

Correlation of oxidative stress markers between serum and colostrum and their association with production performance in lactating sows from a PRRS-unstable herd

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Abstract

Oxidative stress occurs when the production of reactive oxygen species exceeds the antioxidant defense capacity of living organisms. Oxidative stress is commonly assessed using serum samples; however, blood sampling in pigs is often avoided on commercial farms because of disease transmission concerns and animal welfare considerations. This study aimed to evaluate the correlation between oxidative stress markers in serum and colostrum samples and to determine their association with production performance in lactating sows. A total of 34 Landrace × Large White sows from a commercial farrow-to-finish farm were included in the study. Blood and colostrum samples were collected immediately after the first piglet was delivered. Concentrations of malondialdehyde (MDA), superoxide dismutase 1 (SOD1), and glutathione peroxidase 1 (GPX1) were measured using commercial ELISA kits. Production performance indicators during the lactation period were also recorded. The results showed that concentrations of MDA, SOD1, and GPX1 were consistently higher in colostrum than in serum samples, by 1.67-, 1.57-, and 1.58-fold, respectively. A significant positive correlation was observed between serum and colostrum MDA concentrations ($r = 0.866$, $P < 0.001$). Among production indicators, average daily litter weight gain was positively associated with serum SOD1 concentration ($r = 0.472$, $P = 0.013$). Other oxidative stress markers showed no significant correlations with production parameters. These findings suggest that colostrum MDA may serve as a potential alternative indicator for oxidative stress assessment in lactating sows. However, oxidative stress markers showed limited association with sow production performance.

Keywords: antioxidant enzymes, colostrum, lactating sows, oxidative stress, production performance

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Introduction

Oxidative stress refers to an imbalance between free radical production and the antioxidant defense system in living organisms, leading to the excessive generation of reactive oxygen species (ROS) (Sies, 1985; Kurutas, 2016). Under normal physiological conditions, ROS are produced during metabolic processes such as cellular respiration (Ryter *et al.*, 2007; Li *et al.*, 2022). When ROS are produced, organisms possess antioxidant defense systems that neutralize these free radicals, primarily composed of antioxidant enzymes (Hao *et al.*, 2021). However, various external factors, such as heat stress and infections, can stimulate excessive ROS production while overwhelming the antioxidant defense system, ultimately resulting in oxidative stress (Mou *et al.*, 2020). Oxidative stress has become an important topic in both human and animal health research, as it is associated with the development of various diseases and physiological disorders. In swine production, late gestation, farrowing, and lactation are considered critical periods during which sows are particularly susceptible to oxidative stress due to the substantial energy demands required for fetal development and milk production (Meng *et al.*, 2018; Li *et al.*, 2022). This condition is often more pronounced in high-prolific sows, which typically carry larger litters and produce more piglets (Lee *et al.*, 2023). Consequently, oxidative stress may negatively affect sow productivity by reducing the number and growth performance of suckling and weaned piglets (Zhang *et al.*, 2020; Ortega *et al.*, 2022; Papatsiros *et al.*, 2022). In addition, the post-weaning health of sows may be compromised due to deteriorating body condition and weight loss, which can lead to delayed estrus and prolonged service intervals (Black *et al.*, 1993). Measurement of oxidative stress markers has therefore become an important approach for monitoring sow health and productivity. These biomarkers can generally be classified into two categories: markers reflecting oxidative damage caused by free radicals and markers representing the antioxidant defense system (Yang *et al.*, 2023). Because free radicals are difficult to detect directly, by-products generated from ROS-induced oxidative reactions are commonly used as indirect indicators of oxidative stress. Lipid peroxidation, which occurs when ROS oxidize polyunsaturated fatty acids (PUFAs) in cell membranes, produces malondialdehyde (MDA), a widely used biomarker for oxidative stress assessment (Mas-Bargues *et al.*, 2021). Conversely, antioxidant capacity can be evaluated by measuring antioxidant enzymes such as superoxide dismutase (SOD) and glutathione peroxidase (GPX), which play essential roles in protecting cells from oxidative damage (Lubos *et al.*, 2011; Younus, 2018).

Normally, assessment of oxidative stress parameters is performed using serum samples. However, emerging infectious diseases have become a major concern in pig farm management, particularly African swine fever, which has raised significant biosecurity concerns associated with invasive procedures such as blood sampling. As a result, farmers may be reluctant to perform routine blood sampling, since pathogens may potentially spread

through contaminated equipment during blood collection procedures. Moreover, blood collection may induce additional stress in sows, as it can cause physical and psychological stress due to the restraining techniques required for blood sampling (Rubio *et al.*, 2019). Therefore, alternative sampling methods have been considered for oxidative stress assessment, such as oral fluids, colostrum, or milk samples (Lipko-Przybylska and Kankofer, 2012). Among these, colostrum is considered a less invasive and less stressful sampling method for evaluating health status in swine. In addition, colostrum contains several bioactive components, particularly immunoglobulins (Ig), which are commonly used for assessing both sow and piglet health status (Rolinec *et al.*, 2012; Inoue and Tsukahara, 2021). However, information regarding the relationship between oxidative stress markers in serum and colostrum in lactating sows remains limited. Furthermore, the association between oxidative stress markers and production performance in lactating sows has not been well elucidated.

Therefore, the aim of this study is to determine the correlation between oxidative stress markers in serum and colostrum and to examine their association with production performance in lactating sows. In addition, this study evaluates whether colostrum could serve as an alternative sample for oxidative stress assessment.

Materials and Methods

Sample size and sample collection: The sample size was determined based on the primary objective of assessing the correlation between oxidative stress markers in serum and colostrum. The animal use protocol for this study was approved by the Kasetsart University Institutional Animal Care and Use Committee (Approval ID: ACKU68-VET-056). The sample size was calculated using G*Power software version 3.1.9.4 (Faul *et al.*, 2007) based on a two-tailed bivariate correlation model, assuming an effect size (r) of 0.45, a significance level (α) of 0.05, and a statistical power of 0.80. A total of 34 farrowing Landrace $\times$ Large White crossbred sows from a commercial farrow-to-finish farm housed under an evaporative cooling system were included in the study. The herd was classified as PRRS-unstable active based on laboratory results and evidence of ongoing virus circulation, as indicated by routine diagnostic monitoring and clinical history during the study period. In addition, the herd was positive for *Actinobacillus pleuropneumoniae* (APP). Serum and colostrum samples were collected immediately after the delivery of the first piglet. Blood samples (5–10 ml) were collected via jugular venipuncture, while 1.5–2.0 ml of colostrum was obtained from the first pair of teats. Serum and colostrum samples were centrifuged at $4,900 \times g$ for 5 min and $9,000 \times g$ for 10 min, respectively, at 25 °C. Subsequently, 1.0–1.5 ml of serum and colostrum supernatant were aliquoted into microcentrifuge tubes and stored at -80 °C until further analysis.

Oxidative stress markers measurement: The concentrations of three oxidative stress markers, MDA (Boonsoongnern *et al.*, 2019; Mas-Bargues *et al.*, 2021), superoxide dismutase 1 (SOD1) (Younus, 2018;

Boonsoongnern *et al.*, 2019), and glutathione peroxidase 1 (GPX1) (Lubos *et al.*, 2011) were measured in duplicate in both serum and colostrum samples using commercial ELISA kits (Abbexa® Ltd., Cambridge, United Kingdom) in accordance with the manufacturer's instructions. MDA concentrations were determined using an ELISA kit (catalog no. abx257171, lot no. E2406302Q) based on a competitive ELISA principle, with samples diluted 20-fold. SOD1 concentrations were measured using an ELISA kit (catalog no. abx258510, lot no. E2312998N), which employs a sandwich ELISA format, with samples diluted 20-fold. GPX1 concentrations were determined using an ELISA kit (catalog no. abx154931, lot no. E2406918J), also based on a sandwich ELISA format, with samples diluted 80-fold. All assays were performed following the manufacturer's protocols, and the concentrations of each marker were calculated from the corresponding standard curves. The final concentrations were expressed as ng/ml.

Sow production performance indicators collection:

Data on sow production performance indicators were collected at three physiological stages of farrowing, weaning, and post-weaning service. At farrowing, parity, total litter size (TB), number of born-alive piglets (BAL), birth weight, number of stillborn piglets, and number of mummified fetuses (MM) were recorded. The proportions of stillborn piglets and mummified fetuses were subsequently expressed as percentages. At weaning, the number of piglets weaned per litter and weaning weight were recorded. Pre-weaning mortality was calculated as the proportion of piglets that died before weaning, based on the difference between the number of born-alive piglets and the number of piglets weaned. In addition, average daily litter weight gain (ADLWG) was calculated from birth weight and weaning weight data during the lactation period. The first day of post-weaning service was recorded to calculate the wean-to-first service interval (WFSI).

Statistical analysis: Data was analyzed using R Studio version 2025.5.0.496 in R statistical software version 4.3.3 (R Core Team, 2024). Data were evaluated for normality and homogeneity of variance using the Shapiro-Wilk test and F-test, respectively. Oxidative stress markers from both sample types and sow production performance indicators were presented as mean $\pm$ standard deviation (SD). Pearson correlation analysis was performed to evaluate associations between variables, and were reported as correlation coefficients (r) and P -values. A P -value < 0.05 was considered statistically significant, whereas P -values between 0.05 and 0.10 were considered to indicate a statistical trend.

Results

The mean concentrations ($\pm$ SD) of MDA, SOD1, and GPX1 in serum and colostrum samples are presented in Figure 1. Among the oxidative stress markers, only MDA showed a statistically significant

strong positive correlation between serum and colostrum samples (Fig. 2). All markers exhibited higher concentrations in colostrum than in serum samples, with colostrum MDA, SOD1, and GPX1 levels being 1.67-, 1.57-, and 1.58-fold higher than those in serum, respectively.

The higher concentrations of oxidative stress markers observed in colostrum compared to serum may be explained by differences in their biochemical composition. Colostrum is rich in bioactive components, including lipids, proteins, and immunological factors, particularly PUFAs, which are more susceptible to oxidative reactions. This composition may promote the formation and accumulation of lipid peroxidation products such as MDA. In addition, colostrum contains higher concentrations of various proteins and enzymes, which may contribute to the elevated levels of antioxidant-related markers. Furthermore, methodological factors related to differences in sample matrices between serum and colostrum, such as fat and protein content, may also influence the measured concentrations. Therefore, the interpretation of oxidative stress markers should consider the inherent compositional differences between biological fluids. Summary statistics of sow lactation performance are presented in Table 1, providing an overview of the biological and production characteristics of the study population. When oxidative stress markers were compared with sow performance indicators (Tables 2 and 3), ADLWG was significantly positively correlated with serum SOD1 concentration ($r = 0.472$, $P = 0.013$). ADLWG also showed positive trends of association with both serum and colostrum GPX1 concentrations ($r = 0.350$, $P = 0.074$; and $r = 0.357$, $P = 0.067$, respectively). Colostrum GPX1 concentration was significantly positively correlated with sow parity ($r = 0.398$, $P = 0.022$) and showed positive trends toward association with TB and BAL ($r = 0.325$, $P = 0.065$; and $r = 0.301$, $P = 0.089$, respectively). In contrast, the percentage of MM showed a positive trend toward association with serum SOD1 concentration ($r = 0.314$, $P = 0.075$), whereas the WFSI showed a positive trend toward association with serum GPX1 concentration ($r = 0.402$, $P = 0.079$).

Table 1 Means with standard deviations of sow performances.

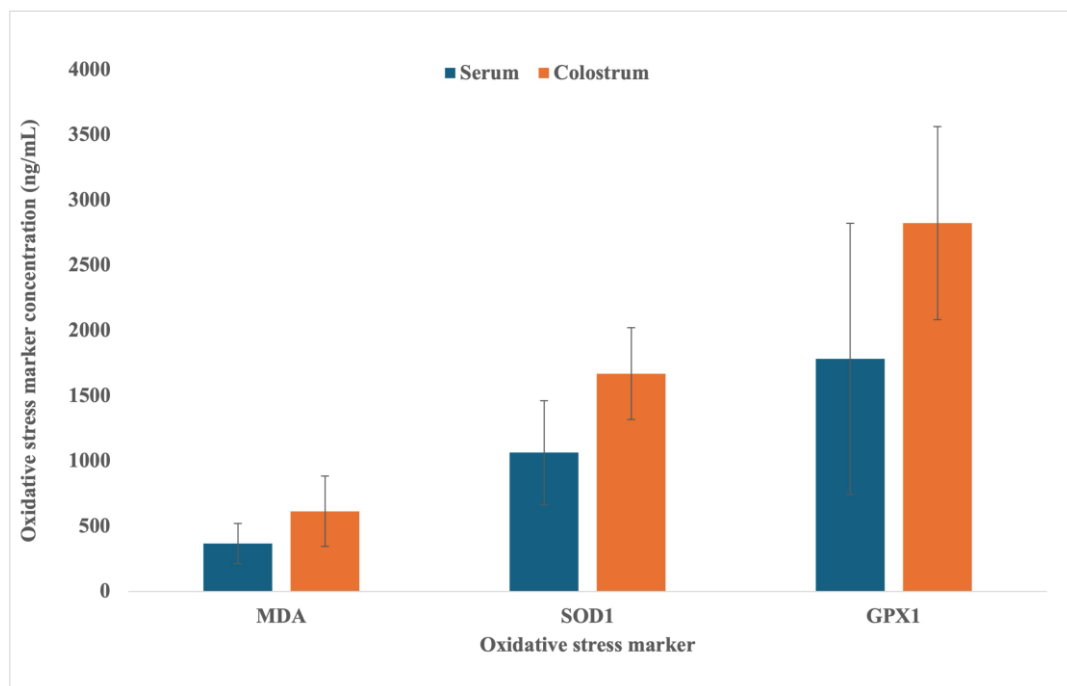
Sow performances	Means $\pm$ SD
Parity	3.45 $\pm$ 3.12
Litter size (piglets)	12.97 $\pm$ 3.91
Born alive piglets (piglets)	9.45 $\pm$ 4.80
Percentage of stillborn fetuses	8.29 $\pm$ 11.44
Percentage of mummified fetuses	21.27 $\pm$ 27.10
Percentage of pre-weaning mortality	17.61 $\pm$ 33.49
Average daily litter weight gain (g/day)	1,945.36 $\pm$ 536.25
Wean-to-first service interval (days)	9.00 $\pm$ 11.86

Table 2 Correlation coefficients between sow performances and oxidative stress parameters in serum samples.

Sow performances	Correlation coefficient (r) and <i>p</i> -value of oxidative stress parameters in serum samples		
	MDA	SOD1	GPX1
Parity	0.064 (0.725)	0.185 (0.302)	0.017 (0.924)
Litter size (piglets)	-0.150 (0.403)	0.166 (0.356)	0.156 (0.385)
Born alive piglets (piglets)	-0.191 (0.286)	-0.062 (0.733)	-0.123 (0.596)
Percentage of stillborn fetuses	-0.063 (0.726)	-0.023 (0.898)	0.282 (0.112)
Percentage of mummified fetuses	0.113 (0.531)	0.314 (0.075)	0.222 (0.215)
Percentage of pre-weaning mortality	-0.231 (0.212)	-0.161 (0.385)	-0.067 (0.722)
Average daily litter weight gain (g/day)	0.026 (0.870)	0.472 (0.013)	0.350 (0.074)
Wean-to-first service interval (days)	0.065 (0.786)	0.225 (0.340)	0.402 (0.079)

Table 3 Correlation coefficients between sow performances and oxidative stress parameters in colostrum samples.

Sow performances	Correlation coefficient (r) and <i>p</i> -value of oxidative stress parameters in colostrum samples		
	MDA	SOD1	GPX1
Parity	0.016 (0.928)	0.244 (0.172)	0.398 (0.022)
Litter size (piglets)	-0.065 (0.718)	-0.100 (0.580)	0.325 (0.065)
Born alive piglets (piglets)	-0.121 (0.504)	0.015 (0.934)	0.301 (0.089)
Percentage of stillborn fetuses	-0.095 (0.599)	-0.258 (0.148)	-0.015 (0.935)
Percentage of mummified fetuses	0.109 (0.547)	-0.007 (0.969)	-0.201 (0.263)
Percentage of pre-weaning mortality	-0.080 (0.669)	-0.287 (0.118)	-0.103 (0.580)
Average daily litter weight gain (g/day)	0.033 (0.872)	0.024 (0.904)	0.357 (0.067)
Wean-to-first service interval (days)	0.148 (0.533)	-0.204 (0.389)	0.170 (0.473)

**Figure 1** Comparison of oxidative stress markers concentrations between serum and colostrum samples in lactating sows. Bars represent the mean concentrations of malondialdehyde (MDA), superoxide dismutase 1 (SOD1), and glutathione peroxidase 1 (GPX1) measured in serum and colostrum samples. Error bars indicate standard deviations. Concentrations are expressed in ng/mL.

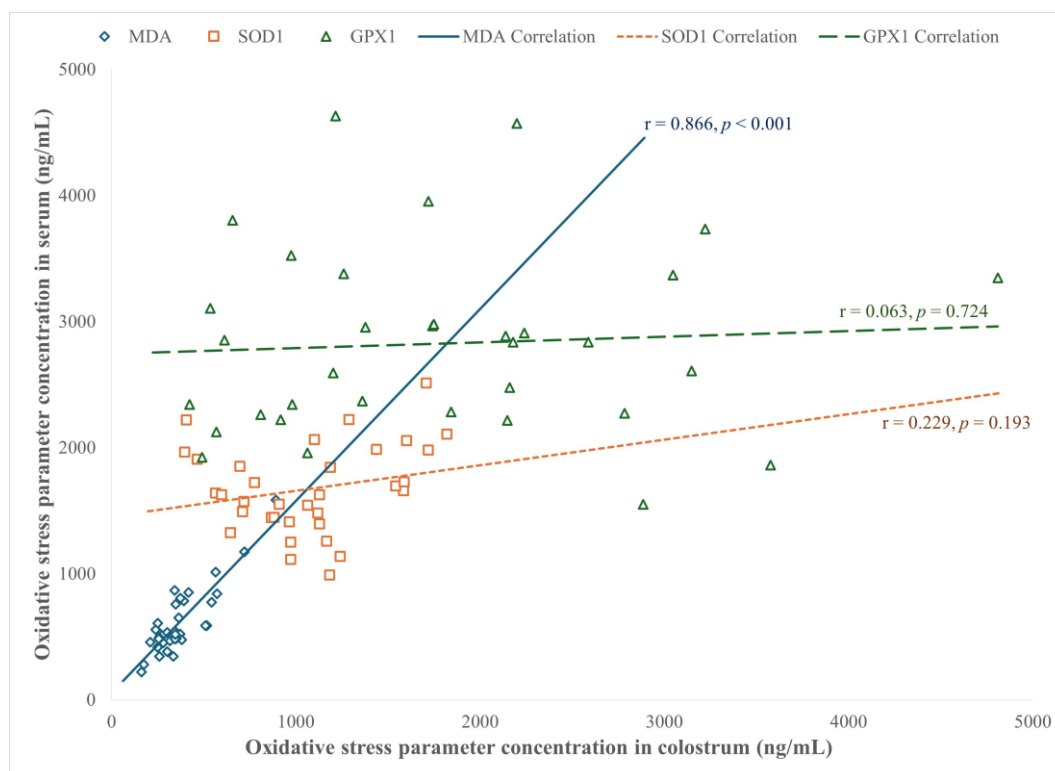


Figure 2 Correlation between oxidative stress marker concentrations in serum and colostrum samples of lactating sows. Scatter plots show the relationships between serum and colostrum concentrations of malondialdehyde (MDA), superoxide dismutase 1 (SOD1), and glutathione peroxidase 1 (GPX1). Solid and dashed lines represent linear regression trends for each marker. A significant positive correlation was observed for MDA ($r = 0.866$, $P < 0.001$), whereas SOD1 and GPX1 showed no significant correlations. Concentrations are expressed in ng/mL.

Discussion

The results of this study showed that MDA concentrations in serum and colostrum samples were positively correlated, whereas the antioxidant enzymes SOD1 and GPX1 did not show similar relationships. The differences in correlation patterns among these biomarkers may be explained by their distinct biological characteristics. MDA is a relatively stable end-product of lipid peroxidation and reflects cumulative oxidative damage, which may enable it to more consistently represent systemic oxidative status across different biological matrices, such as serum and colostrum. In contrast, antioxidant enzymes such as SOD1 and GPX1 are actively regulated components of the antioxidant defense system. Their concentrations may be influenced by local cellular activity, glandular secretion, and metabolic conditions within the mammary tissue, potentially resulting in variability between serum and colostrum samples. Additionally, differences in protein transport and secretion mechanisms into colostrum may further contribute to the lack of correlation observed for these enzymes. Previous studies have suggested that higher total antioxidant capacity (T-AOC) in the serum of lactating sows does not necessarily correspond to increased T-AOC levels in colostrum (Tan *et al.*, 2021). Similarly, Mou *et al.* (2020) reported that increased serum concentration of SOD and GPX were not associated with higher levels of these enzymes in colostrum. In addition, Huang *et al.* (2025) reported no significant differences in SOD and GPX concentrations between serum and colostrum samples. In the present study, the concentrations of MDA, SOD1, and GPX1 in colostrum

were at least 1.5 times higher than those in serum. Although the antioxidant enzyme patterns differed from those reported in previous studies, the transfer of other bioactive proteins through colostrum may indicate comparable distribution pattern. Several studies have reported that immunoglobulin G and A (IgG and IgA) concentrations are 2 to 4 times higher in colostrum than in serum samples (Markowska-Daniel *et al.*, 2010; Segura *et al.*, 2020; Augustyniak *et al.*, 2024; Szabó *et al.*, 2025). A similar pattern has also been reported for IgG in dairy cows during the periparturient period (Lacoste *et al.*, 2023). In addition, certain enzymes such as gamma-glutamyl transpeptidase and alkaline phosphatase have been reported to occur at approximately twofold higher concentration in colostrum than in serum (Pinto *et al.*, 2025). These findings suggest that the enrichment of several bioactive components in colostrum may partly explain the higher concentrations of oxidative stress markers observed in this study.

Based on previous studies, oxidative stress status may potentially be evaluated using colostrum samples. However, the suitability of each biomarker should be carefully determined to identify reliable indicators. The findings of this study suggest that MDA in colostrum could serve as an alternative marker for oxidative stress assessment in lactating sows, as MDA concentrations in colostrum were positively correlated with those in serum and were consistently higher. Moreover, the strong positive correlation observed between serum and colostrum MDA concentrations indicates that colostrum may to some extent, reflect systemic oxidative stress status in lactating sows. The

elevated MDA levels in colostrum may be associated with its biochemical composition, which is rich in lipids and fatty acids, particularly PUFAs. These fatty acids are more susceptible to oxidative reactions than those found in serum or mature milk. Consequently, the abundance of PUFAs in colostrum may increase both the rate and extent of lipid peroxidation induced by ROS (Wilms *et al.*, 2022; Ayala *et al.*, 2024).

A previous study by Lipko-Przybylska and Kankofer (2012) suggested that oxidative enzymes in colostrum, including SOD and GPX, increase with higher sow parity. This finding is consistent with the results of the present study, which demonstrated a positive association between colostrum GPX1 concentration and sow parity. Positive trends in the relationships between ADLWG and SOD1 and GPX1 concentration, especially serum SOD1, observed in this study are consistent with the findings of Zhang *et al.* (2020), who reported that higher levels of T-AOC in lactating sows are associated with increased piglet weaning weight. Furthermore, the positive trends observed between TB, BAL and colostrum GPX1 concentration are in agreement with those reported in a previous study (Ortega *et al.*, 2022). However, it should be noted that most of these relationships were weak or only showed trend-level significance. Therefore, these findings should be interpreted with caution and considered exploratory, as they may not indicate strong or causal relationships between oxidative stress markers and production performance.

Interestingly, the positive trend observed between serum SOD1 concentration and the percentage of MM in this study differs from the findings of Zhang *et al.* (2020) and Ortega *et al.* (2022), who reported either an opposite trend or no correlation between antioxidant status and fetal mummification. One possible explanation for this discrepancy may be the health status of the farm where the present study was conducted. The herd involved in this study had a porcine reproductive and respiratory syndrome virus (PRRSV)-unstable status, and PRRSV infection has been associated with an increased incidence of fetal mummification in sow herds (Zimmerman *et al.*, 2019). Additionally, the occurrence of MM may also be influenced by factors such as larger litter size or physiological stress during the gestation, period rather than conditions occurring at the farrowing stage (Raguvaran *et al.*, 2017).

The results of this study showed a positive trend between serum GPX1 concentration and WFSI. This observation contrasts with the findings of Papatsiros *et al.* (2022), who reported that sows with lower serum oxidative stress levels following farrowing had shorter WFSI. However, no studies have directly examined the relationship between serum GPX concentrations and WFSI. In the present study, weaning and service events occurred several weeks after sample collection, as samples were obtained on the day of farrowing. Therefore, oxidative stress markers measured closer to the weaning period may provide a more accurate indication of their relationship with reproductive performance. In comparison with previous studies conducted in healthy or PRRS-stable sow herds, oxidative stress markers have been reported to show more consistent relationships with reproductive

performance and antioxidant capacity (Zhang *et al.*, 2020; Tan *et al.*, 2021). These findings suggest that, under normal physiological conditions, oxidative stress parameters may more reliably reflect metabolic status and productivity in lactating sows. In contrast, the relatively weak or inconsistent associations observed in the present study may be partly influenced by the PRRS-unstable status of the herd, which could affect both oxidative responses and production performance. Infectious challenges and associated inflammatory processes may disrupt the balance between oxidative stress and antioxidant defense mechanisms, thereby affecting the relationships between biomarkers and production outcomes. Therefore, the interpretation of oxidative stress biomarkers under field conditions should take into account herd health status, particularly in herds with ongoing disease challenges. This study has several limitations that should be considered when interpreting the results. First, the study was conducted on a single commercial farm with a PRRSV-unstable and APP-positive herd status, which may influence oxidative responses and reproductive performance. Consequently, the findings may not fully generalizable to sow populations under different health or management conditions, and herd relationships. Second, the sample size was determined based on the primary objective of correlation analysis between serum and colostrum oxidative stress markers and may not provide sufficient statistical power to detect smaller associations with multiple production performance parameters. This limitation may partly explain the weak or non-significant correlations observed between oxidative stress markers and production outcomes. Therefore, these findings should be interpreted with caution. Third, oxidative stress markers were measured at a single time point immediately after farrowing, whereas some production parameters, such as weaning performance and the wean-to-first service interval, occur several weeks later. Given that oxidative stress is a dynamic process, a single measurement may not fully reflect oxidative status throughout the lactation period. This temporal mismatch may have reduced the ability to detect meaningful relationships between oxidative stress markers and production outcomes. Future studies involving multiple farms with varying health statuses, larger sample sizes, and repeated sampling throughout the lactation period are warranted to provide a more comprehensive understanding of the relationship between oxidative stress status and sow reproductive performance.

In conclusion, this study demonstrated that MDA concentrations in colostrum were significantly correlated with serum MDA levels, suggesting that colostrum sampling may serve as a practical alternative for oxidative stress assessment in lactating sows. However, oxidative stress parameters showed only limited associations with sow production performance indicators. Therefore, serum samples may remain more appropriate for evaluating the relationships between oxidative stress status and production performance in lactating sows. Further studies are warranted to confirm the reliability of colostrum biomarkers for oxidative stress monitoring

across different herd health conditions and production systems.

Conflicts of interest: The authors declare no conflicts of interest.

Declaration of Artificial Intelligence Use: The authors declare that no artificial intelligence tools were used in the preparation and writing of this manuscript.

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CRedit authorship contribution statement: **Supasit Sopin:** Data curation, Methodology, Formal analysis, Writing-original draft preparation, Writing-review & editing. **Yonlayong Woonwoong:** Investigation, Methodology, Writing-review & editing. **Pichai Jirawattanapong:** Formal analysis, Validation, Writing-review & editing. **Prapassorn Boonsoongnarn:** Conceptualization, Visualization, Writing-review & editing. **Wirot Lakkanasombat:** Conceptualization, Funding acquisition, Writing-review & editing. **Alongkot Boonsoongnarn:** Conceptualization, Funding acquisition, Resources, Writing-review & editing, Supervision.

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