports both management adjustments and genetic selection programs.

Genetic improvement programs have targeted high-prolificacy sows; however, the low heritability of most reproductive traits remains a constraint to genetic progress (Tummaruk et al., 2023). Studies in maternal breeds such as Landrace, Large White, and Yorkshire have documented gains in prolificacy, enabling estimation of breeding values and more precise selection (Ehlers et al., 2005). Nevertheless, reproductive performance is also shaped by non-genetic factors, including parity, insemination season, farrowing year, housing type, and management practices, which can substantially influence litter size and weight (Chakurkar et al., 2021; Ek-Mex et al., 2024).

The existing body of research on sow reproductive performance provides a substantial foundation, documenting the complex interplay of genetic and non-genetic factors that shape farrowing and lactation outcomes. Genetic studies consistently report low to moderate heritability estimates for key reproductive traits, underscoring the challenge of achieving rapid genetic progress. For instance, heritability for litter size traits like total number born (TNB) and number born alive (NBA) is typically low (0.10–0.20), while birth weight (BW) often shows moderate heritability (approximately 0.20–0.41) (Boonkum et al., 2025; Rocha et al., 2025). Concurrently, extensive research has characterized major non-genetic influences. Sow parity is a critical factor, with performance generally peaking between parities 2–5 and declining in gilts and aged sows (Koketsu and Iida, 2017). Seasonal effects, particularly high summer temperatures, are reliably linked to reduced fertility and prolificacy (Koketsu and Iida, 2017). Furthermore, detailed investigations into piglet mortality identify risk factors such as increased litter size, low birth weight, extreme gestation length, and high birth order, all contributing to stillbirth and pre-weaning losses (Nam and Sukon, 2021; Kramarenko et al., 2024). While these genetic and environmental factors are often studied separately, there is a recognized need for more integrated models that simultaneously account for both sets of effects to identify robust genetic lines capable of sustaining high performance under variable commercial conditions (Boonkum et al., 2025).

Additionally, there is limited integration of these effects into analytical models that allow for the accurate discrimination of reproductive performance according to genetic lineage under environmental conditions. This limitation hinders the identification of new genotypes capable of maintaining high reproductive performance throughout their lifespan in production systems (Knap et al., 2023). Therefore, it is necessary to characterize the sow's prolificacy and maternal capacity to evaluate performance during farrowing and lactation, integrating indicators that reflect reproductive efficiency, such as piglet survival and growth (Dekkers, 2021). Furthermore, this study will provide applicable information for decision-making in genetic improvement and reproductive management programs in order to contribute to the more efficient allocation of genetic resources and the reduction of losses associated with pre-weaning mortality and low-birth-weight litters (Zotti et al., 2017).

A combined assessment of genetic and non-genetic influences on farrowing and lactation performance is therefore essential for improving reproductive management strategies in commercial herds. The objective of the present study was to quantify these effects on key farrowing and lactation traits in multiparous sows under intensive production and identify genetic lines that sustain high performance under variable conditions. The hypothesis of the assessment was that findings will confirm the multifactorial nature of sow productivity in commercial conditions, suggesting the most important factors to consider for management.

2 Methods and materials

2.1 Animals and management

Data from 1238 farrowings of 283 multiparous sows were collected between 2017 and 2024 at a commercial swine farm in Temascaltepec, Mexico (19°02′47″ N, 100°02′47″ W; 1720 m a.s.l.). The region has a temperate sub-humid climate with a mean annual temperature of 19 °C and annual precipitation of 1100 mm. Sows were the progeny of Landrace boars and Yorkshire dams from seven genetic groups (GG1–GG7), classified by the origin of their paternal and maternal grandsires as follows: GG1, dam Yorkshire PIC 50 % / boar Landrace Genesus 50 %; GG2, dam Yorkshire PIC 25 % / Yorkshire Genesus 25 % / boar Landrace Genesus 50 %; GG3, dam Yorkshire PIC 25 % / Yorkshire Genesus 25 % / boar Landrace Choice 50 %; GG4, dam Yorkshire PIC 25 % / Landrace PIC 25 % / Landrace Choice 50 %; GG5: dam Yorkshire PIC 50 % / Landrace PIC 50 %; GG6: dam Yorkshire PIC 50 % / boar Yorkshire PIC 25 % / Landrace PIC 25 %; and GG7, dam Yorkshire PIC 25 % / Yorkshire Genesus 25 % / boar Yorkshire PIC 25 % / Landrace PIC 25 %. From each of the crosses, the f1 females were obtained, which were crossed with PIC 408 boars to obtain piglets for slaughter.

At 107 d of gestation, sows were moved to the farrowing house supplemented with vitamins, dewormed, and thoroughly washed with water and soap before being placed in individual farrowing crates and assigned a unique identification number. Diets gradually transitioned from gestation to lactation rations, reaching 3 kg d^{-1} by farrowing onset.

During farrowing, each piglet was dried (body and nares), and the umbilical cord was clamped, cut, and treated with iodine. Upon completion, the litter was weighed, and the following data were recorded: farrowing date, parity number (PN), total piglets born (TPBs), live-born piglets (PBAs), stillborn piglets (SPs), total litter birth weight (TLBW), and average piglet birth weight (AWPB). Cross-fostering (CF) was performed when necessary to standardize litter size.

To cross-foster piglets between litters, the number of piglets in each litter was first reviewed to determine which sows with the fewest piglets would adopt one to three piglets. This decision was based on the sow's milk production capacity, body condition, and temperament and was only made possible within the first 48 h postpartum. The litter size threshold was also established for sows with fewer than 10 live-born piglets to be considered recipients and those with more than 15 live-born piglets to be considered donors, if the sow had 14 functional teats for nursing her piglets.

Lactation averaged 24 d, after which the number of piglets weaned (NPWs), total litter weaning weight (LWW), and average piglet weaning weight (AWPW) were recorded. Weaning weights were adjusted to 21 d (AWPB) using a standard correction factor to account for litters weaned at slightly different ages. Sows were weighed upon exit from the farrowing house before returning to gestation pens.

For the genetic evaluation, the databases were structured as follows. For the evaluation of farrowing variables, the following were considered integer variables: the identification of the sow, the grandparent boar, the identification of the maternal grandparents, and the contemporary group, which was formed through the year of farrowing of the sow, the farrowing season, the number of farrowings completed on the farm, and cross-fostering. The following were considered to be real variables: total number of piglets born (TPBs), number of piglets born alive (PBAs), number of piglets born stillborn (SPs), litter weight at birth (TLBW), average piglet weight at birth (AWPB), and sow weight at farrowing (SWF). For the evaluation of lactation variables, the same integer variables were used, and the following were considered real variables: number of piglets that died during lactation (NPDLs), litter weight at weaning at 21 d (LWW21), average piglet weight at weaning at 21 d (AWPW), number of piglets weaned (NPWs), sow weight at farrowing (SWF), and number of piglets born alive (TPBs).

2.2 Statistical analysis

After verifying the normality of the variables through Shapiro–Wilk and normal quantile plots, the genetic and non-genetic effects of factors of each trait were evaluated using a generalized linear model fitted with the GLM procedure in SAS® v9.4 (SAS Institute Inc., Cary, NC, USA):

$$\begin{aligned} \boldsymbol{Y}_{ijklmn} &= \mu + S_i + \mathrm{FY}_j + \mathrm{IS}_k + \mathrm{GG}_l + \mathrm{PN}_m \\ &\quad + \beta_1 \mathrm{SWF}_{ijklm} + \beta_2 \mathrm{GL}_{ijklm} + \varepsilon_{ijklm}, \end{aligned}$$

where $\boldsymbol{Y}_{ijklmn}$ is the vector of observations for TPBs, PBAs, SPs, TLBW, AWPB, and NPDLs; μ is the overall mean; S_i is the individual random effect of the ith sow; FY_j is the fixed effect of the jth farrowing year (2018–2023); IS_k is the fixed effect of the kth insemination season; GG_l is the fixed effect of the lth genetic group (GG1–GG7); PN_m is the fixed effect of the mth parity; β_1 and β_2 are regression coefficients for sow body weight at farrowing (SW) and gestation length (GL), respectively; and ε_{ijklm} is the random residual error.

For traits LWW21, AWPW, NPWs, and NPDLs, IS was replaced with the fixed effect of season farrowings (SFs), and cross-fostering (CF) and total piglets born (TPBs) were included as additional fixed effects, while the GL covariate was excluded. Least squares means were compared using a significance threshold of $P<0.05$. Genetic variance components and parameters were estimated using MTDFREML, with convergence defined as $-2 \log L = 1 \times 10^{-14}$. Normality of traits was assumed after the previous verification. The data set included 1236 records of 256 sows, 9 sires, and 24 dams. The animal model used was

$$\boldsymbol{y} = \mathbf{X}\boldsymbol{b} + \mathbf{Z}\boldsymbol{u} + \mathbf{W}\boldsymbol{c} + \boldsymbol{e},$$

where $\boldsymbol{y}$ is the vector of phenotypic observations; $\boldsymbol{b}$ is the vector of fixed effects; $\boldsymbol{u}$ is the vector of direct additive genetic effects; $\boldsymbol{c}$ is the vector of maternal permanent environmental effects; **X**, **Z**, and **W** are the incidence matrices relating records to the fixed contemporary group integrated by farrowing year, season, PN, and CF, additive genetic effect of the sire, and permanent environmental effects, respectively; and $\boldsymbol{e}$ is the vector of residuals. Estimates of variance for additive genetic (σ_a^2), maternal permanent environmental (σ_c^2), and residual (σ_e^2) effects were obtained and used for the estimation of heritability ($h^2 = \sigma_\mathrm{a}^2/\sigma_\mathrm{p}^2$) and repeatability ($r = (\sigma_\mathrm{a}^2 + \sigma_c^2)/\sigma_\mathrm{p}^2$), where σ_p^2 is the phenotypic variance calculated as $\sigma_\mathrm{p}^2 = \sigma_\mathrm{a}^2 + \sigma_c^2 + \sigma_e^2$.

3 Results

3.1 Descriptive statistics

Summary statistics for reproductive traits indicate that, on average, total piglets born (TPBs) per litter was 12.22 ± 3.25 (CV = 26.6 %), with 11.55 ± 3.17 live-born piglets (PBAs; CV = 27.5 %) and 0.72 ± 1.08 stillborn piglets (SPs; CV = 150.8 %). Total litter birth weight (TLBW) averaged 16.91 ± 4.19 kg (CV = 24.8 %) and mean individual birth weight (AWPB) averaged 1.50 ± 0.25 kg (CV = 17.1 %). During lactation, preweaning mortality (NPDLs) averaged 1.18 ± 1.68 piglets (CV = 142.4 %), while adjusted total litter weaning weight (LWW21) was 61.93 ± 12.56 kg (CV = 20.3 %). Adjusted mean piglet weaning weight (AWPB) was 6.05 ± 0.88 kg (CV = 14.7 %), and the number weaned (NPWs) averaged 10.31 ± 2.00 (CV = 19.4 %).

3.2 Effects on farrowing traits

Farrowing year (FY) significantly affected PBAs ($P<=0.0049$), SPs, TLBW, and AWPB ($P<0.0001$), while parity number (PN) influenced all traits except SPs ($P = 0.3524$) (Table 1). Genetic group (GG) affected TPBs ($P<0.0001$), PBAs ($P = 0.0012$), and AWPB ($P<0.0001$) (Table 2).

Body weight at farrowing (SWF) had a positive linear effect on TPBs ($\beta = 0.01996 \pm 0.0039$ piglets per kg; $P<0.0001$) and PBAs ($\beta = 0.01560 \pm 0.0038$ piglets per kg; $P<0.0001$), equivalent to ∼ one extra piglet per 5–6.5 kg increase in SWF. Gestation length (GL) was negatively associated with TPBs ($\beta = -0.5344 \pm 0.0686$ piglets per day; $P<0.0001$) and PBAs ($\beta = -0.5248 \pm 0.0673$;

Table 1. Least squares means and standard error for total piglets born (TPBs), live-born piglets (PBAs), stillbirths (SPs), total litter birth weight (TLBW), and mean birth weight (AWPB) in multiparous sows by farrowing year, service season, and parity number.

Factor	N	TPBs	PBAs	SPs	TLBW	AWPB
Farrowing year		$P = 0.1432$	$P = 0.0113$	$P = <0.0001$	$P = <0.0001$	$P = <0.0001$
2018	98	10.43 ± 0.62	10.10 ± 0.62	0.25 ± 0.21^{a}	14.94 ± 0.87^{b}	$1.54 \pm 0.05^{a,b}$
2019	131	11.12 ± 0.53	10.21 ± 0.52	0.82 ± 0.18^{b}	14.42 ± 0.73^{b}	1.47 ± 0.04^{b}
2020	186	11.33 ± 0.45	11.05 ± 0.44	0.27 ± 0.15^{a}	14.18 ± 0.61^{b}	$1.36 \pm 0.03^{b,c}$
2021	193	11.28 ± 0.37	10.63 ± 0.37	$0.63 \pm 0.13^{a,b}$	$16.24 \pm 0.50^{a,b}$	$1.57 \pm 0.03^{a,b}$
2022	278	11.93 ± 0.25	11.21 ± 0.24	0.72 ± 0.08^{b}	17.29 ± 0.34^{a}	$1.58 \pm 0.02^{a,b}$
2023	352	12.14 ± 0.22	11.51 ± 0.21	0.76 ± 0.07^{b}	17.18 ± 0.30^{a}	1.53 ± 0.01^{b}
Insemination season		$P = 0.4648$	$P = 0.8539$	$P = 0.0152$	$P = 0.6709$	$P = 0.0078$
Spring	275	11.19 ± 0.37	10.70 ± 0.36	0.47 ± 0.12^{a}	15.92 ± 0.51	1.55 ± 0.03^{a}
Summer	320	11.28 ± 0.33	10.77 ± 0.33	$0.52 \pm 0.11^{a,b}$	15.52 ± 0.47	1.49 ± 0.02^{b}
Autumn	358	11.49 ± 0.33	10.91 ± 0.32	$0.57 \pm 0.11^{a,b}$	15.68 ± 0.45	1.48 ± 0.02^{b}
Winter	285	11.53 ± 0.38	10.76 ± 0.38	0.73 ± 0.13^{b}	15.72 ± 0.53	1.51 ± 0.03^{a}
Parity number		$P = 0.0026$	$P = <0.0001$	$P = 0.3524$	$P = <0.0001$	$P = <0.0001$
1	271	11.56 ± 0.30^{a}	11.07 ± 0.29^{a}	0.54 ± 0.10	$15.52 \pm 0.40^{a,b}$	1.42 ± 0.02^{b}
2	233	$11.38 \pm 0.30^{a,b}$	10.99 ± 0.30^{a}	0.47 ± 0.10	16.81 ± 0.41^{a}	1.57 ± 0.02^{a}
3	209	11.86 ± 0.33^{a}	11.28 ± 0.33^{a}	0.56 ± 0.11	17.02 ± 0.45^{a}	1.56 ± 0.02^{a}
4	184	12.01 ± 0.37^{a}	11.57 ± 0.37^{a}	0.50 ± 0.13	17.22 ± 0.51^{a}	1.53 ± 0.03^{a}
5	139	$11.50 \pm 0.44^{a,b}$	10.92 ± 0.44^{a}	0.54 ± 0.15	15.55 ± 0.60^{b}	$1.48 \pm 0.03^{a,b}$
6	112	10.63 ± 0.51^{b}	9.95 ± 0.50^{b}	0.58 ± 0.17	14.05 ± 0.69^{c}	$1.51 \pm 0.04^{a,b}$
7	90	10.67 ± 0.56^{b}	9.73 ± 0.55^{b}	0.82 ± 0.19	13.79 ± 0.76^{c}	$1.48 \pm 0.04^{a,b}$

$^{a, b, c}$ Means within each factor with different superscripts are statistically different at $P < 0.05$.

Table 2. Least squares means and standard error for total piglets born (TPBs), live-born piglets (PBAs), stillbirths (SPs), total litter birth weight (TLBW), and mean birth weight (AWPB) in multiparous sows by genetic group (GG).

Factor	N	TPBs	PBAs	SPs	TLBW	AWPB
Genetic group		$P = <0.0001$	$P = 0.0012$	$P = 0.4753$	$P = 0.3432$	$P = <0.0001$
L1	108	10.20 ± 0.45^{b}	9.78 ± 0.44^{b}	0.62 ± 0.15	16.23 ± 0.64	1.68 ± 0.04^{a}
L2	55	10.84 ± 0.61^{b}	$10.47 \pm 0.60^{a,b}$	0.38 ± 0.21	15.95 ± 0.87	$1.55 \pm 0.05^{a,b}$
L3	233	$10.81 \pm 0.43^{a,b}$	$10.20 \pm 0.43^{a,b}$	0.57 ± 0.15	15.34 ± 0.61	1.55 ± 0.03^{b}
L4	90	$11.21 \pm 0.57^{a,b}$	$10.68 \pm 0.56^{a,b}$	0.40 ± 0.19	14.64 ± 0.79	1.44 ± 0.05^{b}
L5	677	12.65 ± 0.17^{a}	11.83 ± 0.17^{a}	0.81 ± 0.08	16.67 ± 0.25	1.45 ± 0.01^{b}
L6	38	11.60 ± 0.69^{a}	$10.82 \pm 0.68^{a,b}$	0.70 ± 0.24	15.11 ± 0.97	1.46 ± 0.06^{b}
L7	37	12.30 ± 0.69^{a}	11.72 ± 0.69^{a}	0.54 ± 0.24	16.03 ± 1.00	1.42 ± 0.06^{b}

L1: Yorkshire PIC / Landrace Genesus, L2: Yorkshire PIC–Yorkshire Genesus / Landrace Genesus, L3: Yorkshire PIC–Yorkshire Genesus / Landrace Choice, L4: Yorkshire PIC–Landrace PIC / Landrace Choice, L5: Yorkshire PIC / Landrace PIC, L6: Yorkshire PIC / Yorkshire PIC–Landrace PIC, and L7: Yorkshire PIC–Yorkshire Genesus / Yorkshire PIC–Landrace PIC. $^{a, b, c}$ Means within each factor with different superscripts are statistically different at $P < 0.05$.

$P < 0.0001$). Stillbirths decreased with greater SWF ($\beta = 0.005771 \pm 0.0013$ stillbirths per kg; $P < 0.0001$), indicating one fewer stillbirth per 17.3 kg increase in body weight. TLBW increased by 0.310 kg for each additional kilogram of SWF ($P < 0.0001$) but decreased by 0.55 kg d^{-1} for shorter gestation ($P < 0.0001$). AWPB rose with longer gestation ($\beta = 0.03087 \pm 0.0055\,\mathrm{kg\,d^{-1}}$; $P < 0.0001$).

3.3 Effects on lactation traits

FY, SF, and PN significantly affected one or more lactation traits (Table 3). For NPDLs, FY was significant ($P = 0.0033$), and the TPB covariate indicated one additional death per 3.9 piglets born ($P < 0.0001$). SWF also had a positive effect on mortality ($P = 0.0461$).

For LWW21, FY, PN, and CF were highly significant ($P < 0.0001$). Each extra piglet born increased litter weaning weight by 1.38 kg ($P < 0.0001$), and recipient sows achieved the highest LWW21 values (Table 4). AWPW was influenced by FY ($P = 0.0313$), SF, PN, CF ($P \leq 0.0001$), TPBs (negative; $\beta = -0.1239 \pm 0.0088$ kg per piglet; $P < 0.0001$), and SWF (positive; $\beta = 0.00646 \pm 0.0010\,\mathrm{kg\,kg^{-1}}$; $P < 0.0001$).

For NPWs, AP ($P < 0.0001$), PN ($P = 0.0423$), and CF ($P < 0.0001$) were significant. The TPB factor was positively associated with NPWs ($\beta = 0.4201 \pm 0.018$ piglets per piglet; $P < 0.0001$), while SWF showed a negative relationship ($\beta = -0.0083 \pm 0.0021$ piglets per kg; $P < 0.0001$).

3.4 Genetic parameters

Heritability estimates (h^2) were low (0.00–0.07) for most birth and weaning traits but moderate for LWW21 (0.21 ± 0.124) and AWPW (0.13 ± 0.085) (Table 5). Permanent environmental effects of the sow as a proportion of the phenotypic variance (c^2) ranged from 0.06 to 0.17, suggesting a low to moderate impact of maternal effects on litter size and preweaning survival, with greater influence of permanent maternal environment on weaning traits.

4 Discussion

In this study, FY had a significant influence on all reproductive and performance traits, corroborating earlier reports (Niyazov et al., 2020) that annual variation in sow productivity reflects changes in farm management, seasonal environmental conditions (photoperiod, temperature, humidity), and staff turnover. Between 2020 and 2023, TPBs peaked at 12.14 piglets per litter, surpassing the 11.8 reported by Lavery et al. (2019), under intensive management with dry and wet feeding during gestation. SP values were the lowest in the early years (0.25 piglets) but increased after 2019 (0.82 piglets), likely due to increased workload and herd size; these stillbirth rates remain lower than the 2.0 and 1.11 reported by Tani et al. (2016) for Landrace × Large White sows (one to six parities) and by Rangstrup-Christensen et al. (2017) for Landrace × Yorkshire sows evaluated year round (∼ 6000 females), respectively.

TLBW rose steadily from ∼ 14 kg in 2018–2021 to >17 kg in 2022–2023, reflecting improvements in gestation feeding and sow comfort. Although Lavery et al. (2019) reported 17.7 kg in Ireland (2005–2015) under intensive systems with multiple feeding strategies and Yang et al. (2019) recorded 14.6 kg in intensively housed Yorkshire × Landrace sows (one to nine parities), our data show a progressive increase in AWPB to 1.58 kg by 2022, exceeding the 1.50 kg reported by Lavery et al. (2019) and 1.37 kg by Adi et al. (2024). NPDLs fell below one piglet in 2021–2022 but reached 1.5 piglets in 2019, consistent with Torres Novoa and Hurtado Nery (2007). LWW21 consistently exceeded 60 kg in 2018–2021, aligning with Klimas et al. (2020) (∼ 61 kg for pure large White and Landrace sows at 21 d lactation) and outperforming the results of García-Munguía et al. (2014), who recorded 40.3 kg at 16 d in a technologically advanced system with early litter homogenization and creep feeding from day five. These gains likely reflect enhanced feeding and management protocols for both sows and piglets.

PN significantly affected most traits, in line with Lee et al. (2015), who noted that uterine capacity and physiological maturity peak in mid-parities. In our herd, parities three and four yielded the highest TPBs (11.86 and 12.01 piglets, respectively), exceeding the TPB values of Hernández et al. (2002) but falling below those of Klimas et al. (2020), who reported 12.1 piglets at parity four. First-parity sows had only 11.07 PBAs, lower than the 14.9 reported by Yang et al. (2019), under temperate conditions – likely due to our policy of culling after four parities. Litter birth weight and AWPB peaked in parities two and three, consistent with Petrocelli et al. (2021) and Tummaruk et al. (2023), who observed >20 kg in hyperprolific sows at these parities due to improved embryo implantation and placental development. LWW21 was also the highest in parities two and three (64.7–62.6 kg), matching that of Klimas et al. (2020) (61.8 kg) and exceeding that of Yang et al. (2019) (58.4 kg), reflecting increased lactation capacity with age and experience. In gilts, mammary development and milk yield are still immature.

AWPW averaged ∼ 6 kg in first parities, declining by ∼ 0.5 kg by parity seven, consistent with the results of Zotti et al. (2017) and Klimas et al. (2020) for 22 d lactations, though longer lactations (>28 d) can yield >7.5 kg per piglet (Lavery et al., 2019). NPWs peaked in parity two (10.62 piglets) (Nowak et al., 2020), underscoring the importance of parity-based management. Housing and supervision remain critical for piglet survival: farrowing crates reduce crushing risk (Koketsu and Iida, 2017), while free-range systems promote natural behaviors but can increase neonatal losses.

IS significantly influenced SPs, with the lowest values in spring (0.47 piglets) and the highest in winter (0.73 piglets), similar to the results of Tani et al. (2016), who associated cold stress with delayed farrowing and increased stillbirths. Spring–autumn farrowing produced heavier piglets at birth and weaning, likely due to milder conditions; however Kramarenko et al. (2024) and Suescún-Ospina and Ocampo-Duran (2015) reported that high spring–summer temperatures can reduce fetal growth by impairing sow feed intake and nutrient transfer to fetuses.

Cross-fostering (CF) emerged as a key management tool. Homogenizing litters within 48 h saved surplus piglets (>15 piglets per litter) and low-weight piglets, especially when matched to good milk-producing sows with small litters. In donor sows, CF reduced mortality and improved survival of low-birth-weight piglets, in line with García-Munguía et al. (2014). Recipient sows gained in LWW21 and NPWs, but the trade-off between litter size and individual piglet weight was evident.

Table 3. Least squares means and standard error for preweaning mortality (NPDLs), litter weaning weight adjusted to 21 d (LWW21), mean weaning weight (AWPW), and number weaned (NPWs) in multiparous sows by farrowing year, service season, and parity number.

Factor	N	NPDLs	LWW21	AWPW	NPWs
Farrowing year		$P = 0.0033$	$P < 0.0001$	$P = 0.0313$	$P < 0.0001$
2018	98	1.27 ± 0.28^{b}	62.46 ± 2.67^{a}	6.27 ± 0.18^{a}	$10.16 \pm 0.33^{a,b}$
2019	131	1.52 ± 0.24^{c}	56.31 ± 2.23^{b}	6.02 ± 0.15^{a}	9.65 ± 0.28^{b}
2020	186	$1.18 \pm 0.20^{a,b}$	62.86 ± 1.87^{a}	5.93 ± 0.12^{b}	10.72 ± 0.24^{a}
2021	193	0.85 ± 0.17^{a}	61.10 ± 1.51^{a}	5.85 ± 0.10^{b}	10.59 ± 0.20^{a}
2022	278	0.94 ± 0.11^{a}	$60.60 \pm 1.03^{a,b}$	$5.89 \pm 0.07^{a,b}$	10.44 ± 0.13^{a}
2023	352	$1.13 \pm 0.10^{a,b}$	$58.97 \pm 0.91^{a,b}$	$5.73 \pm 0.06^{a,b}$	$10.32 \pm 0.11^{a,b}$
Farrowing season		$P = 0.4510$	$P = 0.6122$	$P < 0.0001$	$P = 0.0447$
Spring	317	1.25 ± 0.16	60.81 ± 1.58	6.12 ± 0.10^{a}	10.11 ± 0.20^{b}
Summer	291	1.09 ± 0.17	60.36 ± 1.59	5.96 ± 0.10^{b}	10.31 ± 0.20^{a}
Autumn	321	1.16 ± 0.15	59.73 ± 1.45	5.89 ± 0.09^{b}	10.35 ± 0.18^{a}
Winter	309	1.08 ± 0.15	60.63 ± 1.39	5.84 ± 0.09^{b}	10.48 ± 0.17^{a}
Parity number		$P = 0.9797$	$P < 0.0001$	$P < 0.0001$	$P = 0.0423$
1	271	1.14 ± 0.13	$61.68 \pm 1.21^{a,b}$	6.03 ± 0.08^{a}	10.24 ± 0.16^{b}
2	233	1.08 ± 0.13	64.70 ± 1.24^{a}	6.16 ± 0.08^{a}	10.62 ± 0.16^{a}
3	209	1.14 ± 0.15	62.69 ± 1.39^{a}	6.11 ± 0.09^{a}	10.37 ± 0.18^{a}
4	184	1.22 ± 0.17	$61.67 \pm 1.56^{a,b}$	6.01 ± 0.10^{a}	10.45 ± 0.20^{b}
5	139	1.13 ± 0.20	59.95 ± 1.83^{b}	$5.89 \pm 0.12^{a,b}$	10.38 ± 0.23^{b}
6	112	1.21 ± 0.23	$57.87 \pm 2.08^{b,c}$	$5.87 \pm 0.14^{a,b}$	10.11 ± 0.27^{b}
7	90	1.12 ± 0.25	54.12 ± 2.29^{c}	5.57 ± 0.15^{b}	10.02 ± 0.30^{b}

$^{a,\ b,\ c}$ Means within each factor with different superscripts are statistically different at $P < 0.05$.

Table 4. Least squares means and standard error for preweaning mortality (NPDLs), litter weaning weight adjusted to 21 d (LWW21), mean weaning weight (AWPW), and number weaned (NPWs) in multiparous sows by genetic group and cross-fostering.

Item	N	NPDLs	LWW21	AWPW	NPWs
Genetic group		$P = 0.8879$	$P = 0.0934$	$P = 0.1243$	$P = 0.3566$
L1	108	0.97 ± 0.20	64.71 ± 2.01	6.20 ± 0.13	10.51 ± 0.24
L2	55	1.05 ± 0.27	59.97 ± 2.69	5.66 ± 0.18	10.75 ± 0.32
L3	233	1.14 ± 0.19	58.00 ± 1.90	5.87 ± 0.12	10.07 ± 0.23
L4	90	1.33 ± 0.25	58.90 ± 2.39	5.88 ± 0.16	10.17 ± 0.30
L5	677	1.15 ± 0.08	62.19 ± 0.77	6.09 ± 0.05	10.31 ± 0.09
L6	38	1.19 ± 0.31	58.95 ± 2.99	6.02 ± 0.20	10.08 ± 0.37
L7	37	1.21 ± 0.31	59.97 ± 3.10	5.93 ± 0.20	10.29 ± 0.37
Cross-fostering		$P < 0.0001$	$P = < 0.0001$	$P < 0.0001$	$P < 0.0001$
Neutral	664	1.48 ± 0.14^{c}	59.80 ± 1.42^{b}	6.03 ± 0.09^{a}	10.13 ± 0.17^{b}
Donor	300	0.77 ± 0.16^{a}	55.47 ± 1.54^{c}	6.14 ± 0.10^{a}	9.21 ± 0.19^{c}
Receiving	274	1.19 ± 0.17^{b}	65.87 ± 1.57^{a}	5.69 ± 0.10^{b}	11.60 ± 0.20^{a}

L1: Yorkshire PIC / Landrace Genesus, L2: Yorkshire PIC–Yorkshire Genesus / Landrace Genesus, L3: Yorkshire PIC–Yorkshire Genesus / Landrace Choice, L4: Yorkshire PIC–Landrace PIC / Landrace Choice, L5: Yorkshire PIC / Landrace PIC, L6: Yorkshire PIC / Yorkshire PIC–Landrace PIC, and L7: Yorkshire PIC–Yorkshire Genesus / Yorkshire PIC–Landrace PIC. $^{a,\ b,\ c}$ Means within each factor with different superscripts are statistically different at $P < 0.05$.

Table 5. Genetic parameters for studied traits in multiparous sows by univariate analyses.

Trait	h^2	c^2	r	e^2	σ_p^2
TPBs	0.06 ± 0.045	0.06 ± 0.040	0.12	0.87 ± 0.033	9.986
PBAs	0.03 ± 0.039	0.08 ± 0.039	0.11	0.88 ± 0.031	9.449
SPs	0.04 ± 0.039	0.10 ± 0.039	0.14	0.86 ± 0.031	1.145
TLBW	0.04 ± 0.051	0.15 ± 0.048	0.19	0.81 ± 0.034	15.799
AWPB	0.07 ± 0.057	0.15 ± 0.050	0.22	0.78 ± 0.036	0.067
NPDLs	0.0 ± 0.038	0.09 ± 0.043	0.09	0.90 ± 0.035	1.944
LWW21	0.21 ± 0.124	0.13 ± 0.091	0.34	0.66 ± 0.053	142.499
AWPW	0.13 ± 0.085	0.15 ± 0.068	0.28	0.73 ± 0.045	0.673
NPWs	0.0 ± 0.039	0.17 ± 0.049	0.17	0.83 ± 0.037	2.624

Here h^2 is heritability, c^2 is the proportion of the maternal permanent variance with respect to phenotypic variance, r is the repeatability index, e^2 is the environmental effect related to phenotypic variation, and σ_p^2 is phenotypic variance. Total born piglets (TPBs), live-born piglets (PBAs), stillbirths (SPs), total litter birth weight (TLBW), mean birth weight (AWPB), preweaning mortality (NPDLs), litter weaning weight adjusted to 21 d (LWW21), mean weaning weight (AWPW), and number weaned (NPWs).

GG significantly affected TPBs, PBAs, and AWPB. The L5 line averaged 12.07 total piglets born per litter – exceeding pure Yorkshire (10.1 piglets; Ogawa et al., 2019) and comparable to Large White crosses (12.5 piglets; Hagan and Etim, 2019). Although Duroc × Large White crosses can reach 14.2 piglets under climate-controlled conditions (Chakurkar et al., 2021), L5 sows here were naturally mated and housed in individual pens. L1 sows achieved the highest AWPB (1.67 kg), benefiting from higher daily feed allocation ($4\,\mathrm{kg\,d^{-1}}$) and improved late-gestation housing conditions (Hoving et al., 2010; Ogawa et al., 2019).

Heritability estimates for farrowing traits were low ($h^2 = 0.00$–0.07), indicating strong environmental influences, consistent with Freyer (2018) ($h^2 = 0.07$–0.11). Repeatability for weight traits (0.19–0.34) was higher, matching Chansomboon et al. (2010) and Lee et al. (2015) and supporting the need for multiple records per sow to improve genetic evaluation. The heritability of TPBs (0.06) was lower than the value of 0.14 reported by Ehlers et al. (2005), likely due to a smaller dataset size and narrower genetic base. Notably, preweaning mortality exhibited repeatability (0.09), driven almost entirely by a permanent environmental maternal effect ($\mathrm{pe2} = 0.90 \pm 0.035$). This suggests that a sow's behavior (e.g., aggression, crushing) is a consistent, major determinant of piglet survival across parities (Nguyen et al., 2021). Complementarily, as an opportunity for further management, a more complete data recording for better data number and genealogical structure analysis for genetic parameter estimation might improve future assessments focused on administration of genetic selection.

Overall, these findings highlight the multifactorial nature of sow productivity and demonstrate that optimizing reproductive outcomes requires coordinated management of environmental conditions, parity structure, genetic selection, and targeted interventions such as cross-fostering. The significant influence of year and season highlights the critical need for environmental control and consistent protocols to mitigate stressors like extreme temperature. Furthermore, the low heritability but notable repeatability of traits like preweaning mortality emphasizes that management practices, such as optimized feeding, parity-targeted care, and strategic cross-fostering, are more impactful for immediate improvement than genetic selection alone. Ultimately, sustained gains in litter size, piglet weight, and survival require an integrated, data-driven approach that simultaneously addresses housing, nutrition, staff training, and genetic potential.

5 Conclusions

Farrowing year, parity number, and genetic group consistently and significantly influenced sow prolificacy and piglet weights at birth and weaning. Insemination season mainly affected stillbirth rates, whereas weaning period had a marked impact on average piglet weaning weight. Sow body weight at farrowing and gestation length also played important roles, emphasizing the need for precise body-condition management and optimized breeding schedules to enhance productive efficiency. Litter homogenization within the first 48 h after farrowing significantly improved both sow and litter performance, reinforcing its value as a routine management practice to extend sow productive lifespan and increase profitability.

Heritability estimates were low for most traits, except for moderate values for total litter weaning weight and mean piglet weaning weight, confirming the predominance of environmental and management influences. Consequently, the integration of targeted genetic-selection programs, prioritizing lines with higher reproductive potential, with optimized nutritional, environmental, and health management protocols is essential for maximizing reproductive efficiency and economic returns in commercial swine production systems.

Code availability. The statistical code used in this study is available from the corresponding author upon reasonable request.

Data availability. As the data originate from a commercial farm, there are privacy concerns associated with their public release. Therefore, the data are available from the authors upon reasonable request, pending permission from the commercial farm.

Author contributions. Conceptualization, DGS, JFVA, and GMPB; methodology, DGS, JFVA, NLV, and GMPB; software, DGS and GMPB; validation, HHVV, BAP, GGT, NLV, and XFDR; formal analysis, DGS, NLV, and GMPB; investigation, HHVV, BAP, GGT, and XFDR; writing (original draft preparation), DGS, JFVA, NLV, and GMPB; writing (review and editing), HHVV, BAP, GGT, and XFDR. All authors have read and agreed to the published paper.

Competing interests. The contact author has declared that none of the authors has any competing interests.

Ethical statement. The study was conducted on a farm under standard rearing conditions and in accordance with Mexican regulations. Ethical review board approval was not required for this study.

Acknowledgements. The authors are grateful to Las Pulgas Swine Farm for granting access to the herd records used in this study. The first author gratefully acknowledges a scholarship from the Secretariat of Science, Humanities, Technology, and Innovation (Mx SECIHTI), Mexico.

Financial support. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Review statement. This paper was edited by Antke-Elsabe Freifrau von Tiele-Winckler and reviewed by two anonymous referees.

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