10-25-2023

Statistical and Machine Learning Approaches to Describe Factors affecting Preweaning Mortality of Piglets

Md Towfiqur Rahman
University of Nebraska-Lincoln, mrahman8@huskers.unl.edu

Tami M. Brown-Brandl
United States Department of Agriculture-Agricultural Research Service, Meat Animal Research Center, tbrownbrandl2@unl.edu

Gary A. Rohrer
United States Department of Agriculture-Agricultural Research Service, gary.rohrer@usda.gov

Sudhendu R. Sharma
University of Nebraska-Lincoln, raj.sharma@unl.edu

Vamsi Manthena
University of Nebraska-Lincoln, vamsi.manthena@gmail.com

Follow this and additional works at: https://digitalcommons.unl.edu/biosysengfacpub

Part of the Animal Sciences Commons, Applied Statistics Commons, Artificial Intelligence and Robotics Commons, Bioresource and Agricultural Engineering Commons, Biostatistics Commons, Environmental Engineering Commons, Other Civil and Environmental Engineering Commons, Statistical Methodology Commons, and the Veterinary Preventive Medicine, Epidemiology, and Public Health Commons

See next page for additional authors

Authors

Md Towfiqur Rahman, Tami M. Brown-Brandl, Gary A. Rohrer, Sudhendu R. Sharma, Vamsi Manthena, and Yeyin Shi

OXFORD

AMERICAN SOCIETY OF **ANIMAL** SCIENCE

Statistical and machine learning approaches to describe factors affecting preweaning mortality of piglets

Md Towfiqur Rahman,[†,] [iD] **Tami M. Brown-Brandl,**[†,1,] [iD] **Gary A. Rohrer,**[‡] **Sudhendu R. Sharma,**[†] **Vamsi Manthena,**[‖] and **Yeyin Shi**[†]

[†]Department of Biological Systems Engineering, University of Nebraska-Lincoln, Lincoln, NE 68503, USA
[‡]USDA-ARS, US Meat Animal Research Center, Clay Center, NE 68933, USA
[‖]Department of Statistics, University of Nebraska-Lincoln, Lincoln, NE 68503, USA
[1]Corresponding author: tami.brownbrandl@unl.edu

Abstract

High preweaning mortality (PWM) rates for piglets are a significant concern for the worldwide pork industries, causing economic loss and well-being issues. This study focused on identifying the factors affecting PWM, overlays, and predicting PWM using historical production data with statistical and machine learning models. Data were collected from 1,982 litters from the U.S. Meat Animal Research Center, Nebraska, over the years 2016 to 2021. Sows were housed in a farrowing building with three rooms, each with 20 farrowing crates, and taken care of by well-trained animal caretakers. A generalized linear model was used to analyze the various sow, litter, environment, and piglet parameters on PWM. Then, different models (beta-regression and machine learning model: a random forest [RF]) were evaluated. Finally, the RF model was used to predict PWM and overlays for all listed contributing factors. On average, the mean birth weight was 1.44 kg, and the mean mortality was 16.1% where 5.55% was for stillbirths and 6.20% was contributed by overlays. No significant effect was found for seasonal and location variations on PWM. Significant differences were observed in the effects of litter lines on PWM ($P < 0.05$). Landrace-sired litters had a PWM of 16.26% (±0.13), whereas Yorkshire-sired litters had 15.91% (±0.13). PWM increased with higher parity orders ($P < 0.05$) due to larger litter sizes. The RF model provided the best fit for PWM prediction with a root mean squared errors of 2.28 and a correlation coefficient (r) of 0.89 between observed and predicted values. Features' importance from the RF model indicated that, PWM increased with the increase of litter size (mean decrease accuracy (MDA) = 93.17), decrease in mean birth weight (MDA = 22.72), increase in health diagnosis (MDA = 15.34), longer gestation length (MDA = 11.77), and at older parity (MDA = 10.86). However, in this study, the location of the farrowing crate, seasonal differences, and litter line turned out to be the least important predictors for PWM. For overlays, parity order was the highest importance predictor (MDA = 7.68) followed by litter size and mean birth weight. Considering the challenges to reducing the PWM in the larger litters produced in modern swine industry and the limited studies exploring multiple major contributing factors, this study provides valuable insights for breeding and production management, as well as further investigations on postural transitions and behavior analysis of sows during the lactation period.

Lay Summary

Currently, preweaning piglet mortality is a major problem for the global pork industry, causing economic losses, and animal welfare concerns. This research analyzed nearly 2,000 piglet litters born between 2016 and 2021 at the U.S. Meat Animal Research Center in Nebraska. The goal was to understand and predict the factors influencing piglet mortality using historical production data, statistical modeling, and machine learning. The study found that litter size, birth weight, number of stillborns, and sow parity order had a significant impact on piglet mortality. For the location of the farrowing crate, and seasonal variations did not show an impact. A machine learning model called random forest proved to be the most effective in predicting piglet mortality, showing a strong correlation between predicted and observed values. This research highlights the challenges of reducing piglet mortality in larger litters, which are common in modern swine farming. The findings underscore the importance of further research into sow behavior during the lactation period, which could ultimately benefit the pork industry's sustainability and animal well-being. This study provides valuable insights into the factors affecting piglet mortality for pig breeding and production management. It uses statistical and machine learning methods to describe and predict the associated risks, offering valuable guidance to pig breeders and producers.

Key words: machine learning, preweaning mortality, piglets, random forest, swine

Introduction

Losses due to high preweaning mortality (PWM) for piglets are now a significant concern for worldwide pork industries (Tucker et al., 2021). This issue is not only an economic loss for the producers but also associated with animal well-being concerns for the industry. Global pork production has grown fast due to high demand. According to the U.S. Department of Agriculture (USDA), the U.S. ranked third in terms of production (123.83 million metric tons of pork and pork products) after China and European Union. The total number of hogs and pigs in the United States is currently around 74.77 million (USDA-NSASS, 2021). In the United States, the average PWM of piglets has been found to be 17.8% in 2017 (Stalder, 2018), in which about 80% of death (within total PWM) occurs within 72 h after birth (Edwards, 2002). Economic costs are involved with this issue, along with costs of natural resources like water and carbon footprints for meat products. The challenge to production is the cost of

labor for management and monitoring, the cost for feed, infrastructure, and energy. In the United States, energy costs are large to provide an optimal temperature to meet both the piglet's and sow's thermal requirements (Sharpe et al., 2018).

There are several PWM events for piglets reported, e.g., prenatal (mummified), perinatal (stillborn), different diseases, and overlays. It is a complex issue with many different interacting effects including health condition of sow and piglets, environmental factors, congenital abnormalities, disease, and interaction with sows. Piglet death caused by overlays by sows is the most common cause of piglet mortality which is almost one-third of the total PWM (Muns et al., 2016). Weak and slow-moving piglets are more likely to be overlayed by sows. Swine production industries have been using farrowing crates to protect piglets by restraining space for the sow and providing a separate safe space for piglets (Hales et al., 2014; Glencorse et al., 2019). Crate systems have been shown to reduce the number of overlays as compared to free housing systems (Grimberg-Henrici et al., 2019). However, even in these systems, piglet overlaying still occurs and this number varies from litter to litter. Several techniques have been proposed to attract piglets away from the sow such as the use of heat lamps and the adoption of cross-fostering to ensure an equal number of piglets be raised to reduce the possibility of crushing.

From the literature, the factors causing PWM can be divided into three categories including sow factors, piglet factors, and environmental influences (Muns et al., 2016). Table 1 describes these factors, with birth weight being the most important, as it signifies that reduced energy reserves in low birth weight (low body-mass index) piglets could lead to a higher risk of death (Amdi et al., 2013). To improve the viability of piglets, several animal research outputs described the genetic configurations and changes in management actions, which are being implemented at the production level (Tucker et al., 2021). These measures aim to address both the genetic predispositions that may contribute to PWM and optimize the husbandry techniques to ensure better survival rates among piglets, ultimately benefiting swine production systems. Piglet viability defines the capacity to survive against the overall production environment. This is also classified as physical stability and health condition. However, the findings cannot fully explain the survival of piglets during the nursing stage. The PWM also depends on the sex of the piglets as male piglets are at greater risk of death (Edwards, 2002).

Overlaying is also known to be a significant cause of mortality which is affected by the litter size, parity of sow, and environmental factors (Jarvis et al., 2005; Andersen et al., 2011). Many producers are using a farrowing crate during the lactation period of sows to limit the sow's aggressive movement which ultimately results in a low count of overlaid piglets (Condous et al., 2016) and reduces PWM (Martínez-Burnes et al., 2023). Most studies show a higher chance of overlaying piglets after birth when the sows are kept in the open system compared to crate systems (Gustafsson, 1983; Haussmann and Daniels, 2000; Thacker, 2000; Condous et al., 2016). For example, Marchant et al., (2000) experimented on the open system and farrowing crates to determine which one had the lowest mortality rate. Sows kept in farrowing crates have greater number of stillborn piglets compared with open systems; however, the piglet mortality after birth till weaning stage is higher in open systems (Marchant et al., 2000; Condous et al., 2016). Marchant et al. (2000) concluded that the mortality rate in a farrowing crate is associated with litter size, body length of the sow, and piglet birth weight. However, larger crate size nor space provided to a sow during the lactation period did not reduces the crushing of piglets (Leonard et al., 2021).

The impact of various factors on PWM has been widely studied, with factors such as piglet birth weight, litter size, gestation length of sow, and fostering practices being identified as significant contributors to PWM. Le et al. (2002) experimented to determine the risk factors (sow and piglets) associated with stillborn and mummified piglets in a litter. The study found that increased supervision reduces stillbirths, however, lower birth weights, sow or litter live weights, and higher parity were associated with a higher probability of stillbirth. When parturition is prolonged the incidence of stillborn piglets is increased and postnatal mortality may also be affected (Schild et al., 2020). Another study investigated the effect of the variability of mean birth weight of piglets on mortality and concluded mortality increases with decreasing weight. However, birth weight did not create any impact on the likelihood of survival during finishing (Fix et al. 2010; Fordyce et al., 2021). Exchanging or bringing piglets from one sow to another sow is termed fostering. This can help ensure that all piglets have access to adequate maternal care and milk, which is essential for their growth and survival. The rearing ability of a sow depends on the sow's health condition, diseases, and many factors where the goal is to reduce mortality. Alexopoulos et al. (2018) suggested that piglet

Table 1. Summary of different known factors causing preweaning mortality

Category	Factors
Piglet factors	**Birth weight:** low birth weight is associated with increased mortality rates in piglets. **Viability:** piglets that are weak or born prematurely are more likely to die before weaning. **Sex:** male piglets have a higher mortality rate compared to females, potentially due to slower growth rates and higher aggression.
Sow factors	**Behavior:** poor maternal behavior, such as crushing or abandoning piglets, can lead to higher mortality rates. **Colostrum production:** inadequate colostrum intake can weaken piglets and increase the risk of mortality. **Parity:** first parity sows (sows giving birth for the first time) are more likely to have higher mortality rates in their litters. **Litter size:** larger litter sizes can lead to increased competition for milk and other resources, increasing mortality rates.
Environmental factors	**Season:** extreme weather conditions, such as cold temperatures, can increase mortality rates in piglets. **Herd size:** higher herd sizes may result in poorer hygiene and increased risk of disease, leading to higher mortality rates. **Management:** poor management practices, such as inadequate ventilation or poor sanitation, can lead to increased mortality rates.

This table summarizes the factors that impact preweaning mortality in pigs adopted from Muns et al., (2016).
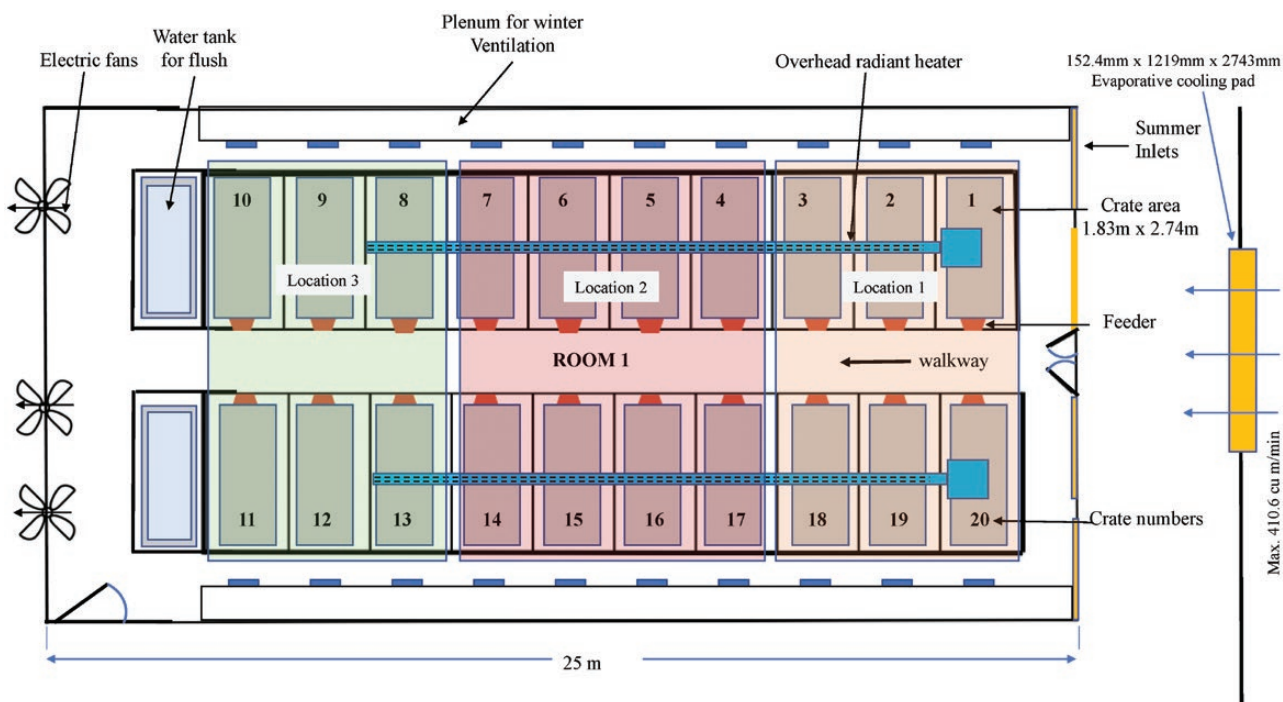
Figure 1. Experimental farrowing stall layouts were used in the study. The farrowing facility has three rooms identical to setup as illustrated. Each room has 20 different crates and two overhead radiant heaters. Air is preconditioned in the hallway using evaporative cooling and force air heaters.

fostering should be done between 12 and 24 h after birth and the movement should be minimized to prevent disease transfer. The environmental effects can vary with the production method like open and housed environments. During winter (sub-zero temperature) and summer, a controlled environment is required for sows during farrowing. PWM during the summer period (11.6%, July to September) was found to be higher than in spring (9.4%, April to June) (Koketsu et al., 2006). Some other studies found that the PWM is higher in the winter due to excessive cold stress. Cold stress is indeed the most important cause of death of newborn piglets. During birth in cold temperatures, piglets lose heat rapidly from their bodies due to high surface area and wet bodies. External heat supply is required for them to survive (Malmkvist et al., 2006; Caldara et al., 2014). External heat supply to the piglets is a common practice in farrowing crate systems. Supplemental heat helps the piglets to become resilient during early development and immune challenges during the lactation period (Zhou and Xin, 1999; Sales et al., 2008; Wheeler and Vasdal, 2008). Moreover, the winter heating systems have another advantage in overcoming piglet crushing by sows since piglets are attracted to the heated area (heat lamps) and away from sows (Leonard et al., 2021). Therefore, control over the room environment (e.g., air temperature and relative humidity) is an important management task during farrowing and lactation periods.

These factors may have different degrees of effect on the PWM directly or indirectly. There is a critical need to know which factors have significant effects on PWM and to what extent compared with others. Considering the challenges to reduce PWM and limited studies investigating interactions of multiple major contributing factors, the objective of this study aimed to identify the significant factors and estimate the extent of those factors associated with the PWM. The specific objectives of this manuscript were to (1) characterize

the effects of various litter, sow, and environmental factors on PWM using two regression statistical models (generalized linear model [GLM], Beta-Regression), and one machine learning model (random forest [RF]) and (2) evaluate the ability of the RF model to predict PWM.

Materials and Methods

Animals and Housing

All the procedures of animal husbandry were followed in compliance with federal and institutional regulations for animal care practice and were approved by the USMARC Institutional Animal Care and Use Committee. The experimental unit is located at the USDA - Agricultural Research Service U.S. Meat Animal Research Center (USMARC) in Clay Center, Nebraska. This has an integrated swine research facility with a capacity of 1,040 litters per year by following standard management practice. Each farrowing facility has three rooms consisting of 20 individual farrowing stalls arranged in two rows of ten stalls each as shown in Figure 1. The farrowing facility was served for the data collection where sows were arranged in rows facing each other across a 1.2 m wide alley with additional alleyways behind each row of stalls. Each individual stall has a heat lamp area for piglets, feeders, and nipple drinkers for sowing. One of the farrowing crates is shown in Figure 2 where sow is in resting position (lying) and nursing piglets. During warm ambient temperatures, evaporative cooling pads were used to pass conditioned air into the common plenum hallway. The hallway was equipped with baffles on one end wall that distributed fresh conditioned air from the hallway into the rooms and fans on the other end wall provided air exchange. A supplementary forced air heater heated hallway air during cold ambient temperatures, and the end wall baffles were
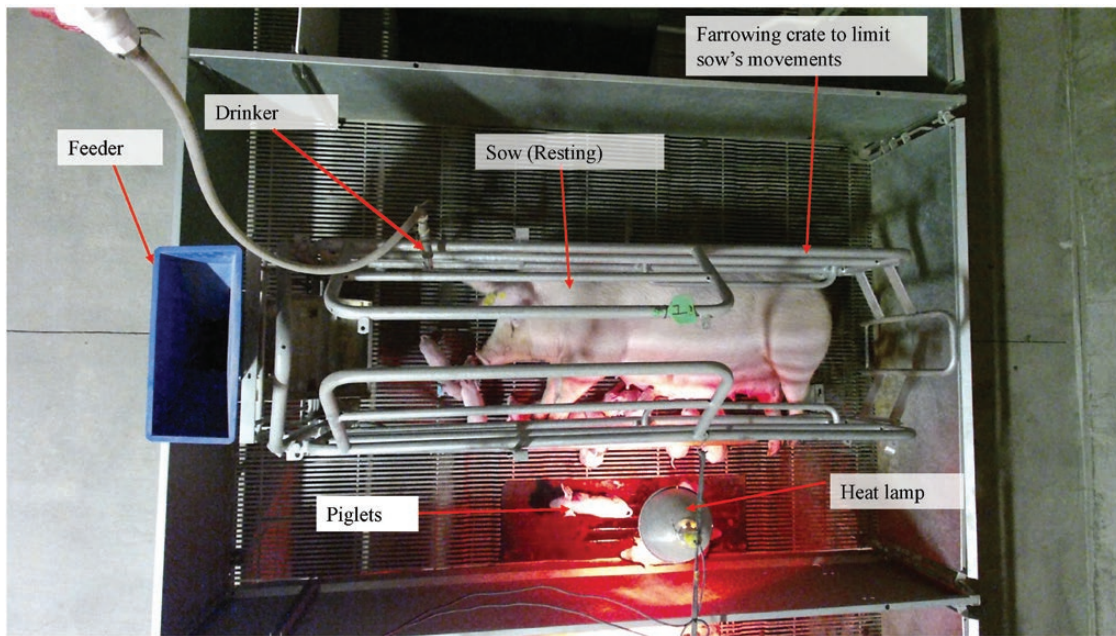
Figure 2. Sow nursing piglets in a 1.83 m × 2.74 m farrowing stall; metal rods frame around the sow area was added limiting sow movement thus protecting piglets. Heat lamp was placed in the stall to supply additional heat to the piglets.

closed. A plenum of fresh air spanned the length of each side of the room and was suspended from the ceiling. Additional radiant tube heaters were suspended from the ceiling in each room and operated as needed.

Management

Two different breeds (Commercial Landrace and Yorkshire) were considered for the study. Sows were maintained for a total of four parities; therefore four parities were considered for the data analysis. For each turn, sows were moved from a group-housed system equipped with an electronic sow feeder into the farrowing room as a group 5 d prior to the anticipated farrowing date and randomly assigned to a stall. The average piglet age at weaning was 26.7 ± 1.9 d. Experienced animal caretakers were assigned to manage the animals and collect data in accordance with standard commercial husbandry practices. Piglets were weighed and ear-tagged on day 1. Cross-fostering was done to maintain uniform litter size. On day 3, the piglets were tail docked, needle teeth clipped, iron shots were administered, and male piglets were castrated. Water was available ad libitum for both sows and piglets via nipple drinkers.

Data Collection

Data were collected over a 5-yr span from Fall 2017 to Winter 2021 from USMARC facility. Trained caretakers maintained the management facility and recorded all the research data related to production during the lactation period. Piglets were manually weighed within 24 h of birth and then inspected daily for diseases. Stillborns and mummies were counted for each sow. All stillborn piglets had birth weight recorded and were included in litter birth weight and average birth weight metrics for analyses. Weights on mummies were not recorded in the herd as many are extremely small and removing extra-embryonic membranes is difficult based on the stage at which the fetus died. To ensure adequate maternal care, piglets from extremely large litters were cross-fostered to smaller litters

when necessary. All the diagnostic history, number of deaths that occurred caused by diseases and crushing by sow were recorded. Four parties, two different litter lines (e.g., Landrace-sired and Yorkshire-sired), mean birth weight, number of stillborns, four different seasons, gestation length (days), and locations were considered for data analysis. A stillborn piglet represents a fetus that was alive at the beginning of parturition but was unable to survive the birthing process; therefore, these piglets should be seen as an opportunity for management to increase litter performance. However, the stillborn fetus received maternal nutrition during gestation increasing the sow's metabolic requirements and if the birthing process was difficult could have impacted the survival of later birthed piglets. Thus, we studied factors that affect stillborn piglets as well as included number of stillborn piglets in many of our statistical models. Weight range of piglets at birth was assigned as heavy (1.75 to 2.75 kg) medium (1.0 to 1.75 kg) and light (0.7 to 1.0 kg) similar to a previous study (Lanferdini et al., 2018). Since each room had 20 crates, the hallway starts with crate 1 and 20 and ends with 10 and 11 at the side of ventilation, therefore the room was assigned 3 different location categories for this study. Crate numbers 1, 2, 3, 20, 19, and 18 (shown in Figure 1) were assigned as location 1, crates 4, 5, 6, 7, 14, 15, 16, and 17 were assigned as location 2 and rest of the crates were assigned as location 3.

Since the temperature difference inside and outside in summer and winter is significant, the study also investigated if there is any effect of outside environment on the piglet mortality. To observe the seasonal variation in mortality, there were four different seasons (Winter, Spring, Summer, and Fall) considered according to the day when sows were moved to the farrowing crate. The month from December to February was assigned as winter season as the temperature is comparatively low in this season. The spring season begins from March to May, summer spans from June to August, and fall extends from September to November. The collected dataset was organized into a Microsoft Excel Spreadsheet (Microsoft Corp.,

Redmond, WA, USA). The dataset was initially processed for easy handling and included columns for percent mortality and percent overlays by using the following equations:

$$Number\ of\ dead\ piglets = D + S \qquad (1)$$

$$PM = \frac{M}{M + W} \times 100 \qquad (2)$$

$$PO = \frac{C}{W + D} \times 100 \qquad (3)$$

Where, PM = percent of morality, PO = percent of overlays, D = number of dead piglets on mothering dam, S = number of stillborns, M = mortality, W = number of piglets weaned, C = number of piglets crushed by sow

Statistical Approach

The dataset was imported into statistical software RStudio (2021.09.0 Build 351) for initial data handling and visualization and SAS Studio 3.8 (SAS Institute Inc., Cary, NC, USA) for detailed analysis. First, a descriptive statistic was calculated for gestation length, mean birth weight, number of piglets born alive, number of piglets weaned, stillborn piglets, overlays, total death counts, percent mortality, and percent overlays. A simple linear relationship was established for mean birth weight, litter size, number of piglets born alive, and the parity order of sow. The number of born alive counts and dead piglet counts were analyzed according to the mean birth weight category of piglets and parity order of sow.

PROC UNIVARIATE with Shapiro–Wilk test in SAS was used to test the normal distribution of the dataset. The variables PWM, and percent overlays were not normally distributed, so these factors were transformed to minimize the effect of heterogeneous variances in a model. The study did not consider the litters having 100% mortality as those were unhealthy and all piglets died. Also, mummified piglets were not considered in this study since the cause for the death is not a factor due to piglets, sow, or environment that is investigated in this study. The present study developed different models: a GLM model, and a Beta-regression model. These models were used to estimate the mortality using the variables: parity, season, location, gestation length, diagnostics, and mean birth weight.

Generalized Linear Model

The PROC GLM model was applied to the dataset to analyze percent mortality and overlays. The GLM with a logit link function was used to investigate the relationship between response (percent mortality and overlays) and several predictor variables. The predictor variables encompassed litter size, mean birth weight, number of stillborn piglets, gestation length, parity, diagnosis, litter line, season, and location. Parity, season, and location were fitted as fixed effects to test their effects on piglet mortality (both overall and overlays) while mean birth weight was used as a covariate. Each individual sow was considered a random effect in the model. Additionally, means of different parameters were calculated using PROC MEANS procedure, and a descriptive statistic with statistical significance for various production parameters

for different parity was analyzed using ANOVA and Tukey's HSD post hoc test.

Beta-regression

Beta-regression is a statistical modeling technique specifically designed for analyzing data where the response variable is bounded between 0 and 1. It can model both the mean and the variance of the response variable as functions of predictor variables, allowing for more accurate modeling of the relationship between predictors and proportions. Beta-regression analysis was performed to investigate the association between the response variables, percent mortality, and overlays, and a set of predictor variables. These predictors included litter size, mean birth weight, number of stillborn piglets, gestation length, parity, diagnosis, litter line, season, and location. Notably, parity, season, and location were considered as fixed effects to assess their impact on piglet mortality, and overlays.

Machine Learning Approach (RF Model)

A RF model was developed using a random 85% of the data for training, while the remaining 15% was reserved for testing. The RF model was trained on the training dataset (85%) using k-fold cross-validation to assess its performance. The same input variables as mentioned previously were used to characterize and predict percent mortality and percent overlays. For model development, we employed a RF multiple tree approach with various configurations, as this approach has shown better predictive performance than other methods. In RStudio (2021.09.0 Build 351) the library package named "randomForest" was used to perform the task. Hyperparameter tuning was conducted to determine the optimal value of 'mtry' for the dataset. A grid search approach and exploring a range of 'mtry' values (2 to 7) were performed and each time cross-validated accuracy was measured. Additionally, to evaluate model performance, correlation coefficients and the root mean squared errors (RMSE) were calculated offering comprehensive insights into the model's predictive accuracy, which was assessed on the independent test dataset, constituting 15% of the original data.

Feature Importance

A feature importance chart was obtained from the RF model to visualize the ranking of factors that influence PWM and percent overlays. This feature importance chart of RF model can be described using mean decrease accuracy (MDA) metric. This metric measures the contribution of each variable to the overall performance of an RF model in reducing the variance of the predicted values. Higher MDA value of a particular variable indicates the more important the feature of the model.

Results

Dataset Description

A summary of the production data are shown in Table 2. For this analysis, litters with 100% mortality were not considered as they were severely affected by diseases. Also, mummified piglets were not considered in this study since this factor is not caused by sow, piglets, or perinatal environment factors. So, 1,936 individual records were used for analysis. The mean mortality and overlay percentage from the dataset were found to be about 16.1% (SE = 0.299) and

Table 2. Summary statistics of the production data

Item	Gestation length, days	Mean Birth weight, kg	Number of piglets born alive	Number of piglets weaned	Number of stillborns	Number overlays	Total dead piglets	PM, %	PO, %
Mean	115.6	1.44	13.19	13.35	0.741	0.82	2.30	16.08	6.19
Standard error	0.033	0.006	0.083	0.056	0.027	0.026	0.050	0.299	0.163
Median	116.0	1.406	14	13	0	0	2	14.286	1
Standard deviation	1.45	0.25	3.64	2.47	1.20	1.5	2.18	13.14	7.18
Sample variance	2.10	0.064	13.21	6.11	1.45	1.31	4.75	172.54	51.52
Minimum	110	0.756	1	2	0	0	0	1	1
Maximum	119	2.72	23	24	14	9	19	91.67	66.68

PM, Percent Mortality and PO, Percent Overlays. The data includes 1,936 litters and excludes those with 100% mortality.

Table 3. Results of generalized linear model for log-transformed percent preweaning mortality and percent overlays

Parameter	Coefficient	*Percent mortality*			Coefficient	*Percent overlays*		
		Std. error	z-value	P-value		Std. error	z-value	P-value
Intercept	6.59	5.58	1.18	0.238	3.03	9.40	0.32	0.747
Litter size	0.10	0.03	2.98	0.002	0.10	0.06	1.78	0.075
Mean birth weight	–0.75	0.31	–2.43	0.015	–0.59	0.51	–1.17	0.244
Gestation length	–0.08	0.05	–1.60	0.109	–0.06	0.08	–0.69	0.490
No. of stillborn	0.24	0.05	4.61	<0.001	–0.10	0.10	–1.00	0.317
Parity								
2 (*n* = 482)	0.02	0.18	0.14	0.891	0.18	0.29	0.64	0.052
3 (*n* = 404)	0.12	0.18	0.67	0.054	0.01	0.31	0.03	0.974
4 (*n* = 313)	0.20	0.20	1.01	0.033	0.07	0.33	0.21	0.832
Diagnosis								
Unhealthy (*n* = 939)	0.21	0.14	1.50	0.13	0.02	0.24	0.07	0.94
Litter line								
Yorkshire (*n* = 991)	–0.05	0.13	–0.42	0.67	–0.10	0.22	–0.44	0.65
Season								
Spring	–0.02	0.19	–0.08	0.94	–0.10	0.31	–0.32	0.748
Summer	0.05	0.18	0.28	0.78	0.02	0.30	0.08	0.938
Winter	0.08	0.18	0.43	0.66	0.04	0.30	0.14	0.888
Locations								
2	–0.01	0.15	–0.04	0.967	–0.01	0.26	–0.03	0.978
3	0.08	0.17	0.45	0.651	–0.04	0.29	–0.16	0.875

This table shows the results of a generalized linear model with a logit link function. The response variables are log-transformed percent PWM (preweaning mortality) and percent overlays. The predictors are litter size, mean birth weight in kilograms, gestation length in days, number of stillborn piglets, parity, diagnosis, litter line, season, and location. The coefficient, standard error, *z*-value, and *P*-value are reported for each predictor. The significance level was set at α = 0.05.

6.2% (SE = 0.163), respectively. Average gestation length was found 115.6 d (SE = 0.033) and mean birth weight was 1.44 kg (SE = 0.006).

A GLM PROC GLM (logit link function) was used for predictors variables of: parity, location, diagnosis, litter line, and season (Table 3). The model also includes covariates for the number of piglets the sow was responsible for (litter size) and mean birth weight of piglets. The response variables were log-transformed to obtain better estimates. From Table 3 the intercept represents the average value of the response variable when all predictors are zero. The coefficient for each predictor represents the change in the log odds of the

response variable per unit change in the predictor variables. The results indicate that, the litter size, mean birth weight, number of stillborn piglets, and parity are statistically significant factors for PWM. Mortality increases when the mean birth weight is low (–0.75 ± 0.31) (*P* < 0.05), and the litter size is large (0.10 ± 0.03) (*P* < 0.05). There was no significant difference in effects on overlays due to seasonal changes (*P* = 0.383) in the barn. Similarly, no significant effects were found for different crate locations (*P* = 0.816) and their interaction effects (*P* = 0.886) with different parity groups.

The effects for litter lines were significantly different for PWM (*P* = 0.002) and marginally for percent overlays

($P = 0.075$). Landrace-sired piglets had higher percent mortality (16.26 ± 0.13) than Yorkshire-sired piglets (15.91 ± 0.128). The percent overlays were 5.02% (±0.065) and 4.65% (±0.057) for Landrace and Yorkshire-sired piglets, respectively. Mean birth weight of piglets has a significant relationship with the number of piglets born alive ($P < 0.001$) and parity order of sow ($P < 0.001$) as seen in Table 4.

The production parameters e.g., litter size, number of piglets born alive, mean birth weight, stillborns, total dead piglets, and percent mortality presented in Table 5, are intended to visualize statistical differences among the different parity groups. Based on the results, there were significant differences in various parameters among different parity. Litter size increased with parity, with the mean litter size of sows in parity 4 being the highest piglet counts at 14.3 ± 2.61 compared to early parity sows ($P < 0.05$). Similarly, the mean number of piglets born alive also increased with parity, with sows in parity 2 having the highest number of piglets born alive (14.0 ± 3.47), while sows in parity 1 had the lowest (12.5 ± 3.56) ($P < 0.05$). There were also significant differences in mean birth weight among the different parties, with sows in parity 2 having the highest mean birth weight (1.50 ± 0.265 kg) and sows in parity 1 having the lowest mean birth weight (1.41 ± 0.228 kg) ($P < 0.05$). Gestation length, on the other hand, did not vary significantly among the different parity ($P = 0.699$). The number of stillborn piglets was significantly different among the different parties, with sows in parity 4 having the highest number of stillborn piglets (1.03 ± 1.58) and sows in parity 1 having the lowest number of stillborn piglets (0.630 ± 1.07) ($P < 0.05$). Furthermore, the total number of

dead piglets increased significantly with parity ($P < 0.05$). Finally, there were significant differences in the percentage of piglet mortality and overlays among the different parity. Sows in parity 4 had the highest percentage of piglet mortality (0.203 ± 0.147%) and sows in parity 1 had the lowest (0.142 ± 0.124%) ($P = 0.032$).

For this dataset, the mean birth weight of piglets varied with the number born alive (maximum of 2.72 kg, minimum 0.76 kg, and mean of 1.437 kg). Figure 3 shows the number of piglets born alive for different mean birth weight classes and different sow parity orders. The mean number of born alive piglets are higher when the mean birth weight is low compared to the heavy piglets (Figure 3A). Overall, the mean number of survived piglets were found slightly higher in fourth parity (13.89 ± 3.58) compared to the first parity (12.50 ± 3.55) (mean ± sd) also illustrated in Figure 3B. Additionally, piglet deaths were seen more when they had lower birth weight and higher sow parity shown in Figure 3C and Figure 3D. For overlays, parity is a similarly important parameter as mean birth weight to quantify piglet mortality. Higher parity sows have greater number of overlaid piglets.

PWM Prediction

The root means squared error (RMSE) value for the RF model is 2.28 which is lower than the Beta-regression model (5.18) for predicting percent mortality. The correlation coefficient for RF model is 0.89. Figure 4A shows a strong linear relationship between the percent mortality and the predicted mortality. Similarly, Figure 4B shows the results of using the RF model for predicting overlays. For predicting overlays, the correlation coefficient and RMSE of the model was 0.95 and 1.39, respectively. Therefore, the model fits well with the dataset for percent mortality and overlay prediction.

The relative importance chart Figure 5A and Figure 5B shows the variable importance in predicting mortality percentage and overlays percentage for RF model. For predicting percent mortality, litter size, and mean birth weight of piglets are the most important factors. The MDA was measured in the importance chart that was calculated by randomly permuting the values of a predictor variable and measuring the resulting decrease in model accuracy (e.g., decrease in R-squared). For example, if we do not include the mean birth weight for PWM prediction model, the prediction error would increase by about 25. For overlays, we can see that the parity is most

Table 4. Linear model for Mean birth weight with the relationship with sow parity and number of piglets born alive ($n = 1,936$)

Mean birth weight, kg			
Variables	Estimates	CI*	P
Intercept	1.82	1.78 to 1.78	<0.001
Parity	0.02	0.01 to 0.03	<0.001
Number born alive	−0.03	−0.3 to 0.03	<0.001

$N = 1,936$, $R^2 = 0.208$.
*Confidence interval calculated with 5% significance level.

Table 5. Production parameters for different parity of sow (MEANS ± SD)

Variable	Parity				P-value
	1 ($n = 737$)	2 ($n = 482$)	3 ($n = 404$)	4 ($n = 313$)	
Litter size	12.5 ± 2.35[a]	13.5 ± 2.16[a,b]	13.9 ± 2.47[b]	14.3 ± 2.61[c]	<0.001
Born alive	12.5 ± 3.56[a]	14.0 ± 3.47[b]	12.9 ± 3.74[a]	13.9 ± 3.59[b]	<0.001
Mean birth weight, kg	1.41 ± 0.228[a]	1.50 ± 0.265[a,b]	1.44 ± 0.253[b,c]	1.42 ± 0.275[c]	<0.001
Gestation length, d	115 ± 1.43	116 ± 1.45	116 ± 1.43	116 ± 1.43	0.699
Stillborns	0.630 ± 1.07[a]	0.645 ± 1.03[a]	0.837 ± 1.24[b]	1.03 ± 1.58[c]	<0.001
Total dead piglets	1.87 ± 1.87[a]	2.07 ± 1.96[a,b]	2.71 ± 2.29[b]	3.13 ± 2.67[c]	<0.001
Percent mortality. %	14.2 ± 12.4	14.6 ± 12.4	18.0 ± 13.0	20.3 ± 14.7	0.032
Percent overlays, %	4.38 ± 5.60[a]	5.20 ± 6.70[b]	4.79 ± 6.00[a]	5.30 ± 6.00[b]	0.039

Data are presented as mean ± standard deviation. [a, b, c]Different letters within a row indicate significant differences ($P < 0.05$) based on Tukey's HSD post hoc test for ANOVA. n = number of observations.

important variable for the prediction model with mean birth weight the next most important factor.

Discussion

According to Roehe and Kalm (2000), season can be a major contributing factor to PWM since variation in outside meteorological parameters affects piglet thermoregulation which leads to pathogenic and immunological factors associated with piglet mortality during the nursing period. In this study, there was no significant difference in effects found on mortality caused by seasonal variations and different crate locations in the room. This is because of efficient thermal management of micro-environments in the farrowing facility which includes heating during winter and the ventilation for cooling during summer which makes sow and piglets comfortable. These results agree with several other findings (Yeske et al., 1994; Li et al., 2010; Vande Pol et al., 2021).

Parity order of sow is an important factor that causes PWM and overlays which is evident from this study. This sow factor contributes to larger variations for mean birth weight and number of piglets born and dead as well as health conditions. Due to health effects for different parity levels, sows are more prone to have higher piglet mortality in higher parity order. Our finding that litter size increased with parity is consistent with previous studies (Vanderhaeghe et al., 2010). However,
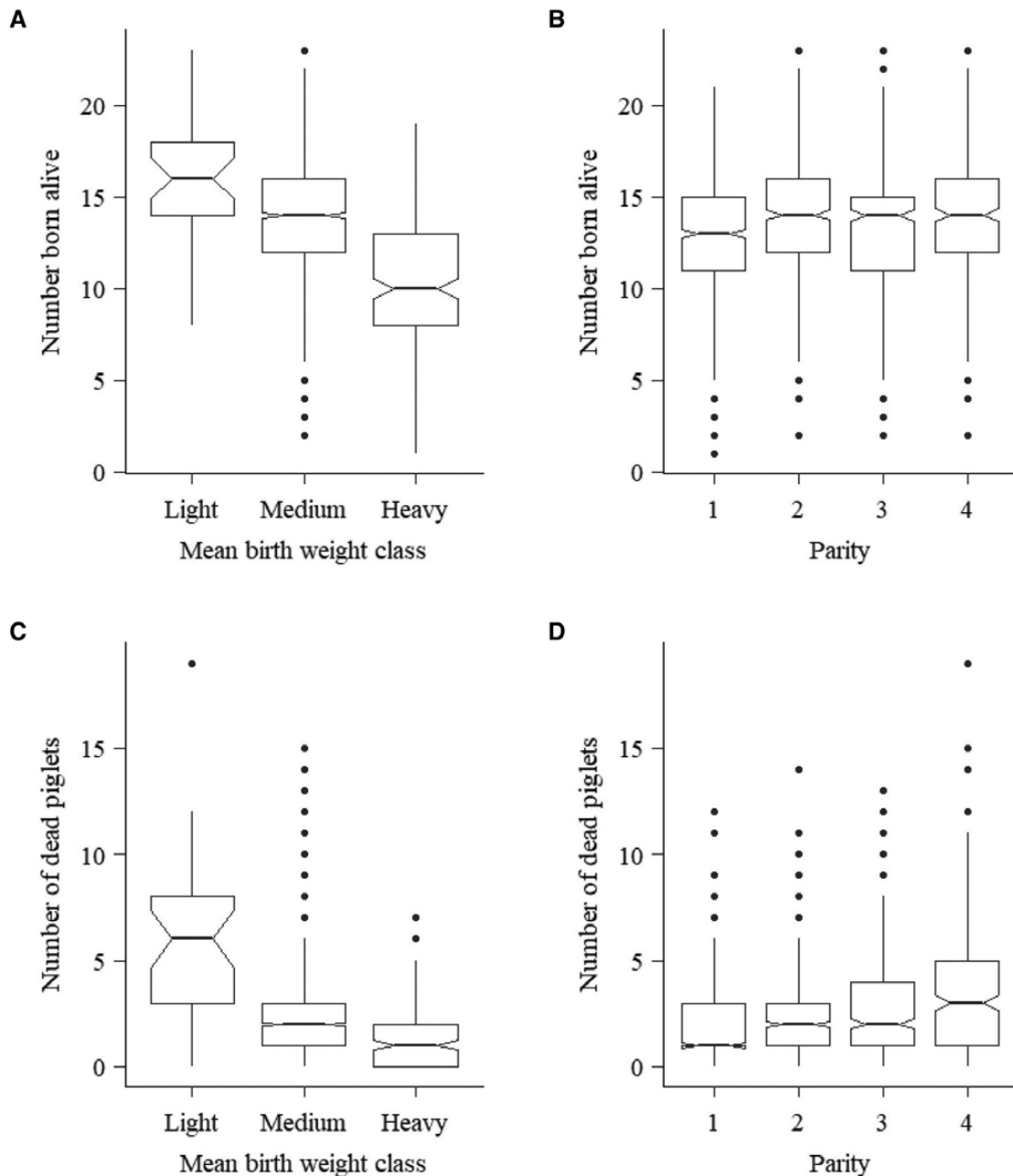
Figure 3. Notched boxplots for number of piglets born alive (A) by three different mean birth weight class (heavy—1.75 to 2.75 kg; medium—1.0 to 1.75 kg; and light—0.7 to 1.0 kg) and (B) Sow Parity (1 to 4), and number of dead piglets (C) by three different mean birth weight class (heavy—1.75-2.75 kg; medium—1.0 to 1.75 kg; and light—0.7 to 1.0 kg) and (D) Sow parity (1 to 4). Notch represents the confidence interval (CI). Total number of piglets used in the analysis was 1,936.
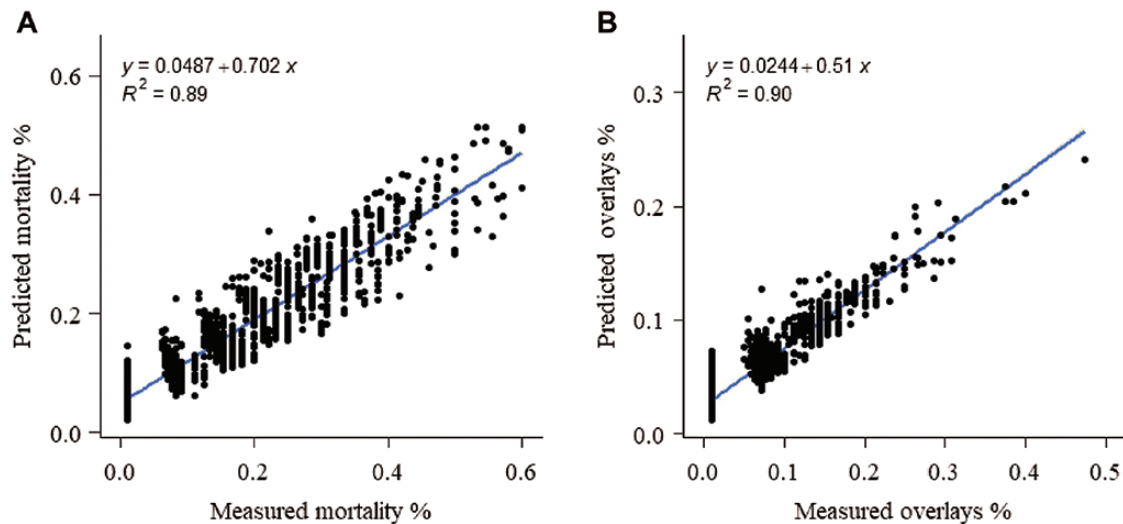
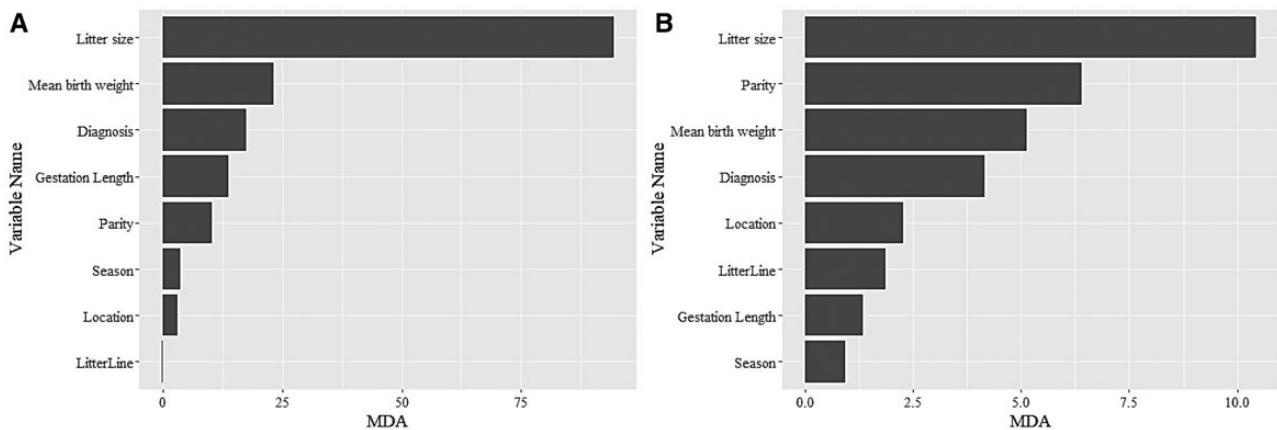**Figure 4.** Random forest model for predicting (A) percent mortality and (B) percent overlays.

Figure 5. Variable importance chart from random forest (RF) model (A) Percent mortality and (B) Percent overlays. Mean decrease accuracy (MDA) is a metric for RF model used to calculate the importance of features in predicting outcome variables. The bar shows the level of MDA for each feature in the RF model where a higher MDA indicates greater importance of the corresponding feature in predicting preweaning mortality and overlays.

it is important to note that litter size was highest in fourth parity, but this parity group also had the highest number of total dead piglets and stillborn piglets. This may be due to decreased placental efficiency with increasing parity (Wilson et al., 1999). This suggests that the increase in litter size may have resulted in decreased piglet viability by stressing sows during gestation, which may raise the question for negative welfare consequences (Rutherford et al., 2013).

This study found that, mean birth weight increases slightly as the parity increases. In addition to that, literature tells us there is evidence for having increased number of survived piglets when parity increases; however, overall mortality also increases (Edwards, 2002; Wientjes et al., 2012). Since the number of fetuses (number of piglets that a pregnant sow carries inside her uterus prior to giving birth) tends to increase with parity, more mummified and stillborn piglets are seen (Christianson, 1992). The sow with larger litter may have experienced dystocia or became fatigued before completing the birthing process and this stress could lead to health issues and cause increased PWM. Moreover, higher parity sows tend to have more gestation issues which leads to more stillborn piglets. Since a stillborn piglet represents a fetus that was alive

at the beginning of parturition but was unable to survive the birthing process, these piglets are an opportunity for management to increase litter performance. Managing higher parity sows differently may be able to correct the perinatal factor which results in greater number of stillborns if that factor can be discovered. The amount and quality of colostrum production (an essential source of energy, nutrients, and immunity for the piglet) is influenced by the parity of sow. Mid-parity levels (parity 2 to 4) produce more colostrum and have higher fat and lactose concentrations than the first and later (fifth or higher) parities (Nuntapaitoon et al., 2020; Amatucci et al., 2022; Ferrari et al., 2014).

The overlay rates are higher in later parities which indicates that older sows have more tendency to laziness or lameness resulting in crushed piglets. Overlaying by sow may also be affected by the environment or genotype which may change the way sows transition from standing to lying (causing overlays) (Baxter et al., 2011). For the prediction of mortality due to overlays, parity order was the most important parameter followed by litter size. Therefore, younger sows can handle the gestation period and lactation stage more robustly than older sows as stated (Uddin et al., 2022).

Mean birth weight and litter size of piglets are the major parameters to define PWM. An additional piglet born in a litter results in decreased mean birth weight. Experienced animal husbandry personnel decide on cross-fostering piglets considering a sow's capability for weaning according to the health status of both sow and piglets, birth weight of piglets, and their equal distribution. Sows having large litter size, resulted in higher number of overlays due to increased competition for access to teats during lactation. Furthermore, piglets having lower birth weight may have more trouble and health issues due to hypothermia and other diseases which ultimately cause death and also make them more prone to overlay similarly stated by Feldpausch et al. (2019). It is clear from the importance chart for RF model that the mortality prediction is mostly affected by the litter size. As the number of piglets increases, piglets tend to be smaller and are more prone to death due to space limitations, health condition, weaning, and activity which is already documented (Lund et al., 2002). Cross-fostering can improve piglet survival (Milligan et al.,2001; Deen and Belkei, 2004), however, cross-fostering considering only litter size is not a good practice as some literature suggests maintaining similar birth weight in litters for weaning survival (Huting et al., 2017).

Conclusion

Piglet preweaning mortality is a significant concern in U.S. pork industries. This involves cost and energy, and indeed it reduces productivity and increases welfare concerns. Factors such as birth weight, litter size, genetic information, parity of sow, and the environmental data are considered but for these large number of influencing factors, it is difficult to conclude a meaningful solution for PWM when they are considered individually. A complex relationship exists for PWM with the sow genetic and the environmental effects as well as other factors related to the sow and piglet health. In addition to those factors, the physical behavior of sows such as posture changes during the lactation period may be related to piglet mortality. Some producers collect data for the cause of death for each piglet during production, but more detailed data are necessary for commercial herds to adequately address this issue. This study investigated a large production dataset focused on a multivariate effect to determine and predict the preweaning mortality of piglets. The study shows 16.1% PWM where 5.55% was for stillbirths and 6.2% of piglets died due to overlays. The dataset from five years of production also reveals that there is a significant difference in mortality rate among different parity groups and litter lines. Landrace-sired litter has higher piglet mortality than Yorkshire-sired litters. Mean birth weight decreases when the number of born alive piglets increases with the parity order. Stillborn and overlays increases in higher parity order of sow due to certain health issues and complexity which leads to higher PWM. Overall, the younger sows have good mothering ability in farrowing crate system production since they have fewer overlays. RF model predicted the PWM quite accurately compared to Beta-regression and GLM models as the observed correlation coefficient (r) for PWM and overlays prediction was 0.89 and 0.9, respectively for RF model. Litter size, birth weight, gestation length, diagnosis report, and the parity phases are important parameters to predict PWM of piglets. The litter size is the most contributing factor for overall PWM while the parity order is most influential

for the overlays. In addition, physical behavior of sows such as posture changes during the lactation period may affect piglet mortality. Further studies on the postural transitions and behavior patterns need to be studied to identify causative factors related to PWM for piglets.

Conflict of Interest Statement

The authors declare no conflict of interest.

Literature Cited

Alexopoulos, J. G., D. S. Lines, S. Hallett, and K. J. Plush. 2018. A review of success factors for piglet fostering in lactation. Animal. 8:38. doi: 10.3390/ani8030038

Amatucci, L., D. Luise, F. Correa, P. Bosi, and P. Trevisi. 2022. Importance of breed, parity and sow colostrum components on litter performance and health. Animals (Basel). 12:1230. doi: 10.3390/ani12101230

Amdi, C., U. Krogh, C. Flummer, N. Oksbjerg, C. F. Hansen, and P. K. Thei. 2013. Intrauterine growth restricted piglets defined by their head shape ingest insufficient amounts of colostrum. J. Anim. Sci. 91:5605–5613. doi: 10.2527/JAS.2013-6824

Andersen, I. L., E. Nævdal, and K. E. Bøe. 2011. Maternal investment, sibling competition, and offspring survival with increasing litter size and parity in pigs (Sus scrofa). Behav. Ecol. Sociobiol. 65:1159–1167. doi: 10.1007/s00265-010-1128-4

Baxter, E. M., S. Jarvis, L. Sherwood, M. Farish, R. Roehe, A. B. Lawrence, and S. A. Edwards. 2011. Genetic and environmental effects on piglet survival and maternal behaviour of the farrowing sow. Appl. Anim. Behav. Sci. 130:28–41. doi: 10.1016/j.applanim.2010.11.020

Caldara, F. R., L. S. Dos Santos, S. T. MacHado, M. Moi, I. D. A. Nääs, L. Foppa, R. G. Garcia, and R. D. K. S. D. Santos. 2014. Piglets' surface temperature change at different weights at birth. Asian-Australasian J. Anim. Sci. 27:431. doi: 10.5713/AJAS.2013.13505

Christianson, W. T. 1992. Stillbirths, mummies, abortions, and early embryonic death. Vet. Clin. North Am. Food Anim. Pract. 8:623–639. doi: 10.1016/s0749-0720(15)30708-8

Condous, P. C., K. J. Plush, A. J. Tilbrook, and W. H. E. J. van Wettere. 2016. Reducing sow confinement during farrowing and in early

lactation increases piglet mortality. J. Anim. Sci. 94:3022–3029. doi: 10.2527/jas.2015-0145

Deen, M. G. H., and G. Bilkei. 2004. Cross fostering of low-birthweight piglets. Livest. Prod. Sci. 90:279–284. doi: 10.1016/j.livprodsci.2004.02.012

Edwards, S. A. 2002. Perinatal mortality in the pig: environmental or physiological solutions? Livest. Prod. Sci. 78:3–12. doi: 10.1016/s0301-6226(02)00180-x

Feldpausch, J. A., J. Jourquin, J. R. Bergstrom, J. L. Bargen, C. D. Bokenkroger, D. L. Davis, and M. J. Ritter. 2019. Birth weight threshold for identifying piglets at risk for preweaning mortality. Transl. Anim. Sci 3:633–640. doi: 10.1093/tas/txz076

Ferrari, C. V., P. E. Sbardella, M. L. Bernardi, M. L. Coutinho, I. S. Vaz, Jr, I. Wentz, and F. P. Bortolozzo. 2014. Effect of birth weight and colostrum intake on mortality and performance of piglets after cross-fostering in sows of different parities. Preven. Vet. Med. 114:259–266. doi: 10.1016/j.prevetmed.2014.02.013

Fix, J. S., J. P. Cassady, J. W. Holl, W. O. Herring, M. S. Culbertson, and M. T. See. 2010. Effect of piglet birth weight on survival and quality of commercial market swine. Livest. Sci. 132:98–106. doi: 10.1016/j.livsci.2010.05.007

Fordyce, A. L., E. A. Hines, E. M. Edwards, S. Plaengkaeo, K. J. Stalder, J. D. Colpoys, and H. D. Tyler. 2021. Measuring birth weight and umbilical cord diameter at birth to predict subsequent performance in swine. Transl. Anim. Sci. 5:1–9. doi: 10.1093/TAS/TXAA214

Glencorse, D. P., S. Hazel, D. D'Souza, and M. Hebart. 2019. Impact of non-confinement accommodation on farrowing performance: a systematic review and meta-analysis of farrowing crates versus pens. Animals (Basel). 9:957. doi: 10.3390/ani9110957

Grimberg-Henrici, C. G. E., K. Büttner, R. Y. Lohmeier, O. Burfeind, and J. Krieter. 2019. The effect of group-housing with free-farrowing pens on reproductive traits and the behaviour of low-risk and high-risk crushing sows. Appl. Anim. Behav. Sci. 211:33–40. doi: 10.1016/j.applanim.2018.12.001

Gustafsson, B. 1983. Effects of sow housing systems in practical pig production. Trans. ASAE 26:1181–1185. doi: 10.13031/2013.34101.

Hales, J., V. A. Moustsen, M. B. Nielsen, and C. F. Hansen. 2014. Higher preweaning mortality in free farrowing pens compared with farrowing crates in three commercial pig farms. Animal 8:113–120. doi: 10.1017/S1751731113001869

Haussmann, M. F., M. J. Daniels, and D. C. Lay, Jr. 2000. Consideration of piglet behavior may allow alterations in sow housing to increase both piglet and sow welfare. In: Swine Housing, Proc. First Int. Conf. ASAE:126-132. doi: 10.13031/2013.99

Huting, A. M. S., K. Almond, I. Wellock, and I. Kyriazakis. 2017. What is good for small piglets might not be good for big piglets: the consequences of cross-fostering and creep feed provision on performance to slaughter. J. Anim. Sci. 95:4926–4944. doi: 10.2527/jas2017.1889

Jarvis, S., R. B. D'Eath, and K. Fujita. 2005. Consistency of piglet crushing by sows. Anim. Welf. 14:43–51. doi: 10.1017/s0962728600028918

Koketsu, Y., S. Takenobu, and R. Nakamura. 2006. Preweaning mortality risks and recorded causes of death associated with production factors in swine breeding herds in Japan. J. Vet. Med. Sci. 68:821–826. doi: 10.1292/jvms.68.821

Lanferdini, E., I. Andretta, L. S. Fonseca, R. H. R. Moreira, V. S. Cantarelli, R. A. Ferreira, and M. L. T. Abreu. 2018. Piglet birth weight, subsequent performance, carcass traits and pork quality: a meta-analytical study. Livest. Sci. 214:175–179. doi: 10.1016/j.livsci.2018.05.019

Le Cozler, Y., C. Guyomarc'h, X. Pichodo, P. Y. Quinio, and H. Pellois. 2002. Factors associated with stillborn and mummified piglets in high-prolific sows. Anim. Res. 51:261–268. doi: 10.1051/ANIMRES:2002017

Leonard, S. M., H. Xin, T. M. Brown-Brandl, B. C. Ramirez, A. K. Johnson, S. Dutta, and G. A. Rohrer. 2021. Effects of farrowing stall layout and number of heat lamps on sow and piglet production performance. Applied Anim. Behav. Sci. 239:105334. doi: 10.1016/j.applanim.2021.105334

Li, Y., L. Johnston, and A. Hilbrands. 2010. Pre-weaning mortality of piglets in a bedded group-farrowing system. J. Swine Health and Prod. 18:75–80. doi:10.4141/cjas2011-068.

Lund, M. S., M. Puonti, L. Rydhmer, and J. Jensen. 2002. Relationship between litter size and perinatal and pre-weaning survival in pigs. Anim. Sci. 74:217–222. doi: 10.1017/s1357729800052383

Malmkvist, J., L. J. Pedersen, B. M. Damgaard, K. Thodberg, E. Jørgensen, and R. Labouriau. 2006. Does floor heating around parturition affect the vitality of piglets born to loose housed sows? Appl. Anim. Behav. Sci. 99:88–105. doi: 10.1016/j.applanim.2005.10.007

Marchant, J. N., A. R. Rudd, M. T. Mendl, D. M. Broom, M. J. Meredith, S. Corning, and P. H. Simmins. 2000. Timing and causes of piglet mortality in alternative and conventional farrowing systems. Vet. Rec. 147:209–214. doi: 10.1136/vr.147.8.209

Martínez-Burnes, J., A. Orihuela, N. Dumniem, R. Boonprakob, T. D. Parsons, and P. Tummaruk. 2023. Pen versus crate: a comparative study on the effects of different farrowing systems on farrowing performance, colostrum yield and piglet preweaning mortality in sows under tropical conditions. Animals (Basel). 13:233. doi: 10.3390/ANI13020233

Milligan, B. N., D. Fraser, and D. L. Kramer. 2001. The effect of littermate weight on survival, weight gain, and suckling behavior of low-birth-weight piglets in cross-fostered litters. J. Swine Health Prod. 9:161–166. https://doi.org/10.1016/S0168-1591(01)00136-8.

Muns, R., M. Nuntapaitoon, and P. Tummaruk. 2016. Non-infectious causes of pre-weaning mortality in piglets. Livest. Sci. 184:46–57. doi: 10.1016/j.livsci.2015.11.025

Nuntapaitoon, M., P. Juthamanee, P. K. Theil, and P. Tummaruk. 2020. Impact of sow parity on yield and composition of colostrum and milk in Danish Landrace× Yorkshire crossbred sows. Preven. Vet. Med. 181:105085. https://doi.org/10.1016/j.prevetmed.2020.105085 .

Roehe, R., and E. Kalm. 2000. Estimation of genetic and environmental risk factors associated with pre-weaning mortality in piglets using generalized linear mixed models. Anim. Sci. 70:227–240. doi: 10.1017/s1357729800054692

Rutherford, K. M. D., E. M. Baxter, R. B. D'Eath, S. P. Turner, G. Arnott, R. Roehe, B. Ask, P. Sandoe, V. A. Moustsen, F. Thorup, S. A. Edwards, P. Berg and A. B. Lawrenc. 2013. The welfare implications of large litter size in the domestic pig I: biological factors. *Anim Welf*. 22:199–218. doi: 10.7120/09627286.22.2.199

Sales, G. T., E. T. Fialho, T. Y. Junior, R. T. F. D. Freitas, V. H. Teixeira, R. S. Gates, and G. B. Day. 2008. Thermal environment influence on swine reproductive performance. Livest. Env. VIII. ASABE. 767–772. doi: 10.13031/2013.25582

Schild, S.-L. A., E. M. Baxter, L. J. Pedersen. 2020. A review of neonatal mortality in outdoor organic production and possibilities to increase piglet survival. Applied Anim. Behav. Sci., 231, 105088. doi:10.1016/j.applanim.2020.105088

Sharpe, K. T., M. H. Reese, E. S. Buchanan, J. E. Tallaksen, K. A. Janni, and L. J. Johnston. 2018. Electrical and thermal energy consumption in midwest commercial swine facilities. Appl. Eng. Agric. 34:857–864. doi: 10.13031/aea.12771. 5

Stalder, K. J. 2018. 2016 Pork industry productivity analysis. National Pork Board research grant report.

Thacker, B. J. 2000. Retrospective investigation of farrowing performance as affected by crate and floor type. In: Swine Hous. Conf. (p. 1). ASABE 1–4. https://doi.org/10.13031/2013.119.

Tucker, B. S., J. R. Craig, R. S. Morrison, R. J. Smits, and R. N. Kirkwood. 2021. Piglet viability: a review of identification and pre-weaning management strategies. Animals (Basel). 11:2902. doi: 10.3390/ani11102902

Uddin, M. K., S. Hasan, O. Peltoniemi, and C. Oliviero. 2022. The effect of piglet vitality, birth order, and blood lactate on the piglet growth performances and preweaning survival. Porc. Health Manag. 8:1–9. https://doi.org/10.1186/s40813-022-00299-2

Vande Pol, K. D., A. F. Tolosa, C. M. Shull, C. B. Brown, S. A. S. Alencar, C. A. Lents, and M. Ellis. 2021. Effect of drying and/or warming piglets at birth under warm farrowing room temperatures on piglet

rectal temperature over the first 24 h after birth. Transl. Anim. Sci. 5:1–12. doi:10.1093/TAS/TXAB060

Vanderhaeghe, C., J. Dewulf, S. De Vlieghe, G. A. Papadopoulos, A. de Kruif, and D. Maes. 2010. Longitudinal field study to assess sow level risk factors associated with stillborn piglets. Anim. Reprod. Sci. 120:78–83. doi: 10.1016/j.anireprosci.2010.02.010

Wheeler, E. F., G. Vasdal, A. Flø, and K. E. Bøe. 2008. Static space requirements for piglet creep area as influenced by radiant temperature. Trans. ASABE 51:271–278. doi: 10.13031/2013.24220

Wientjes, J. G. M., N. M. Soede, C. M. C. Van der Peet-Schwering, H. Van den Brand, and B. Kemp. 2012. Piglet uniformity and mortality in large organic litters: effects of parity and pre-mating diet composition. Livest. Sci. 144:218–229. doi: 10.1016/j.livsci.2011.11.018

Wilson, M. E., N. J. Biensen, and S. P. Ford. 1999. Novel insight into the control of litter size in pigs, using placental efficiency as a selection tool. J. Anim. Sci. 77:1654–1658. doi: 10.2527/1999.7771654x

Yeske, P., S. L. Ott, and H. S. Hurd. 1994. Facility effects on preweaning mortality: a report of the NAHMS National Swine Survey. *J Swine Health and Prod*. 2:11–18. Retrieved from https://www.aasv.org/shap/issues/v2n5/v2n5p11.pdf.

Zhou, H., and H. Xin. 1999. Effects of heat lamp output and color on piglets at cool and warm environments. Appl. Eng. Agric. 15:327–330. doi: 10.13031/2013.5785