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Prevalence and severity of pale, soft, and exudative (PSE)-like zones in crossbred pigs (Yorkshire x Hampshire): Insights into season, gender, slaughter weight and technological meat traits

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HIGHLIGHTS

- Seasonal variations significantly affect the prevalence of PSE-like zones in pigs.
- Female pigs show a higher incidence of PSE-like zones than immuno-castrated males.
- Slaughter weight correlates with prevalence of PSE-like zones.
- Meat lightness (L*) and yellowness (b*) links to both prevalence and severity of PSE-like zones.

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ABSTRACT

Pale, soft, and exudative (PSE)-like zones in pork is a growing concern, affecting several meat quality attributes as well as production economics. This study investigates the prevalence and severity of PSE-like zones in Swedish commercial crossbred pigs (Yorkshire dam x Hampshire sire), focusing on the effects of the key factors such as season, gender, slaughter weight and technological meat quality traits. A total of 192 pigs were sampled during four seasons (autumn, winter, spring, summer) and assessed for post-slaughter PSE-like zones. Results revealed that season significantly influenced the prevalence of PSE-like zones, with a notably lower prevalence observed in summer compared to other seasons. Gender differences were also significant, with female pigs showing a higher incidence of PSE-like zones compared to immuno-castrated males. Additionally, slaughter weight was significantly associated with the prevalence of PSE-like zones, while the proportion of affected muscle weight notably influenced severity levels. Among technological meat quality traits, lightness (L^*) and yellowness (b^*) showed strong associations with both prevalence and severity, while redness (a^*) demonstrated a significant association solely with severity. Additionally, ultimate temperature (Temp_{24h}) had a significant effect on prevalence of PSE-like zones. These findings underscore the importance of season-specific environmental management and handling practices to minimize the prevalence and severity of PSE-like zones. Future strategies integrating genetic selection, stress reduction measures, and optimized slaughter processes hold potential for improving meat quality outcomes in commercial pork production systems.

1. Introduction

Pale, soft and exudative (PSE)-like zones is a widely discussed quality problem for pork meat. Its incidence has been rising worldwide over time, leading to financial losses due to diminished sliceability of hams. PSE-like zones are mainly found in the deep regions of *Musculus semimembranosus* and *Musculus adductor*, making up a significant portion of the ham (Van de Perre et al., 2010). Several factors including genetics, production systems, environment, and handling of both live animals as well as carcasses can contribute to development of PSE-like zones (Lee and Choi, 1999). Intense genetic selection for fast growth, efficient feed conversion, and high lean meat content (Adzitey and Nurul, 2011)

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increases the proportion of glycolytic white muscle fibres, which are more prone to anaerobic metabolism under stress (Warner et al., 1993). This predisposes pigs to pre-slaughter stress syndrome (PSS) and leads to rapid post-mortem glycolysis (Briskey and Wismer-Pedersen, 1961). The abnormally rapid post-mortem glycolysis results in a quick drop in pH while the carcass is still warm, causing proteins to denature and lose their functionality (Briskey, 1964). This induces paleness, caused by increased light reflectance, exudation or reduced water-holding capacity, meaning a decreased ability to retain water, along with softness from fluid being forced out of myofibrils, which disrupts the connective tissues (Bertram et al., 2001; Offer, 1991). PSE-like zones and classical PSE share many characteristics, yet they differ in their extent and impact. Classical PSE affects the entire carcass, leading to widespread economic losses, whereas PSE-like zones are localized defects, occurring only in deep muscle areas (Schwob et al., 2018). Both conditions are associated with accelerated post-mortem glycolysis, rapid pH decline, protein denaturation, and impaired water-holding capacity (Laville et al., 2005; Minvielle et al., 2001).

Genetic factors in classical PSE, such as the n allele of the RYR1 gene (Halothane gene; hal^n allele) and the RN^- allele of the PRKAG3 gene (Rendement Napole gene; RN^-200Q allele), may still apply in the development of PSE-like zones, depending upon geographical location or breed (Mashood et al., 2023a). The RN^-200Q mutation is found in purebred Hampshire and in Hampshire crosses, whereas another variant of the PRKAG3 gene, the V199I mutation appears to segregate in several breeds including Duroc, Landrace, and Pietrain (Galve et al., 2013; Ramos et al., 2008). In Sweden, Hampshire crosses make up a significant share of the pigs slaughtered for meat production and approximately 65 % of all slaughter pigs sired by Hampshire boars carry the RN^- allele (Josell et al., 2000). Moreover, carcass weight of pigs has gradually increased over time in Sweden following the global pattern (Mashood et al., 2023a). Carcass weight is an important factor affecting pork quality (Kim et al., 2005), extensively associated with the presence of PSE-like zones (Minvielle et al., 2001). Higher carcass weight, with increased muscular mass, may slow down the post-mortem temperature decline. Larger hams, as a result of increased carcass weight, combined with a low post-mortem pH, boosts the incidence of PSE-like zones in the core of the hams (Kurt et al., 2020). Previous research has shown a gender-related influence on the incidence of classical PSE, with male pigs having a 0.5 % higher risk than females (Guàrdia et al., 2004), probably attributed to variations in aggressiveness, energy levels, stress resistance, and recovery capabilities (van der Wal et al., 1999). A recent pilot study also discovered a notable gender difference in the occurrence of PSE-like zones, where female pigs of higher slaughter weights exhibited more of these zones compared to immuno-castrated males (Mashood et al., 2023b). In general, higher environmental temperatures have a detrimental impact on the well-being and meat quality of pigs, with a higher occurrence of PSE during summer than during winter (Guàrdia et al., 2004), as pigs lack functioning sweat glands which makes them more susceptible to high temperatures.

While earlier studies looked at factors influencing PSE-like zones, they did not specifically measure their prevalence (how frequently they occur) or severity (the degree of quality deterioration within affected muscle regions) of PSE-like zones. To assess these features separately, can result in a more complete understanding of PSE-like zones in pork quality studies. Hence, the objective of this study was to introduce a novel approach to assess the prevalence and severity of PSE-like zones in hams of crossbred pigs (Yorkshire dam x Hampshire sire) in Sweden. The study also aimed to examine the impacts of season, gender, and slaughter weight on the occurrence and severity of these zones in Swedish slaughter pigs. In addition technological traits at different time points after slaughter, including early pH (pH_{45min}), ultimate pH (pH_{24h}), early temperature ($Temp_{45min}$), ultimate temperature ($Temp_{24h}$), and colour traits (lightness, redness, and yellowness), were evaluated to assess their relationships with both the prevalence and severity of PSE-like zones.

2. Material and methods

2.1. Animals and seasons

This study involved 192 crossbred pigs (Yorkshire x Hampshire), raised under routine management practices at the Swedish Livestock Research Centre at Swedish University of Agricultural Sciences, Lövsta, Sweden. The Hampshire (sire) semen doses were sourced from Svenska Köttföretagen (Hållsta Seminstation), while the Yorkshire (maternal grandsire) semen doses were obtained from Topigs Norsvin. Sampling of the crossbreds was conducted at the peak of each season (autumn, winter, spring, summer) and each sampling was further divided into two sampling occasions per season, with a one-week in-between, resulting in a total of eight sampling dates. Pigs were selected to be of similar age and comparable final body weight at the time of slaughter. Fifty-five pigs (17 males and 38 females) were slaughtered in October 2023 for the autumn sampling, 48 pigs (24 males and 24 females) in February 2024 for the winter sampling, 44 pigs (22 males and 22 females) in May 2024 for the spring sampling and finally 45 pigs (23 males and 22 females) in July 2024 for the summer sampling. All male pigs used in the experiment were immuno-castrated.

At the Lövsta research station, pigs receive their last meal on the evening before transport to the slaughterhouse. The feeding system operates between 18:00 and 22:00, with feeding times varying slightly depending on the stable. Because transportation always takes place early in the morning, pigs do not receive a morning meal before departure. The transport duration is approximately 15 min, and animal density during transport adheres to Swedish regulatory standards.

2.2. Slaughter conditions

During transportation and at the slaughterhouse resting area, the experimental pigs were kept isolated from other animals to prevent both aggressive behaviour towards other pigs and cross-contamination. All pigs were rested for 2 h under conditions designed to minimize stress, i.e. with free access to water, minimal noise, and limited human interaction. The resting area comprised three pens, each measuring 3.20 m x 1.95 m, with a capacity of 8–9 pigs per pen. This allocation provides approximately 0.75 m^2 per pig, which aligns with recommended welfare standards for finishing pigs in lairage facilities (Council Regulation (EC) No 1099/2009; OIE, 2021).

Slaughter procedures were standardized, with all pigs processed at the same abattoir. Pigs were stunned in pairs in a chamber using a 90–92 % CO_2 gas mixture, with a cycle duration of approximately 2 min, followed by exsanguination within 45 s post-stunning. Carcasses were split in halves approximately 7–8 min post-mortem, following veterinarian inspection, and then placed in a chilling tunnel at 2 °C for around 30 min. After initial chilling, carcasses were stored for approximately 20 h in a cooling area at 0–2 °C before being transported the next morning for de-boning and further processing.

2.3. Data collection

Carcass weights (kg) were recorded on the slaughter line. pH and temperature measurements were taken 45 min post-slaughter (pH_{45min} and $Temp_{45min}$) and after 24 h (pH_{24h} and $Temp_{24h}$) by inserting a Testo-205 probe (Nordtec Instrument AB, Gothenburg, Sweden) into the *semimembranosus* muscle of the ham on the right half of the carcass, accessed from the internal side near the bone. This half was subsequently used for PSE-like zone analysis. After 24 h, all pigs were deboned, and the *semimembranosus* and *adductor* muscles were separated for visual inspection of PSE-like zones. Each muscle sample consisting of the *adductor* and *semimembranosus,* muscles was individually weighed and the proportion of sampled muscle weight relative to the total slaughter weight (percentage of sample per slaughter weight; prsampslwe) was calculated to account for differences in muscle-to-carcass weight ratios across animals. This measure reflects the relative muscularity of the animals, as all muscle samples were collected consistently by trained personnel using a standardized procedure.

Following a 30-minute blooming period, colour properties were measured using a Konica Minolta device (Minolta Chroma Meter CR-300, Tokyo, Japan), with values for lightness (L^*), redness (a^*), and yellowness (b^*) recorded at nine spots on the outer side of the ham sample (Strat and Vautier, 2015) after calibration against a white ceramic cap delivered by the instrument producer (CR-A43). Additionally, three measurements were taken on the inner side of the ham samples, particularly in areas where PSE-like zones were present, typically two on the *semimembranosus* and one on the *adductor* near the joint. The average colour values from areas with PSE-like zones were compared to those from areas without such zones. All samples were weighed, vacuum-packed, and transported at 4 °C for further grading of PSE-like zones.

2.4. Grading of PSE-like zones

A two-cycle grading process was employed for all hams. In the first cycle, conducted 24 h post-slaughter, a panel of three assessors visually analysed and graded the presence of PSE-like zones on the semimembranosus and adductor muscles of ham samples. The same panel conducted the grading across all four seasons and on all slaughter dates to ensure consistency. The grading was based on changes in colour, softness, and exudation, with the presence of PSE-like zones recorded as either 'yes' or 'no'. In the second cycle, 48 h after deboning, a more detailed re-evaluation was performed. During this cycle, all hams were re-analysed for PSE-like zones and further graded using a modification of the IFIP quotation scale (IFIP, 2005). In this modified system, Grade 0 was assigned to ham samples with completely normal muscle structure, showing no signs of PSE-like characteristics. Grade 1 included ham samples with slight colour variations (pale to dark) but a firm, fibrous

Grade Category	Grade	Appearance	Muscle structure	Surface affected	Deep lesions	Images
No (PSE-like zones)	0	Normal	Normal, well-structured muscle fibres	No surface alterations	No deep lesions	
Mild (PSE-like zones)	1	Pale to dark, slight discolouration	Firm, fibrous, but initial signs of softening	Minimal surface irregularities	No deep lesions	
	2	Pale & slightly exudative	Unstructured, Absence of fibrillary structure	Around and between 5-10 cm^2	Surface	
Severe (PSE-like zones)	3	Very pale & viscous exudative	Unstructured, Absence of fibrillary structure, Soft pasty structure	≥ 50% inner surface	< 2cm	
	4	Very pale & viscous exudative	Unstructured, Absence of fibrillary structure, Soft pasty structure	> 50% inner surface	> 2cm	

Fig. 1. Modified grading criteria for PSE-like zones.

texture and no structural degradation. Grades 2 to 4 were grouped to represent increasing severity, with Grades 1 and 2 combined as 'Mild PSE-like zones' and Grades 3 and 4 as 'Severe PSE-like zones'. This approach was adopted to accommodate hams that exhibited characteristics of multiple grades, as not all ham samples displayed all the features associated with a single grade in the original IFIP scale. The introduction of Grade 0 in the modified scale allows for a more sensitive differentiation between truly normal ham samples and those with minor but visible deviations from normal muscle structure. The modified grading is outlined in Fig. 1.

2.5. Statistical analysis

The statistical analysis was conducted to investigate how various factors are effect the prevalence and severity of PSE-like zones in crossbred pigs (Yorkshire x Hampshire). The statistical models were developed stepwise forward including two and three way interactions. Final models were set based on significance level and biological relevance.

The effect of season, gender, slaughter weight and sample weight on prevalence of PSE (0 = no PSE-like zones, 1 = PSE-like zones including both mild and severe cases, $N = 192$) was analysed using a generalized linear mixed model (GLMM) in PROC GLIMMIX procedure in SAS 9.4 (SAS institute, Inc. Cory, NC), with a binomial distribution and a logit link function (model 1). The severity of PSE-like zones (1 = mild, 2 = severe, $N = 105$) was analysed with the same model (model 1). Additionally, associations between prevalence and severity of

PSE-like zones and technological meat quality traits (pH, temperature, colour readings) were analysed for one meat quality trait at the time with a univariate model (model 2). The final models used were specified as:

Model 1: $Y_{ijkm} = \mu + S_i + G_j + b_1 \text{ x } SW_k + b_2 \text{ x } Prsampslwe_k + b_3 \text{ x } Prsampslwe_k(G_j) + e_{ijkm}$

Model 2: $\mathrm{Y_{ijkm}} = \mu + \mathrm{b_4 \text{ x } Q_k} + \mathrm{e_{ijkm}}$

Where Y_{ijkm} is the response variable (prevalence or severity of PSE-like zones, both binary i.e. o or 1); μ is the overall mean; S_i is the fixed effect of season (i= 1,2,3,4); G_j is the fixed effect of gender (j = female or male); SW_k is the slaughter weight in kg and b_1 is the coefficient for linear regression on slaughter weight; $prsampslwe_k$ is the percentage of sample per slaughter weight and b_2 is the coefficient for linear regression on prsampslwe; b_3 is the coefficient for linear regression on prsampslwe nested within gender; Q_k is a meat quality trait (either pH, temperature or colour readings) and b_4 is the coefficient for linear regression on meat quality, and e_{ijkm} is the random residual.

Statistical significance was set at $p \leq 0.05$ for all tests.

3. Results

3.1. Effect of season

A significant effect of season on the prevalence of PSE-like zones was observed ($p = 0.031$). Pairwise comparisons revealed that the prevalence of PSE-like zones in summer was significantly lower compared to in the autumn ($p = 0.008$), winter ($p = 0.023$), and spring ($p = 0.014$) as seen in Fig. 2a. There was no significant effect of season on the severity (mild or severe) of PSE-like zones, indicating consistent severity patterns across all seasons (Fig. 2b).

The descriptive Fig. 3 presents the seasonal variations in the presence of PSE-like zones in the data, including both mild and severe cases. The combined percentage of individuals with mild or severe PSE-like zones was highest in autumn (61.8 %), followed by winter (58.3 %), and spring (59.1 %). Summer had the lowest combined percentage at 37.8 %. Overall, 45.3 % of pigs were unaffected by PSE-like zones, while 54.7 % exhibited some degree of PSE-like zones, with the majority being mild cases (37.0 % of all pigs), as shown in Fig. 3.

3.2. Effect of gender

The descriptive Fig. 3 illustrates that the percentage of individuals classified as normal was higher among male pigs (53.5 %) compared to females (38.7 %). The prevalence of PSE-like zones was significantly influenced by gender ($p = 0.020$), as demonstrated in Fig. 4a. Specifically, females exhibited a higher likelihood of developing these zones compared to immuno-castrated males, with a p-value of 0.047. However, gender did not have a significant effect on severity levels among affected pigs (Fig. 4b).

3.3. Effect of slaughter weight and proportion of affected muscle

Slaughter weight was significantly influenced the prevalence of PSE-like zones ($p = 0.041$) but had no significant effect on severity ($p = 0.134$). The percentage of the sample weight relative to slaughter weight

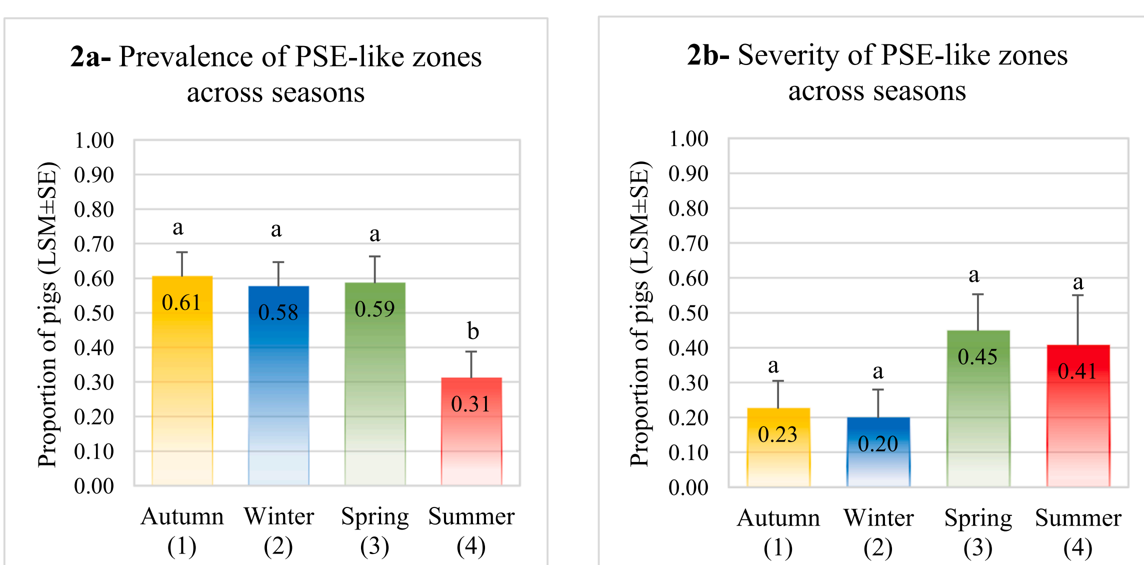

Fig. 2. Estimated least squares mean (LSM) for proportion of all crossbred pigs (Yorkshire x Hampshire) with any PSE-like zones regardless of severity is shown for each season in 4a ($N = 192$), and the LSM for proportion of severe cases among crossbred pigs with PSE-like zones is shown per season in 4b ($N = 105$).

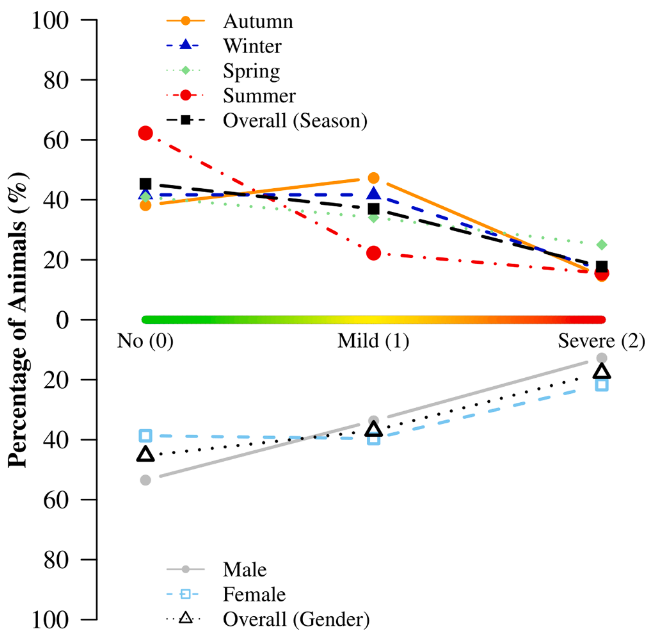

Fig. 3. Seasonal and Gender Variations in PSE-Like Zones in crossbred pigs (Yorkshire x Hampshire): A Descriptive Overview of No (0), Mild (1), and Severe Levels (2).

(prsamplswe) did not influence the presence of PSE-like zones ($p = 0.239$) but had a highly significant effect on severity levels among the affected pigs ($p = 0.004$). Additionally, a significant interaction was observed between prsampslwe and gender for the prevalence of PSE-like zones ($p = 0.012$), indicating that the relationship between prsampslwe and PSE-like zones prevalence differs between genders. However, this interaction was not significant for severity ($p = 0.855$) (Table 1).

3.4. Technological meat characteristics

There was no significant effect of early pH (pH_{45min}), ultimate pH (pH_{24h}), or early temperature ($Temp_{45min}$) on the prevalence or severity of PSE-like zones. However, ultimate temperature ($Temp_{24h}$) significantly affected prevalence ($p = 0.021$), though it did not influence severity of PSE-like zones as shown in Table 2.

Among the colour traits, lightness (L*) and yellowness (b*) were significantly associated with both prevalence ($p < 0.0001$) and severity ($p = 0.015$ and $p = 0.008$) respectively. Additionally, redness values (a*) were significantly associated ($p = 0.007$) with severity (Table 2).

4. Discussion

We found a significant effect of season on the prevalence of PSE-like zones, with pigs slaughtered in the summer showing fewer PSE-like zones compared to other seasons. These results are consistent with previous findings, as a 15-month survey period for meat quality distribution clearly showed that the presence of PSE was much lower in the summer months (O'Neill et al., 2003). Similarly, Van de Perre et al. (2010) reported much lower prevalence of PSE in summer compared to winter. However, a previous study showed higher incidence of PSE in summer (Guàrdia et al., 2004), but this study was conducted in Catalonia, Spain, where summer conditions are significantly hotter compared to Sweden. Given that pigs lack functional sweat glands, heat stress in warmer climates may increase their physiological stress response, potentially leading to higher PSE incidence.

In our study, despite consistent transportation times of approximately 15 min and uniform resting conditions across all four seasons (2 h in a well-ventilated, spacious, quiet environment with minimal human interaction), the lower occurrence of PSE-like zones in summer might be explained by the relatively moderate early morning temperatures (not overly hot), which likely prevented excessive heat stress while keeping pigs comfortable during transport and resting. The average

Table 1
Effect of slaughter weight and percentage of the sample weight relative to slaughter weight, and its interaction with gender on prevalence and severity of PSE-like zones in crossbred pigs (Yorkshire x Hampshire).

Factors	Prevalence		Severity	
	Estimate ± S.E	*p*-value	Estimate ± S.E	*p*-value
Slaughter weight	0.059 ± 0.029	**0.041**	0.060 ± 0.040	0.134
prsampslwe	4.388 ± 1.628	0.239	5.533 ± 2.180	**0.004**
prsampslwe*gender	−5.966 ± 2.346	**0.012**	0.666 ± 3.630	0.855

prsampslwe = percentage of the sample weight relative to slaughter weight; Estimate = *b*-value estimate; *S.E* = standard error; Significant ($p = \leq 0.05$) values in bold.

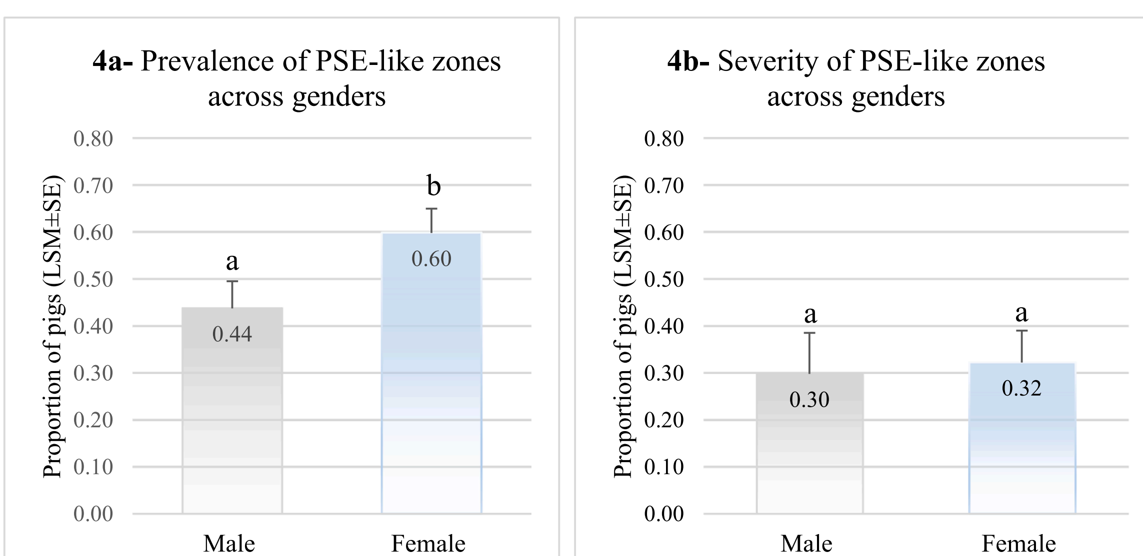

Fig. 4. Estimated least squares mean (LSM) for proportion of all crossbred pigs (Yorkshire x Hampshire) with any PSE-like zones regardless of severity is shown for each gender in 4a ($N = 192$), and the LSM for proportion of severe cases among crossbred pigs with PSE-like zones is shown per gender in 4b ($N = 105$).

Table 2
Effect of technological meat characteristics on prevalence and severity of PSE-like zones in crossbred pigs (Yorkshire x Hampshire).

Factors	Overall Mean ± S.D	Prevalence		Severity	
		Estimate ± S.E	*p*-value	Estimate ± S.E	*p*-value
pH_{45min}	6.517 ±0.178	0.250 ± 0.816	0.759	−1.680 ± 1.210	0.168
pH_{24h}	5.674 ± 0.232	−0.900 ± 0.633	0.157	−1.160 ± 1.952	0.226
$Temp_{45min}$	39.15 ± 0.845	0.195 ± 0.179	0.278	0.491 ± 0.325	0.134
$Temp_{24h}$	4.727 ± 1.129	0.309 ± 0.133	**0.021**	0.009 ± 0.184	0.961
Lightness (L^*)	50.50 ± 5.427	1.492 ± 0.313	**<0.0001**	0.185 ± 0.075	**0.015**
Redness (a^*)	2.343 ± 1.143	−0.008 ± 0.127	0.950	0.498 ± 0.180	**0.007**
Yellowness (b^*)	11.95 ± 2.226	1.890 ± 0.292	**<0.0001**	0.387 ± 0.145	**0.008**

Estimate = *b*-value estimate; *S.D*= standard deviation; *S.E* = standard error; Significant ($p = \leq 0.05$) values in bold.

temperatures during the sampling months in Uppsala, Sweden, where the experiments were conducted, were as follows: 2.89–8.60 °C in autumn (October) with 83.48 % humidity, −2.81 to 1.59 °C in winter (February) with 88.53 % humidity, 7.86–20.65 °C in spring (May) with 59.16 % humidity, and 14.22–22.28 °C in summer (July) with 76.62 % humidity (SMHI, 2025). Although pigs are generally more adapted to cooler temperatures, exposure to sudden drops in temperature, cold drafts, or high humidity during transport and resting may have contributed to greater physiological stress responses in the colder seasons. Cold stress, particularly in winter, is known to elevate cortisol levels, leading to increased glycolysis and a rapid post-mortem pH decline in muscles, a hallmark of PSE meat (Fujii et al., 1991). Additionally, fluctuating ambient temperatures and humidity levels in autumn and spring may have increased pigs' vulnerability to stress, potentially triggering aggressive behaviours and transport stress, as observed in previous studies (Čobanović et al., 2021, 2020). During our sampling periods, temperatures ranges were 2.89–8.60 °C in autumn and 7.86–20.65 °C in spring. While these temperatures were not as extreme as in winter, sudden fluctuations in ambient conditions, combined with humidity changes, may have contributed to physiological stress responses. Cold exposure is well-documented to increase metabolic stress, particularly when combined with transport conditions (Čobanović et al., 2021; Fujii et al., 1991). However, we acknowledge that further research would be necessary to confirm whether these seasonal effects fully mimic winter stress responses. Despite our efforts to maintain standardized handling conditions, these seasonal variations in environmental stressors likely influenced the observed prevalence of PSE-like zones.

Based on our observations of the pigs involved in this study, which were transported for only 15 m15 minpeared to engage in prolonged fighting behaviour upon arrival at the slaughterhouse, compared to what is generally reported for pigs transported over longer distances. This suggests that the short transportation time may have left them with sufficient energy to engage in such behaviours before calming down. This difference in behaviour could potentially influence stress levels and consequently, the development of PSE-like zones. Studies have indicated that short transport durations can lead to increased stress responses in pigs, as they may not have sufficient time to recover from the initial stress of loading and unloading, potentially exacerbating aggressive behaviours upon arrival at the slaughterhouse (Rioja-Lang et al., 2019).

There was a significant effect of gender on the prevalence of PSE-like zones, where female pigs were more prone to develop PSE-like zones than immuno-castrated males. However, there was no effect of gender on the severity of PSE-like zones. Our findings are in accordance with a pilot study, where female pigs with higher average slaughter weight compared to immuno-castrated males developed more PSE-like zones than the males (Mashood et al., 2023b). This difference may be attributed to muscle fibre composition and post-mortem glycolysis, which are key factors in PSE-like zone development. Some studies suggest that gender may influence muscle fibre composition, with differences observed in fibre diameter, total fibre number, and metabolic properties (Haizlip et al., 2015; Okrouhlá et al., 2014). Hormonal differences between females and immuno-castrated males are crucial in determining meat quality and susceptibility to PSE-like zones. Immuno-castration leads to a significant reduction in testosterone levels and its derivatives, stabilizing metabolic activity (Škrlep et al., 2010). As a result, immuno-castrated males exhibit altered hormone profiles and reduced stress levels, which contribute to slower rates of glycogen depletion (Pauly et al., 2009). This stabilization can mitigate the rapid pH decline often associated with PSE-like zones. Additionally, female pigs typically have higher levels of estrogen, which influences muscle metabolism by enhancing glycolytic enzyme activity (Dunshea et al., 2013; Rosenvold and Andersen, 2003). This increase in glycolytic activity leads to a faster post-mortem pH decline (Lebret, 2008), making female pigs more susceptible to developing PSE-like zones compared to immuno-castrated males.

In our study, there was a significant effect of slaughter weight on the prevalence of PSE-like zones, which is in accordance with previous findings of Franck et al. (1999) that reported that the development of PSE-like zones is extensively associated with higher slaughter weights. Several other studies reported that pigs with heavier carcass weight show higher incidence of PSE-like zones (Djordjevi et al., 2016; Mashood et al., 2023b). Sweden is following the global trend of increasing slaughter weight over time, from 84.5 kg in the year 2000 to 92.0 kg in 2022 (Mashood et al., 2023a). A higher slaughter weight and higher muscular mass might have slowed down the post-mortem temperature decline particularly in larger hams compared to in smaller hams. Oksbjerg et al. (2000) found that higher slaughter weight led to slower cooling rates, causing elevated muscle temperatures, which, combined with rapid pH decline, increased the likelihood of PSE meat. Kurt et al. (2020) stated that any further increase in slaughter weight would lead to even larger hams and continue to boost the incidence of PSE-like zones in the core of hams. Some studies also found a relationship between stress and higher carcass weights, and that pigs with higher carcass weight displayed more pronounced meat quality defects due to stress related metabolic changes (Channon et al., 2000). However, our findings did not show a significant effect of slaughter weight on the severity of PSE-like zones. This suggests that while heavier pigs are more likely to develop PSE-like zones, the extent or intensity of these zones is not necessarily greater in heavier animals. This distinction between prevalence and severity indicates that factors other than slaughter weight, such as genetic predisposition, pre-slaughter handling, and environmental conditions, may play more critical roles in determining the severity of PSE-like zones.

We also found significant relationship between the proportion of the sample over slaughter weight (prsampslwe) and the severity of PSE-like zones. This indicates that pigs with a higher proportion of their muscle mass of *semimembranosus* and *adductor* relative to their slaughter weight are more likely to exhibit severe PSE-like zones. Pigs with excessive weight gain or fat deposition often display altered muscle fibre composition, characterized by a higher proportion of fast-twitch glycolytic fibres, which are more susceptible to rapid pH decline and the resulting in PSE-like conditions (Warner et al., 1997). Additionally, heavier pigs tend to have a higher prevalence and severity of meat quality defects, including PSE, likely due to metabolic stress and changes in muscle biochemistry associated with larger muscle mass (Warriss, 2000). Moreover, the highly significant interaction between prsampslwe and gender suggests that the relationship between the proportion of the sample over slaughter weight and the prevalence of PSE-like zones differs between male and female pigs. This could be attributed to gender-specific differences in growth patterns, muscle composition, or stress response. This physiological divergence may influence how muscle tissues respond to stress during slaughter, contributing to the observed interaction effect on PSE-like zones prevalence (Mashood et al., 2023b; Škrlep et al., 2010).

There was significant effect of ultimate temperature ($Temp_{24h}$) on prevalence of PSE-like zones, suggesting potential inefficiencies in the chilling procedures at the slaughterhouse. In our study, operational inconsistencies, such as loading and transporting carcasses from the slaughterhouse to the cutting plant, may have slowed the chilling process in certain carcass regions, resulting in higher ultimate temperatures. The rate of post-slaughter carcass chilling is a critical factor in meat quality and can significantly impact PSE-like zones development in commercial pork, with slow chilling increasing PSE-like zones in hams more than threefold (Vautier et al., 2010). Rosenvold and Andersen (2003) also observed that the combination of high temperature and low pH creates ideal conditions for the prevalence of PSE-like zones. By contrast, a faster carcass chilling rate, coupled with a gradual post-mortem pH decline, can reduce PSE-like zones incidence (Kurt et al., 2020). In PSE meat, high temperature and low pH cause protein denaturation, reducing water-holding capacity (WHC) as myofibrillar components expel fluid into extracellular spaces, giving the meat a characteristic exudative quality (Adzitey and Nurul, 2011). Shrinkage in the myofilament lattice increases light reflection, making PSE meat appear less red and more yellow (Warriss, 2000). In our study, ultimate temperature did not significantly affect the severity levels of PSE-like zones. We believe that an inefficient chilling process may have exposed more areas of the carcass to a combination of high temperature and low pH, thereby increasing the number of zones affected (prevalence). However, once the protein denaturation threshold was reached, additional exposure to high temperature likely did not increase PSE-like zones severity, as the primary protein denaturation had already occurred.

Finally, our findings confirmed that lightness (L^*) and yellowness (b^*) were significantly associated with both the prevalence and severity of PSE-like zones, reinforcing their critical role in identifying and characterizing these zones. While, redness (a^*) had a significant association solely with severity of PSE-like zones, highlighting its distinct role in PSE meat quality assessment. These results highlight the strong relationship between colour metrics and PSE-like zones, which is closely linked to structural and biochemical changes in muscle fibres. Increased lightness (L^*) and yellowness (b^*) values in PSE-like zones are well-documented characteristics of PSE meat, primarily driven by protein denaturation, fluid loss, and reduced water-holding capacity (Adzitey and Nurul, 2011; Joo et al., 1999; Rosenvold and Andersen, 2003; Sayre and Briskey, 1963). Both lightness and yellowness have been shown to correlate significantly with PSE-like zones, as structural changes in muscle proteins lead to enhanced light reflectance, giving affected meat a paler and yellower appearance (Rosenvold and Andersen, 2003; Vautier et al., 2010). While lightness is often considered the primary indicator of PSE, however yellowness appears to have a stronger association with both prevalence and severity, likely due to its close link with protein denaturation and fluid expulsion, which further contribute to the exudative texture of PSE meat (Adzitey and Nurul, 2011). Numerous studies have confirmed that PSE meat exhibits significantly higher lightness and yellowness values compared to normal meat, with the reasoning being that rapid post-mortem pH decline leads to changes in myofibrillar protein structure, altering light scattering properties (Joo et al., 1999; Rosenvold and Andersen, 2003). Additionally, fluid expulsion during protein denaturation contributes to these changes, exacerbating the exudative appearance of PSE meat. Vautier et al. (2010) demonstrated that high lightness values in PSE samples are reliable markers for detecting PSE meat in commercial meat processing systems, reinforcing the value of objective colour measurements in quality control. In contrast, redness (a^*) primarily reflects the extent of PSE severity rather than its occurrence, likely due to changes in myoglobin oxidation and muscle structure during protein denaturation (Adzitey and Nurul, 2011). These findings underscore the relevance of lightness (L^*) and yellowness (b^*) as reliable indicators for detecting and characterizing PSE-like zones in commercial pork processing systems. Although water losses were not measured in this study due to the challenge of obtaining a representative sample from PSE-like zones, particularly in mild cases where affected areas can be thin or of very low weight. Future research could explore the relationship between water-holding capacity and the severity of PSE-like zones. Such studies could provide additional insights into the extent of protein denaturation and fluid loss in different grades of PSE-like zones, further refining meat quality assessments.

Overall, we found significant effects of season, gender, and slaughter weight on the prevalence and severity levels of PSE-like zones. Additionally, certain technological traits were significantly associated with the prevalence and severity of these zones, reflecting the structural and biochemical changes in the muscle caused by PSE-like zones. However, these factors may be significantly influenced by the genetic profile of the crossbred pigs (Yorkshire x Hampshire) used in this study, particularly since a substantial portion of slaughter pigs in Sweden with Hampshire lineage are carriers of the RN^- (200Q) allele of the PRKAG3 gene (Josell et al., 2000). Future research should focus on measuring cortisol levels or tracking ambient temperatures with greater precision to better understand the seasonal stress impact on PSE-like zones incidence. A Genome-Wide Association Study (GWAS) would be valuable for trying to identify genomic regions associated with the trait, which could give valuable insights to the mechanisms underlying PSE-like zones. These findings suggest that to minimize the risk of PSE-like zones, producers may need to adapt their handling and environmental management practices seasonally, particularly during colder months.

5. Conclusion

This study highlights factors influencing the prevalence and severity of PSE-like zones in crossbred pigs, particularly focusing on seasonal variation, gender, slaughter weight, and technological traits. Our findings reveal that summer conditions in a Nordic climate are associated with a reduced occurrence of PSE-like zones, likely due to milder temperatures during early morning transport and resting periods, which contribute to lower stress levels. Gender differences also play a significant role, with female pigs displaying a greater susceptibility to PSE-like zones compared to immuno-castrated males, which can be attributed to hormonal influences and muscle fibre composition. Moreover, the impact of slaughter weight on PSE-like zones prevalence underscores the need for careful management practices in the context of increasing market trends towards heavier pigs.

CRediT authorship contribution statement

Qasim Mashood: Writing – original draft, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anna Wallenbeck:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Susanne Eriksson:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Anna M. Johansson:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Anders H. Karlsson:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Katarina Arvidsson Segerkvist:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declared no conflict of interest.

Ethics approval

This study did not require official national or institutional ethical approval.

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