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Risk factors and prevalence of carcass lesions associated with pre-slaughter logistics and ultimate meat pH in finishing pigs under mountainous tropical conditions

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ABSTRACT

Globally, the pre-slaughter logistics chain in the pork industry must meet commercial demands while operating through interconnected nodes, from the farm of origin to transport and abattoir operations. The present study evaluated 1841 carcasses of finishing pigs at abattoir level, assessing six anatomical regions for skin lesions, tail injuries and claw cracks, along with ultimate pH and detailed pre-slaughter logistics. Skin lesions were highly prevalent, exceeding 97% of carcasses, with severe damage in 8% and consistent patterns in the neck–shoulder, flank and loin regions. Multivariate models showed that lesion risk depended on the production system, road quality, journey dynamics and lairage duration. Tail lesions were rare (<10%), while claw cracks (~20%) were associated with farm size, carcass weight and transport conditions. Meat quality was strongly influenced by logistics, with 7% of carcasses classified as PSE, 27% as DFD and 34% as borderline DFD. DFD was related to long and fast journeys on paved mountain routes, whereas PSE was linked to injuries in the head–ear region. Overall, carcass-based indicators provided an integrated retrospective assessment of welfare in tropical mountain systems, where transport demands and infrastructure variability influence both welfare and meat quality.

1. Introduction

The welfare of pigs throughout the different nodes of the pork production chain is currently understood as a multidimensional concept. This integrates health, ethical, commercial, and regulatory aspects, as well as its demonstrated influence on consumer trust, food safety, and the quality of meat and its by-products (Schrøder-Petersen et al., 2025). In this sense, lesions to carcasses, such as those affecting the skin, tail, and claws of pigs, are of concern not only from ethical and food safety perspectives, but also due to the pain, anxiety and suffering they cause by virtue of tissue damage that triggers an inflammatory response, an accentuated stress reaction, and affects meat quality (Kschonek et al., 2025). The increase in these lesions is primarily associated with social mixing, rough handling, high stocking densities, and inadequate housing and transport conditions (Čobanović et al., 2025). Furthermore, these lesions have been shown to serve as early and easily identifiable indicators of deficiencies in supervision, and welfare control practices throughout the various stages of the production process (Teixeira & Boyle, 2014; Van Staaveren et al., 2015).

Consequently, the incorporation of carcass lesions into the protocols for animal welfare assessment and monitoring at the abattoir is imperative, as they are regarded as "iceberg indicators" that offer valuable insights into potential animal welfare issues originating from the rearing phase on the farm and extending to the pre-slaughter conditions (Huanca-Marca et al., 2025). In this context, one of the most strategic stages for the meat industry is the pre-slaughter logistics chain, which includes the selection of animals on the farm, fasting, handling, loading, transport, unloading, lairage, and finally, the humane slaughter at an authorized abattoir (Miranda-de La Lama et al., 2018). Nonetheless, despite the fact that such logistics chains are generally distinguished by elevated levels of planning, contemporary infrastructure, and synchronisation among the implicated parties (Ljungberg et al., 2007), their effect on animals is contingent on the production context and the geographical, climatic, and operational conditions particular to each region or country (Huanca-Marca, Estévez-Moreno, Pastrana-Camacho, et al., 2025).

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Colombia poses significant logistical challenges for pig production and pre-slaughter operations, attributable to the nation's complex geography and tropical climate. The Colombian territory is traversed by three Andean Mountain ranges (Western, Central, and Eastern) that divide the country into a series of inter-Andean valleys, mountains, and high plateaus, generating significant variations in altitude, relief, and climatic conditions throughout the national territory (Rodríguez-Realpe, 2024). This is of particular significance given that national pig production is concentrated in the inter-Andean valleys and foothill zones, where intensive breeding and fattening systems are located, while industrial abattoirs are usually found in cities situated at higher altitudes (Trujillo-Díaz et al., 2021). Consequently, pigs are transported along roads with fluctuating slopes, sharp curves, and alternating unpaved and paved sections. Under such conditions, there is a greater likelihood of longer journey times and sudden temperature fluctuations. These can cause bodily injury, leading to stress, pain, and suffering, as well as decreasing meat quality (Paranhos da Costa et al., 2024).

Pre-slaughter stress has the potential to compromise both animal welfare and meat quality, with its effects being reflected in carcass lesions and post-mortem muscle metabolism (Ferguson & Warner, 2008). Pale, soft, and exudative (PSE) meat is associated with acute stress shortly before slaughter, as well as with genetic factors that accelerate post-mortem glycolysis. This process leads to a rapid decline in muscle pH while the carcass is still warm, resulting in protein denaturation and reduced water-holding capacity (Mashood et al., 2025). In contrast, prolonged exposure to stressors throughout the pre-slaughter logistics chain can result in dark, firm, and dry (DFD) meat, due to the depletion of muscle glycogen reserves and reduced lactic acid production, which leads to a higher ultimate meat pH (Guàrdia et al., 2005). Carcass lesions, have been proposed as retrospective or iceberg indicators of welfare impairment and may therefore provide complementary information to ultimate meat pH regarding the pre-slaughter stress. Despite the relevance of these interactions, studies linking carcass lesions, pre-slaughter logistics and meat quality under tropical conditions with complex topography remain scarce. Therefore, this study aimed to evaluate the risk factors and prevalence for carcass lesions (including tail, claw, and skin lesions, such as bruises and scratches) in finishing pigs and analyse their association with pre-slaughter logistics and ultimate meat pH under tropical mountainous conditions in Colombia.

2. Materials and methods

The present study was conducted from March to June 2022 at a pig abattoir located in the municipality of Santuario, Risaralda, Colombia (4°99′69″ N, 75°90′70″ W; 1516 m a.s.l.). The region's climate is classified as temperate, ranging from semi-humid to humid, with an average annual temperature of 20 °C and an annual precipitation between 2000 and 2500 mm, according to the Colombian Institute of Hydrology, Meteorology and Environmental Studies (Instituto de Hidrología, 2025). The abattoir is officially authorized to operate at the national level by the National Institute for Food and Drug Surveillance (Invima, by its Spanish acronym) and is regulated under Decree 1500 of 2007, issued by the Colombian Ministry of Social Protection (MPS). The geographical location of the establishment renders it an ideal site for the processing of pigs from the central-western region of Colombia. Data collection was conducted through direct observation under commercial operating conditions. The study adhered to principles of scientific integrity, with no use of live animals and no involvement in the slaughter process. Carcasses were subjected to a thorough assessment, and pH measurements were taken in accordance with the personnel flow requirements stipulated in Resolution 240 of 2013, issued by the Colombian Ministry of Health and Social Protection (MSPS).

2.1. Study description

A total of 1841 finishing pigs, with a mean weight of 90–140 kg, were selected for the study. These pigs originated from fourteen intensive farms that were operating under a continuous-flow system, with two or three production cycles. The farms under scrutiny in this study maintained breeding inventories of 100–600 sows and total herd inventories of 700–9000 finishing pigs. The animals used in this study were commercial Landrace × Large White crosses, with a sex distribution of approximately 59.6% castrated males (98% immunocastrated and 2% surgically castrated) and 40.4% females. From the perspective of the pre-slaughter logistics chain, the operations in our study comprise three main nodes: the origin node (farm of origin and truck specifications), the intermediate node (journeys), and the destination node (abattoir). Independent variables describing these three nodes are summarized in Table 1; data were obtained from abattoir and farm records, direct observation at the abattoir, and online mapping and GIS tools, and are described in detail in the following sections.

2.1.1. Origin node: Farm of origin and truck specifications

According to the available records, all farms from which the evaluated animals originated had loading docks, and 57.1% also had holding pens for separating animals before loading. All farms implemented a feed withdrawal period prior to loading; however, detailed information on fasting duration before transport was not available at farm level. All finished pigs included in this study were transported using three types of commercial vehicles: medium-sized trucks (two-axle), known locally as "turbo trucks," with a load capacity of 4 to 5 metric tons (30% of the animals in the study), large-trucks (three-axle) with a load capacity of 8–10 metric tons (55% of the animals in the study), and tractor-truck (three or fourth-axles) and a load capacity of approximately 20 metric tons (15% of the animals assessed). All vehicles used for transportation were equipped with two non-slip aluminium loading floors, thereby reducing the risk of slippage. Additionally, they were fitted with roofs to safeguard animals from inclement weather conditions, and metal side rails were incorporated to facilitate adequate ventilation. The compartmentalisation of large-trucks and tractor-trucks on each floor was implemented for the purpose of physically separating groups of pigs. It was exclusively the tractor-trucks that were equipped with drinking troughs to provide water during transport. According to existing guidelines, the number of pigs transported per vehicle varies by truck

Table 1
Distribution of farm-level, journey-related, and abattoir-level variables included in the study.

Variable	%	Variable	%
Origin node: Farm of origin and truck specifications		Intermediate node: Journey	
Sex[1]		Journey type (distance[4] - time[3])	
Female	40.4	Short-fast	42.1
Male	59.6	Long-fast	28.3
Farm size (fattening pigs)[2]		Long-slow	29.6
>4000	21.5	Journey conditions (% paved road - altitudinal range)[4]	
3000–4000	29.0	>90% P – F	51.4
700- < 1200	49.5	<90% P-F	21.1
Production system type[2]		>90% P-H	14.7
Finishing	55.8	<90% P-H	12.9
Farrow to finish	44.2	Destination node: Abattoir	
Holding pen[2]		Lairage time[3]	
No	42.9	<10 h	29.2
Yes	57.1	10–14 h	25.2
Vehicle type[3]		>14–16 h	17.9
Medium-truck	29.5	>16 h	27.6
Large-truck	57.1	Hot carcass weight (kg)[3]	
Tractor-truck	13.3	62–95.3	33.4
Intermediate node: Journey		95.4–104.3	33.4
Vehicle loading density[3]		104.4–129.0	33.2
Within vehicle capacity	63.1		
Overloaded	36.9		

Data obtained from [1] direct observation during the study, [2] farm records (Porkcolombia), [3] slaughterhouse records, and [4] online mapping and GIS tools.

type (Resolution 6915 [Ministerio de Transporte. MT, 2022]), with reference ranges of 50–54 pigs for medium-trucks, 57–63 pigs for large-trucks, and 61–67 pigs for tractor-truck. Based on these reference ranges, the slaughterhouse classified journeys according to whether the number of pigs transported exceeded the recommended values, with 36.9% of the animals being transported in overloaded vehicles upon arrival at the abattoir. Direct measures of transport density (e.g. animals per unit area or live weight per unit area) were not available.

2.1.2. Intermediate node: Journeys

The animals evaluated in this study were transported in a total of 50 journeys from the farms to the abattoir. As indicated by the records maintained by the abattoir, journey duration was initially recorded in four time categories and subsequently grouped into two distinct categories for analytical purposes, reflecting the range of transport times observed under the commercial conditions of the study. Journeys were classified as short (30–90 min, representing 70.4% of animals) or long (90–150 min, representing 29.6% of animals). For each transport journey, the route from farm to abattoir was digitised in Google Earth Pro to obtain total distance and the maximum and minimum elevations along the path (elevation profile tool). The KML/KMZ files were imported into QGIS and then intersected with the national road network, which had previously been obtained from the "Roads of Colombia" dataset published by the *Instituto Geográfico Agustín Codazzi* (Instituto Geográfico Agustín Codazzi. IGAC, 2023). This process enabled the calculation of the proportion of paved road segments. The distances traversed by the trucks in this study ranged from 23 to 78 km, and these journeys were categorized into two distinct groups: short journeys (20–50 km; 42.1%) and long journeys (>50–80 km; 57.9%). During the transportation process, the maximum altitude recorded was 2065 M.a.s.l., with the minimum altitude being 895 M.a.s.l. The altitudinal range per journey (maximum–minimum elevation) was utilised to categorise the routes as either hilly (600–1200 m elevation difference; 27.5% of animals) or flat (<400 m; 72.5% of animals). With respect to the road surface, 66.1% of the animals were transported on routes where more than 90% of the distance was paved, while the remaining 33.9% journeyed on routes with less than 90% paved surface. Journey-related continuous variables derived from spatial analysis were categorized to facilitate interpretation of their associations with carcass-based welfare indicators. Categories were defined based on the distribution and structure of the observed data and on operationally relevant contrasts, while avoiding sparsely populated groups.

2.1.3. Destination node: Abattoir

The abattoir where the study was conducted operated from Monday to Saturday (08:00–16:00) with a monthly processing capacity of about 10,000 pigs. The unloading, herding, and handling of live animals were standardized and carried out by the same abattoir-workers throughout the sampling period, using auditory herding tools (plastic bottles partially filled with stones). Animals were unloaded by positioning each transport vehicle at an adjustable platform in the reception area, adjusted to match the height of the animal deck. Two abattoir-workers systematically unloaded pigs from the upper deck first and herded them to the weighbridge using the previously described handling tools. After unloading, pigs were identified with a consecutive batch number per transport journey using a tattoo hammer and weighed in groups of 15 animals. Each group was then herded to its designated pre-slaughter lairage pen.

Pigs remained in the pre-slaughter holding pens for a variable period depending on the slaughter schedule and the availability of refrigerated storage rooms, which comprised seven units with a combined capacity of 580 carcasses. Lairage time was recorded at the batch level and was therefore consistent for all animals within the same journey. To facilitate the description and subsequent analysis of this variability under commercial conditions, lairage duration was summarized into four time categories reflecting the distribution of the observed data. Animals from different journeys were never mixed during lairage. Overall, 29.2% of pigs spent less than 10 h in lairage before slaughter, 25.2% spent 10–14 h, 17.9% spent 14–16 h, and 27.6% spent more than 16 h. After this period, pigs were herded toward the exit gate using the same handling tools and moved in groups of 5–10 through the stunning chute leading to the stunning area. At the end of the chute, pigs were sprayed with water to remove dirt and prepare the skin surface before entering the slaughter floor. The slaughter process included two-point electrical stunning, vertical exsanguination, scalding, dehairing, evisceration, carcass weighing, backfat thickness measurement, carcass washing and disinfection, followed by chilling and storage in refrigerated rooms.

2.2. Carcass lesions assessment

Carcass assessment was performed in the weighing area. Each carcass was visually assessed and divided into six anatomical regions: R1: Head–ears; R2: Neck–shoulders; R3: Flanks; R4: Loin; R5: Ham; and R6: Legs (Fig. 1). Skin lesions (scratches and bruises) were evaluated in each anatomical region according to its severity level. Scratches were defined as marks or wounds on the skin, subcutaneous tissue, or muscle caused by the disruption of blood vessels via abrasion by contact surfaces. Damage caused by scratches in each anatomical region was classified into three levels of severity: None = no visible marks on the skin or only minor scratches less than 2 cm in length; Moderate = scratches longer than 2 cm that did not penetrate muscle tissue; and Severe = scratches longer than 2 cm that penetrated muscle tissue (adapted from Teixeira & Boyle, 2014; Carroll et al., 2018). Bruises were defined as injuries beneath the epidermis caused by blunt trauma, characterized by extravascular accumulation of erythrocytes in a localized area with palpable inflammation (Harris & Flaherty, 2010; Miranda-de la Lama, 2024). Bruises in each anatomical region were classified into four levels of severity: None = no visible bruises; Mild = bruises less than 10 cm in length or diameter; Moderate = bruises 10 to 20 cm in length or diameter; and Severe = bruises more than 20 cm in length or diameter

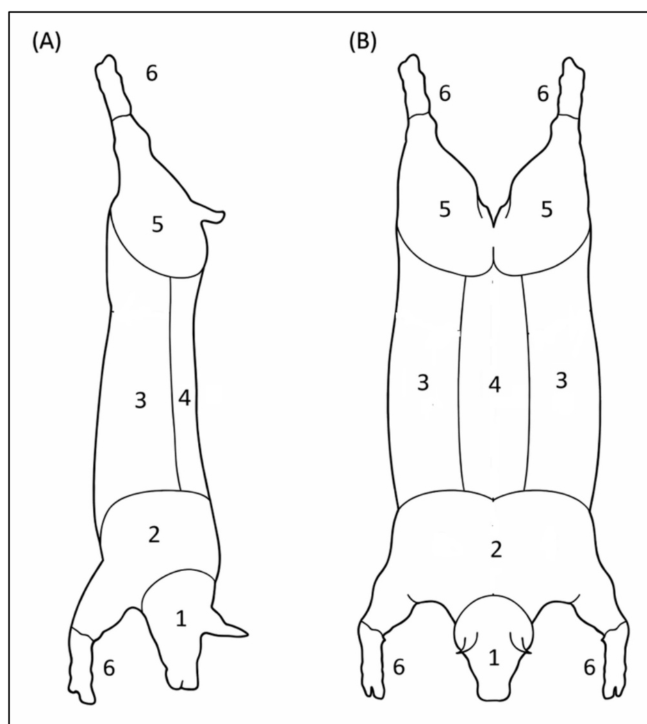

Fig. 1. Anatomical regions of the pig carcass evaluated. (A) Lateral view and (B) dorsal view of the carcass. 1, Head–ears (R1); 2, Neck–shoulders (R2); 3, Flanks (R3); 4, Loin (R4); 5, Ham (R5); and 6, Legs (R6).

(*Institut Technique du Porc* - Institute Technique du Porc, 1996). Tails were visually examined for docking status (docked or intact) and for the presence of tail lesions, defined as partial or total tail loss, as well as superficial skin damage consistent with bite or puncture wounds, with or without signs of inflammation or infection (adapted from Teixeira & Boyle, 2014; Carroll et al., 2018). Fore and hind claws were visually examined for the presence or absence of cracks, defined as visible fissures or splits affecting the claw sole (Fitzgerald et al., 2012). Hot carcass weight data were provided by the slaughterhouse and, for descriptive and analytical purposes, carcasses were grouped into three weight categories of similar size.

2.3. pH measurement

The intramuscular pH of each carcass was measured 24 h post-mortem in the refrigerated storage rooms. A wireless meat pH meter with automatic temperature compensation (Hanna HALO 2 HI9810322, Hanna Instruments, Woonsocket, RI, USA) was used. After every 25 measurements, the pH meter was calibrated on site using buffer solutions at pH 4 and pH 7. Measurements were taken on the ventral surface of the *Longissimus thoracis* (LT) muscle of the left carcass half, perpendiculars to the muscle fibres, through a small incision made with a scalpel between the 9th and 10th ribs.

2.4. Statistical analysis

All data were analysed using the R Statistical Programming Language (version 4.5.1) and RStudio (version 2025.09.1 + 401; Posit Software, Boston, MA, USA). Univariate analyses were conducted to determine the prevalence of scratches and bruises across the six carcass regions, as well as the prevalence of claw cracks and tail lesions. Mixed-effects logistic regression models were used to evaluate the associations of farm characteristics (sex, weight, herd size, production system, presence of a holding pen) and pre-slaughter logistics (vehicle type, loading density, journey distance and time, altitudinal range, road surface, and lairage time) with the probability of carcass lesions (skin scratches and bruises, tail lesions, and claw cracks) and meat quality conditions, including dark, firm, dry (DFD), borderline DFD, and pale, soft, exudative (PSE) pork. Fasting time was not included due to insufficiently precise data. These models included:

1. Carcass damage by region: one model for each of the six anatomical carcass regions (R1: Head–ears; R2: Neck–shoulders; R3: Flanks; R4: Loin; R5: Ham; R6: Legs). Response variable: 1 = Yes, presence of skin lesions (bruises or scratches), 0 = No skin lesions (without bruises or scratches).
2. Severe carcass damage (SCD): 1: Yes, carcasses with ≥2 regions showing severe skin lesions (i.e., with severe scratches or bruises), 0 = No, <2 regions with severe skin lesions.
3. Tail lesions: 1 = Yes, present 0 = No.
4. Claw cracks: three separated models for the presence of cracks in fore claws (FC), hind claws (HC), and both fore and hind claws (FHC). For all model = Yes, presence and 0 = No, absence of lesions.
5. Meat quality: meat with pH24h = 5.5–<6.0 was considered normal. Each model compared the category of interest with the normal meat group as the reference. Separate models were fitted for:
   PSE meat: 1 = pH24h <5.5; 0 = normal pH.
   DFD meat: 1 = pH24h ≥6.0; 0 = normal pH.

Furthermore, within the normal pH range (5.5–<6.0), the probability of occurrence of DFD borderline meat was modelled.

DFD borderline meat: 1 = pH24h ≥5.8–<6.0; 0 = normal pH 5.5 < 5.8.

To avoid potential problems of collinearity and to improve interpretability, combined variables were created from some of the initial journey-related factors: journey type (short–fast, long–fast, long–slow), integrating journey distance and journey time; and *journey conditions* (<90% paved–flat, <90% paved–hilly, >90% paved–flat, >90% paved–hilly), integrating road surface and altitudinal range. These combined variables replaced the original ones in all subsequent models. The initial random-effects structure included both the farm of origin and the transport batch nested within the farm (1|Farm/Batch). After fitting this full structure, the variance component attributed to the farm was estimated to be negligible, indicating that the farm level did not contribute substantial residual variability once the transport batch and the pre-slaughter logistics variables included as fixed affects were accounted for. Therefore, the random-effects structure was simplified by retaining only the transport batch as a random intercept. Associations between each predictor and the outcomes were first assessed using univariable mixed-effects logistic regression. Variables showing an association of $p < 0.20$ were retained for multivariable modelling (Dohoo et al., 2012). Collinearity among the retained predictors was then evaluated using the adjusted Generalized Variance Inflation Factor ($GVIF^{1/(2 \cdot Df)}$), which accounts for categorical variables with multiple levels. A $GVIF^{1/(2 \cdot Df)}$ value >5 was considered indicative of problematic collinearity; when this occurred, the variable deemed biologically more plausible was preferentially retained (Zhu et al., 2023). With the final selection of predictors, a backward stepwise procedure based on likelihood ratio tests was used to remove non-significant variables ($p > 0.05$). Variables whose removal altered any odds ratio of the retained predictors by ≥25% were considered potential confounders and were forced back into the model to reduce bias in effect estimates (Dohoo et al., 2012).

3. Results

This study evaluated the risk factors and prevalence of carcass skin, tail and claw lesions, as well as ultimate meat pH, in slaughtered commercial pigs. Furthermore, variables related to the pre-slaughter logistics chain were analysed to determine their influence on lesion occurrence and meat quality parameters.

3.1. Prevalence and severity of carcass lesions

Table 2 summarizes the anatomical distribution of bruises and scratches. A total of 97.1% of the carcasses had at least one of the six anatomical regions affected by bruises or scratches. Scratches were substantially more prevalent than bruises: 94.1% of carcasses presented scratches, whereas 55.1% showed bruising. Regarding bruising severity, 2.8% of carcasses exhibited severe bruising in at least one region. An additional 12.9% displayed bruising of moderate maximum severity,

Table 2
Distribution (%) of bruises, scratches, and overall skin lesions across anatomical carcass regions ($n = 1841$ animals).

	R1	R2	R3	R4	R5	R6	Total
Bruises							
None	96.2	81.6	88.5	75.9	88.1	90.1	44.9
Mild	3.2	13.1	8.5	17.8	8.1	8.1	39.4
Moderate	0.5	4.6	2.4	5.1	3.3	1.6	12.9
Severe	0.1	0.6	0.5	1.2	1.5	0.1	2.8
Scratches							
None	76.2	38.2	42.2	61.0	72.1	97.6	5.9
Moderate	21.9	50.0	47.6	32.6	23.5	2.3	68.5
Severe	1.8	11.8	10.3	6.4	4.3	0.1	25.5
Skin lesions (bruises + scratches)							
None	75.7	36.1	40.6	57.3	69.1	95.9	5.0
Moderate	22.4	51.7	48.7	35.5	26.1	3.9	68.1
Severe	1.8	12.2	10.7	7.2	4.8	0.2	26.9

R1: Head–ears; R2: Neck–shoulders; R3: Flanks; R4: Loin; R5: Ham; R6: Legs.

and 39.4% presented exclusively mild bruising. In terms of scratching, 26.9% of carcasses presented severe scratches, while 68.5% only showed scratches of moderate severity. In addition, 26.9% of the carcasses had at least one anatomical region with severe damage from scratches and/or bruises. Bruising was most frequent in the loin (R4, 24.1%) followed by the neck–shoulders region (R2, 18.4%), whereas scratches were most observed in the neck–shoulders region (R2, 61.8%) and in the flanks (R3, 57.8%). Conversely, the head–ear region (R1) showed the lowest prevalence of bruising (3.8%), and the legs were the least affected by scratches (2.4%). Across all anatomical regions, severe lesions (both bruises and scratches) were observed at substantially lower frequencies than those of lesser severity. When bruises and scratches were grouped into a single category, skin lesions, the anatomical regions with the highest prevalence were the neck–shoulder (R2, 63.9%), followed by the flanks (R3, 59.4%) and the loin (R4, 42.7%), whereas the legs (R5) exhibited the lowest prevalence (4.1%).

A total of 8.1% ($n = 150$) of the carcasses were classified as SCD, defined as having severe skin damage (severe bruises or severe scratches) in two or more anatomical regions. The most frequent patterns of combined severe skin damage involved the neck–shoulder and flanks (R2–R3) or neck–shoulder and loin (R2–R4) regions, either occurring alone or in combination with additional affected regions ($n =$ 85 or 4.6%). Regarding tail, no carcasses showed total or partial loss, nor evidence of bite or puncture wounds with signs of infection. Lesions with evidence of tail biting or puncture but without infection were observed in 0.3% of carcasses, while mild skin lesions occurred in 9.2%. These two categories were therefore combined for subsequent analyses as tail lesions (9.5%). No significant association was found between the presence of tail lesions and tail docking status (docked vs. intact) ($p = 0.567$). Finally, claw cracks showed a similar prevalence across fore claws (FC, 22.2%), hind claws (HC = 20.4%), and cases where both were affected (FHC = 20.3%).

3.2. Risk factors for skin lesions

Multivariate logistic regression models showed that several factors related to the farm and pre-slaughter logistics are significantly associated to the probability of occurrence of skin lesions (scratches and/or bruises) across the six carcass regions (Table 3). For the head–ears region (R1), a higher probability of lesions was observed in pigs held in lairage for >16 h compared with those lairaged <10 h (OR = 1.98; 95 CI %: 1.0–3.5; $p < 0.05$). In the neck–shoulder region (R2), lesion prevalence increased in carcasses from farrow-to-finish systems relative to finishing farms (OR = 1.59; 95% CI: 1.2–2.1; $p < 0.01$), whereas shorter lairage times (⟨10*h*) were associated with a reduced probability of lesions compared with lairage times of 14–16 h (OR = 0.59; 95% CI: 0.4–0.9; $p < 0.01$). In the flank region (R3), lesions were more frequently detected in pigs transported in tractor-trucks (OR = 3.02; 95 CI%: 1.9–4.9; $p < 0.001$), than in those transported in medium-trucks, and pig lairaged for <10 h showed a lower probability of flank lesions

Table 3
Multivariable logistic regression models of risk factors associated with skin lesions (moderate to severe) across anatomical zones in pigs (n = 1841).

Variable	R1 OR(IC95%)	R2 OR(IC95%)	R3 OR(IC95%)	R4 OR (IC95%)	R5 OR (IC95%)	R6 OR (IC95%)
Intercept	0.27 (0.2-0.4)^{c}	2.00 (1.5-2.7)^{c}	1.57 (1.2-2.1)^{b}	1.50 (1.2-2.0)^{b}	0.45 (0.4-0.6)^{c}	0.13 (0.1-0.3)^{c}
***Farm size (fattening pigs):* (>4000 - ref.)**						
3000-4000						
700-<1200						
***Production system type:* (Finishing- ref.)**						
Farrow-to finish		1.59 (1.2-2.1)^{b}				0.52 (0.28-0.98)^{a}
***Vehicle:* (Medium truck– ref.)**						
Large-truck			1.27 (0.9-1.7)			
Tractor-truck			3.02 (1.9-4.9)^{c}			
***Vehicle loading density:* (Within vehicle capacity- ref.)**						
Overloaded				0.61 (0.4-0.9)^{a}	1.54 (1.1-2.2)^{a}	
***Journey type:* (short-fast- ref.)**						
Long-fast						1.20 (0.6-2.5)
Long-slow						2.34 (1.1-4.8)^{a}
***Journey conditions:* (>90% P-F-ref.)**						
<90% P-F						0.60 (0.3-1.3)
> 90% P-H						0.61 (0.3-1.3)
<90% P-H						1.41 (0.6-3.1)
***Lairage time:* (<10 h - ref.)**						
10–14 h	1.33 (0.7-3.0)	0.98 (0.7-1.4)	0.81 (0.6-1.2)			
>14–16 h	0.50 (0.2-1.1.0)	0.59 (0.4-0.9)^{b}	0.50 (0.3-0.7)^{c}			
>16 h	1.98 (1.0-3.5)^{a}	1.14 (0.8-1.7)	0.93 (0.7-1.3)			

R1: Head–Ears; R2: Neck–Shoulders; R3: Flanks; R4: Loin; R5: Ham; R6: Legs. P-F: Paved-Flat; P-H: Paved-Hilly. Superscripts denote significance levels: a: $p < 0.05$. b: $p < 0.01$. c: $p < 0.001$. Blue shading indicates odds ratios <1 (protective effect). red shading indicates odds ratios >1 (risk effect).

than those lairaged for 14–16 h (OR = 0.50; 95 CI%: 0.3–0.7; $p < 0.001$). Lesions in the loin region (R4) were less likely in pigs transported in overloaded vehicles compared with those transported in vehicles within the vehicle's loading capacity (OR = 0.61; 95 CI%: 0.4–0.9; $p < 0.05$). In contrast, for the ham region (R5), transport in overloaded units was associated with an increased probability of lesions (OR = 1.54; 95% CI: 1.1–2.2; $p < 0.05$). For the legs (R6), lesions occurrence was higher following long–slow compared with short–fast ones (OR = 2.34; 95 CI%: 1.1–4.8; $p < 0.05$), and less likely in those originating from finishing production systems (OR = 0.52; 95 CI%: 0.28–0.98; $p < 0.05$).

Severe carcass damage (SCD, defined as ≥2 regions with severe scratches or bruises) was associated with journeys involving <90% paved-hilly roads (OR = 0.22; 95 CI%: 0.1–1.0; $p < 0.01$), and was less likely in pigs kept in lairage for 10–14 h compared with those held for <10 h (Table 4) (OR = 0.39; 95 CI%: 0.2–0.8; $p < 0.01$). Tail lesions occurred more frequently in males than in females (OR = 1.92; 95 CI%: 1.0–3.7; $p < 0.05$), and in pigs kept in lairage for 10–14 h compared with those held for less than 10 h (OR = 5.32; 95 CI%: 1.1–25.1; $p < 0.05$). Cracks in the FC, HC, and FHC were consistently associated with farm size, hot carcass weight, and journey conditions. Cracks were less frequent in pigs from smaller farms (700– < 1.200 pigs) than in those from the largest farms (> 4.000 pigs) ($p < 0.05$), and their occurrence increased in animals with heavier carcasses (> 95 kg) compared with lighter ones ($p < 0.05$). A higher prevalence of cracks was also observed following transport on <90% paved, hilly routes compared with ≥90% paved, flat routes ($p < 0.05$). Additionally, FC and FHC cracks were more frequent in pigs from farms without holding pens that in those with holding pens ($p < 0.05$).

3.3. Prevalence and risk factors associated with meat quality

Based on muscle pH measured 24 h post-mortem, meat from 7.6% of the pork carcasses was classified as PSE ($n = 140$, pH < 5.5), 27.2% as DFD ($n = 500$, pH ≥ 6.0), and 34.5% as borderline DFD (pH ≥ 5.8 to <6.0) (Table 5). Risk factors associated with these meat quality conditions included pre-slaughter logistics and farm-related variables. Transport on roads with >90% paved and hilly surfaces significantly increased the likelihood of PSE pork (OR = 4.56; 95 CI%: 1.8–11.5; $p < 0.01$), whereas lairage times longer than 14 h reduced it ($p < 0.05$). Skin lesions in the head–ear region (R1) were also linked to a higher probability of PSE (OR = 1.69; 95 CI%: 1.1–2.5; $p < 0.05$). Pigs transported on long–fast journeys and > 90% paved–hilly roads were more likely to

Table 4
Multivariable logistic regression models of risk factors associated with severe damaged carcass. Tail lesions and claw cracks in pigs (n = 1841).

Variable	SDC OR (IC95%)	Tail lessions OR(IC95%)	Cracks FC OR(IC95%)	Cracas HC OR (IC95%)	Cracks FHC OR (IC95%)
Intercept	0.14 (0.1-0.2)[c]	0.02 (0.0-0.1)[c]	1.47 (0.2-7.6)	0.84 (0.2-3.7)	0.85 (0.2-3.7)
Sex **(Female - ref.)**					
Male		1.92 (1.0-3.7)[a]			
Farm size (fattening pigs): **(>4000 - ref.)**					
3000-4000			0.21 (0.0-11)	0.25 (0.1-1.2)	0.25 (0.1-1.2)
700-<1200			0.11 (0.0-0.5)[b]	0.2 (0.1-0.8)[a]	0.2 (0.1-0.8)[a]
Holding pen: **(No - ref.)**					
Yes			0.32 (0.1-0.8)[a]		0.30 (0.1-0.7)[b]
Vehicle type: **(medium truck - ref.)**					
Large-truck			1.26 (0.4-3.6)	0.6 (0.2-1.5)	0.6 (0.2-1.5)
Tractor-truck			0.39 (0.1-1.8)	0.28 (0.1-1.3)	0.28 (0.1-1.3)
Journey type: **(short-fast – ref.)**					
Long-fast		0.29 (0.1-1.4)			
Long-slow		0.51 (0.1-2.1)			
Journey conditions: **(> 90% P-F- ref.)**					
<90% P-F	0.850 (0.4-1.6)		0.28 (0.1-1.2)	0.35 (0.1-1.6)	0.35 (0.1-1.6)
> 90% P-H	0.930 (0.5-1.7)		0.77 (0.2-3.1)	0.52 (0.1-2.0)	0.49 (0.1-2.0)
<90% P-H	0.220 (0.1-0.6)[b]		2.7 (0.9-7.9)[a]	3.37 (1.2-9.4)[a]	3.36 (1.2-9.3)[a]
Lairage time: **(<10 h - ref.)**					
10–14 h	0.39 (0.2-0.8)[b]	5.32 (1.1-25.1)[a]	0.98 (0.4-2.7)		0.996 (0.4-2.8)
>14–16 h	0.61 (0.3-1.2)	0.5 (0.1-3.2)	2.21 (0.8-6.4)		2.228 (0.8-5.9)
>16 h	0.60 (0.3-1.0)	3.07 (0.7-12.8)	0.81 (0.3-1.9)		0.785 (0.3-1.9)
Hot carcass weight (kg): **(62–95.3 - ref.)**					
95.4 –104.3			1.680 (1.2-2.4)[b]	1.59 (1.1-2.3)[a]	1.59 (1.1-2.3)[a]
104.4–129.0			1.610 (1.1-2.4)[a]	1.54 (1.1-2.3)[a]	1.50 (1.0-2.1)[a]

SDC: Severely Damaged Carcass. FC: Fore Claws. HC: Hind Claws. FHC: Fore + Hind Claws. P-F: Paved-Flat. P-H: Paved-Hilly. Superscripts denote significance levels: a: $p < 0.05$. b: $p < 0.01$. c: $p < 0.001$. Blue shading indicates odds ratios <1 (protective effect). red shading indicates odds ratios >1 (risk effect).

Table 5
Multivariable logistic regression models of risk factors for associated with PSE. DFD borderline. and DFD pork (n = 1841).

Predictor	PSE (pH24h <5.5) OR(IC%95)	DFD-B pH24h ≥5.8 - <6.0) OR (IC%95)	DFD (pH24h ≥6.0) OR (IC%95)
Intercept	0.02 (0.0-0.1)[c]	0.88 (0.6-1.3)	0.40 (0.1-2.03)
Farm size: (fattening pigs). **(>4000 - ref.)**			
3000–4000	4.5 (0.8-23.9)		0.31 (0.1-1.4)
700–<2000	4.0 (0.8-19.7)		0.40 (0.1-1.7)
Journey type: **(Short-fast – ref.)**			
Long-fast	2.26 (0.5-10.4)	1.23 (0.8-2.0)	4.13 (1.2-14.8)[a]
Long-slow	1.16 (0.2-7.1)	1.32 (0.77-2.27)	1.19 (0.3-5.6)
Vehicle: **(Medium truck – ref.)**			
Large-truck	1.46 (0.3-7.0)		0.84 (0.2-3.1)
Tractor-truck	1.43 (0.3-6.3)		1.90 (0.5-6.9)
Journey conditions: **(>90% paved/flat – ref.)**			
<90% P-F	2.58 (0.4-15.9)	2.28 (1.4-3.8)[b]	1.00 (0.2-5.7)
>90% P-H	4.56 (1.8-11.5)[b]	0.69 (0.4-1.2)	0.94 (0.3-3.0)
<90% P-H	0.64 (0.2-2.3)	1.57 (0.9-2.8)	3.82 (1.4-10.4)[b]
Lairage time: **(<10 h – ref.)**			
10–14 h	0.53 (0.2-1.3)		
>14–16 h	0.39 (0.2-1.0)[a]		
>16 h	0.38 (0.2-0.8)[a]		
Skin lesions in R1 (head/ears): **No (ref.)**			
Yes	1.69 (1.1-2.5)[a]		

Superscripts denote significance levels: a: $p < 0.05$. b: $p < 0.01$. c: $p < 0.001$. P-F: Paved-Flat; P-H: Paved-Hilly; DFD-B: DFD Borderline. Blue shading indicates odds ratios <1 (protective effect). red shading indicates odds ratios >1 (risk effect).

produce DFD meat compared with those on short–fast journeys and > 90% paved–flat roads ($p < 0.05$). Finally, borderline DFD was associated with <90% paved–flat journeys (OR = 2.28; 95 CI%: 1.4–3.8; $p < 0.01$).

4. Discussion

In recent years, the Colombian government has pursued an ambitious agenda to advance animal welfare, encompassing the legal recognition of sentience (Law 1774 of 2016) and the establishment of specific standards for pigs (Resolution 136 of 2020). These advances have been made possible thanks to collaboration between authorities, national and international academia, and producer associations (Machado-Reyes et al., 2025). However, it may require a significant period of time to observe the impact of the new legislation on animals, as evidenced by previous studies conducted in Europe and Oceania (Miranda-de La Lama & Estévez-Moreno, 2025). In this context, the results of our study demonstrate that pre-slaughter logistical conditions have a considerable influence on animal welfare and meat quality in tropical mountain conditions (Rosero & Lukešová, 2008), highlighting the need to incorporate these factors into strategies aimed at improving welfare and sustainability in the pig sector in such circumstances. The relevance of this study is further supported by the concentration of pig production in tropical regions worldwide, particularly in parts of Asia and Latin America, where mountainous topography is a common feature of many pig production systems (Roppa et al., 2024; Wang & Li, 2024).

4.1. Prevalence and severity of carcass lesions

Our findings indicate a high prevalence of carcass lesions (i.e., >97%), with bruises or scratches affecting at least one of the six anatomical regions, consistent with reports from analogous climatic and geographical contexts (100% in Varón-Álvarez et al., 2014; 93.6% in Corrales et al., 2018; 99.5% in Hernández et al., 2023). Beyond the national context, the prevalence of carcass skin lesions varies considerably across commercial categories, climatic conditions, and production systems worldwide. Research carried out in European slaughterhouses have generally reported lower prevalence of skin lesions in pigs from intensive production systems. For instance, in finished pigs (110–120 kg), a prevalence of 10.7% has been reported in Denmark (Kongsted & Sørensen, 2017) and 5.7% in Italy (Maisano et al., 2020), whereas in heavy pigs (170 kg) in Italy a prevalence of 64% has been described (Bottacini et al., 2018). Higher lesion prevalence has been associated with greater variability in management, infrastructure, and journey conditions, which supports the relevance of the patterns observed in the present study (Dalmau et al., 2014).

Therefore, skin lesions are indicative of exposure to stimuli that cause pain, discomfort and stress, thereby reducing the animal's ability to cope with unfamiliar environments such as the abattoir (EFSA Panel on Animal Health and Welfare (AHAW) et al., 2020). In our study, scratches were found to be more prevalent than bruises, due to the differing causal mechanisms involved. Scratches resulted from interactions between conspecifics associated with high densities, competition for resources, or inappropriate handling (Dalmau et al., 2014). In contrast, bruises were caused by impacts, loss of balance, or collisions with surfaces during transport and handling (Dalla-Costa et al., 2007). The distribution of skin lesions in the six anatomical regions evaluated showed a concentration in the neck–shoulders (R2), flanks (R3), and back (R4), which is consistent with the combination of social conflicts, high densities, and the effects of transport on uneven terrain. In such conditions, vibrations, changes in slope, and curves increase the risk of rubbing, lateral displacement, and internal collisions within the vehicle (Paranhos da Costa et al., 2024). While it was not possible to determine the precise phase of origin for each injury, the injuries are consistent with cumulative mechanical and social factors experienced during the pre-slaughter logistics chain. This lends further support to the value of skin injuries as “iceberg” indicators in post-mortem assessment systems (Huanca-Marca et al., 2025).

Severe carcass injuries generate economic losses for producers and abattoirs, either due to the depreciation of the affected carcasses or their exclusion from certain market segments (Faucitano, 2001). The proportion of carcasses classified as severely damaged in our study is relatively low (i.e. < 8%), although the anatomical pattern of these injuries reveals key information about their causality. The present study identified a recurrent pattern of injuries affecting the neck-shoulder (R2) and flank (R3) regions, or between R2 and the loin (R4), which were found to be significantly associated with social conflicts, high densities, and accidents including falls (both individual and group). The observed patterns of damage and their prevalence are consistent with those reported by Driessen et al. (2020a) in pigs that were regrouped and not regrouped during pre-slaughter. Furthermore, the fact that these patterns are persistent suggests that they are not randomly distributed, but rather follow a biomechanical pattern associated with group movement and contact with loading/unloading ramp structures, the interior of the truck, corridors, and lairage pens.

In contrast to the high prevalence of carcass lesions, tail lesions were rare (i.e. $< 9.5\%$), and no cases presented with total or partial loss of the tail or infected lesions. This finding suggests that tail biting behaviour does not constitute a significant problem in adult animals in our study. The absence of any discernible differences between pigs with docked and intact tails serves to reinforce this interpretation, particularly in view of the fact that, in contexts where tail biting is a frequent occurrence, clear contrasts between the two groups are often observed (Valros et al., 2020). When considered as a whole, these findings suggest that the caudal lesions detected are indicative of low-intensity events rather than persistent agonistic dynamics (Valros & Heinonen, 2015). It is important to note that, although cracks in the claws can affect the well-being of finishing pigs by causing pain, difficulty in walking, and lameness, the literature indicates that there is not always a direct association between the presence of foot lesions and the manifestation of lameness (Heinonen et al., 2024). In the present study, the prevalence of cracks was found to be significantly lower than the 63% reported by Nielsen et al. (2001) in finishing pigs. The similarity in prevalence between FC, HC, and FHC supports the hypothesis that cracks arise more as a series of cumulative microtraumas, resulting from interaction with the substrate, especially due to accelerated weight gain during fattening, than as a single acute event (De Carvalho et al., 2009).

4.2. Risk factors for skin lesions

Evidence specifically addressing risk factors for carcass skin lesions at abattoir level remains limited (e.g. Guàrdia et al., 2009). The present study contributes by analysing the association between multiple pre-slaughter logistic components and the occurrence of carcass lesions under commercial conditions. The multivariate analysis performed here suggests that risk factors for skin injuries do not act uniformly, but rather reflect a combination of behavioural, postural and biomechanical mechanisms that are specific to each anatomical region, modulated by interactions between transport conditions, handling practices and lairage duration. For example, in the head–ear region (R1), a substantial increase in risk was observed in animals with lairage times exceeding 16 h, in comparison to those with stays of approximately 10 h. This finding is in accordance with studies suggesting that protracted lairage periods encourage social conflicts stemming from competition for resources (water and resting areas) and instability engendered by the merger of animals from disparate origins (Fàbrega et al., 2013). In the neck-shoulder region (R2), injuries were more prevalent in carcasses from farrow-to-finish systems than from feedlots. This may be attributable to mass handling and frequent regrouping in these types of systems, factors that increase the opportunities for fighting (Fredriksen et al., 2008). In the flank region (R3), the highest probability of injuries was found in animals transported in tractor-truck and with short stays in lairage (<10 h). Tractor-truck have been shown to generate more pronounced lateral oscillations on mountainous routes, thereby increasing instability, falls and collisions with internal partitions (Miranda-de La Lama et al., 2018). Furthermore, the necessity for inclines can heighten the probability of incidents during the processes of loading and unloading (Driessen et al., 2020b). In circumstances where these animals spend minimal time in the lairage, the absence of recovery and social stabilisation following the journey can perpetuate elevated levels of activity during the initial hours of lairage, thereby promoting additional sudden contacts (Lee et al., 2023).

Injuries in the loin (R4), ham (R5), and legs (R6) regions do not respond to a single mechanism, but rather to the interaction between dynamic stability during transport, spatial constraints, and the capacity for recovery during lairage. In the loin (R4), the increased probability of injuries in non-overloaded vehicles indicates that greater freedom of movement during transport may precipitate slippage or dorsal contact with the internal structures of the truck (Driessen et al., 2020b). Conversely, injuries to the hindquarters (R5) were more prevalent in trucks with high densities, which is consistent with increased compression and animals mounting each other, resulting in loss of stability and falls (Ministerio de Transporte. MT, 2022). In the case of the leg region (R6), the highest risk was associated with long, slow journeys, in conjunction with prolonged stays in lairage (>16 h). This result indicates the presence of cumulative processes of muscle fatigue resulting from sustained postural effort during transport and abattoir handling (Werner et al., 2007).

Severe carcass damage (SCD) is a category distinct from isolated injuries, as it involves severe multiple bruising accumulated at different stages of the pre-slaughter process, causing pain and suffering to the animals (EFSA Panel on Animal Health and Welfare (AHAW) et al., 2020). Its association with journeys involving less than 90% pavement in mountainous terrain demonstrates that even on paved roads, changes in altitude and winding sections can induce significant stress responses, thereby promoting motion sickness, falls and blunt force trauma (Randall & Bradshaw, 1998). Despite the low prevalence of SCD in our study, it demonstrates that there is invariably a cohort of animals with reduced fitness to transport or pre-existing health conditions that impede their capacity to withstand physically arduous journeys (Thodberg et al., 2020). The finding that SCD was more prevalent in animals with less than 10 h in lairage is an unexpected discovery, as it is generally assumed that prolonged lairage times increase physical aggression (Faucitano, 2010). One potential explanation for these findings is that animals with multiple injuries are slaughtered immediately after being detected by veterinary inspection, perhaps to prevent their condition from worsening and the eventual confiscation of the carcass. Such immediate slaughter upon detection is standard practice in several commercial abattoirs, which supports the plausibility of this interpretation (Alban et al., 2022). With regard to tail injuries, these have been found to be more prevalent in males, as reported by Clark and D'Eath (2013) and Vanheukelom et al. (2012). These authors describe a greater degree of aggression in males during mixing and handling, which increases the risk of superficial injuries. Furthermore, the increase observed between 10 and 14 h of lairage suggests that, under certain lairage conditions in novel environments, interactions persist that may favour episodes of tail biting (Van Staaveren et al., 2015). It is important to note that not all tail lesions correspond to tail-biting outbreaks, and in many cases represent minor, isolated events rather than sustained behavioural problems.

With regard to claw cracks (FC, HC, and FHC), we found that the risk increases when pigs come from large farms (>4000 animals). This pattern indicates that these injuries are unlikely to be circumstantial, but instead reflect structural features of the production system, such as the available infrastructure and specific management practices (mass handling, moving batches over longer distances within the farm, and floor wear) conditions that favour the progressive deterioration of claws (EFSA Panel on Animal Health and Welfare (AHAW) et al., 2022). In addition, the effect of journeying on roads with less than 90% pavement and mountainous topography is to force repeated postural adjustments during transport, which can exacerbate the previous wear and tear generated on the farm (EFSA Panel on Animal Health and Welfare (AHAW) et al., 2022). Furthermore, the higher frequency of FC and FHC cracks in pigs from farms without pre-shipment holding pens suggests a potential association between the organisation of animal flow and the risk of injury. The absence of these facilities can lead to faster loading and reduced ability to regulate the movement of batches. Conversely, the higher prevalence of claw cracks in animals with heavier carcasses (>95 kg) is consistent with sustained mechanical stress on the limbs, which increases susceptibility to fissures when transit surfaces are sub-optimal or poorly maintained (Kilbride et al., 2009). Finally, our results support the usefulness of monitoring claw cracks at the abattoir level as key indicators (or iceberg indicators) of animal welfare. Their prevalence reflects structural conditions that can be corrected through improvements in management, loading, unloading, and transport processes, as well as in the quality and maintenance of facilities (Gonzalez-Ramiro et al., 2025; Huanca-Marca et al., 2025).

4.3. Prevalence and risk factors associated with meat quality

Conventionally, the ultimate meat pH value is the primary metric employed to assess meat quality in commercial settings (Gregory, 2007). The results of the study demonstrate that the quality of the meat, as determined by pH 24 h post-mortem, is influenced by specific logistical and lairage conditions. For instance, in the case of meat classified as PSE, although its prevalence was very low (7%), an association was found with journeys on routes with more than 90% paved sections and steep topography typical of mountainous conditions. This suggests that such journeys may have created demanding conditions for the animals, causing fatigue, falls, and conditions consistent with acute stress (Dalla-Costa et al., 2017). It is important to note that the lower probability of PSE observed in animals with lairage times greater than 14 h could indicate that a longer rest period allows animals to recover before slaughter. The findings of this study are consistent with those reported by Dokmanović et al. (2014), who established that a lairage time of less than three hours is associated with a higher incidence of PSE meat compared to a lairage time of more than 14 h. A noteworthy finding is the association identified between skin lesions in the head-ear region (R1) and the prevalence of PSE meat. There is ample documentation of the correlation between skin lesions on the head and ears and social conflicts (Boyle et al., 2022). Such lesions have been associated with periods of heightened excitement and stress in the proximity to slaughter, which are also consistent with the occurrence of lower meat pH values (D'Eath et al., 2010).

Conversely, the prevalence of DFD meat was almost four times higher (27%) than that reported in PSE, and is associated with pigs transported on long, fast journeys on paved roads and mountainous terrain. These results may be attributed to a combination of relatively high speeds with steep slopes, frequent curves, and constant changes in acceleration, forcing pigs to make continuous postural adjustments to maintain balance, which increases physical effort and associated fatigue (EFSA Panel on Animal Health and Welfare (AHAW) et al., 2022). Furthermore, extended journeys in mountainous regions may be accompanied by elevated levels of noise, vibration, and thermal variability, environmental factors that, although not directly measured, frequently compromise muscle energy balance prior to slaughter (Miranda-De la Lama et al., 2021). Finally, borderline DFD meat had a high incidence (34%) and was associated with journeys with less than 90% paved roads, but on relatively flat terrain. This indicates an intermediate state of stress in which the animals do not experience intense acute activation but do experience sufficient physical and postural wear and tear to partially compromise post-mortem glycolysis. This suggests that road quality, as well as topography, can influence the type of predominant stress (acute vs. prolonged) and, consequently, the ultimate meat pH distribution (Driessen et al., 2020a).

5. Conclusions

In conclusion, the high prevalence and severity of skin lesions indicate substantial exposure to mechanical and social stressors, particularly in animals with lower transport fitness. Distinct injury patterns by anatomical region reflected specific risk factors related to the production system, transport conditions and lairage, reinforcing the value of carcass lesions as sensitive indicators of critical points in the pre-slaughter chain. The quality of the meat was found to be closely associated with logistical variables. PSE was linked to head-ear injuries, while DFD and borderline DFD reflected prolonged physical fatigue and environmental variability prior to slaughter. Collectively, these results underscore the significance of training and preventive strategies, and substantiate the abattoir as a crucial nexus for retrospective, on-abattoir welfare assessment to provide feedback and optimise the pre-slaughter logistics chain.

Author declaration template

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). He is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author (Genaro *C. Miranda*de la Lama) and which has been configured to accept email from genaro@unizar.es

CRediT authorship contribution statement

Adriana P. Pastrana-Camacho: Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation. **Genaro C. Miranda-de la Lama:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Nancy F. Huanca-Marca:** Validation, Methodology, Investigation. **Laura X. Estévez-Moreno:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Formal analysis, Data curation, Conceptualization.

Ethical statement

The present study was conducted in accordance with the regulatory framework governing the protection of animals during production, transportation, and slaughter in Colombia, as stipulated by Decree 1500/2007, Resolutions 240/2013 and 6915/2022. It is imperative to note that all pigs were handled and slaughtered in authorized facilities that met national welfare and sanitary requirements. It is important to note that no live animals were subjected to experimental or invasive procedures; all assessments were performed post-mortem on carcasses during routine slaughter. Consequently, ethical approval was not a prerequisite as stipulated by national or institutional guidelines.

Declaration of competing interest

None of the authors have any conflict of interest.

Data availability

Data will be made available on request.

References

Alban, L., Vieira-Pinto, M., Meemken, D., Maurer, P., Ghidini, S., Santos, S., & Langkabel, N. (2022). Differences in code terminology and frequency of findings in meat inspection of finishing pigs in seven European countries. *Food Control, 132*, Article 108394. https://doi.org/10.1016/j.foodcont.2021.108394

Bottacini, M., Scollo, A., Edwards, S. A., Contiero, B., Veloci, M., Pace, V., & Gottardo, F. (2018). Skin lesion monitoring at slaughter on heavy pigs (170 kg): Welfare indicators and ham defects. *PLoS One, 13*(11), Article e0207115. https://doi.org/10.1371/journal.pone.0207115

Boyle, L. A., Edwards, S. A., Bolhuis, J. E., Pol, F., Šemrov, M. Z., Schütze, S., & Valros, A. (2022). The evidence for a causal link between disease and damaging behavior in pigs. *Frontiers in Veterinary Science, 8*, Article 771682. https://doi.org/10.3389/fvets.2021.771682

Carroll, G. A., Boyle, L. A., Hanlon, A., Collins, L., Griffin, K., Friel, M., … O'Connell, N. E. (2018). What can carcass-based assessments tell us about the lifetime welfare status of pigs? *Livestock Science, 214*, 98–105. https://doi.org/10.1016/j.livsci.2018.04.020

Clark, C. C., & D'Eath, R. B. (2013). Age over experience: Consistency of aggression and mounting behaviour in male and female pigs. *Applied Animal Behaviour Science, 147*(1–2), 81–93. https://doi.org/10.1016/j.applanim.2013.04.014

Čobanović, N., Grković, N., Vićić, I., Radaković, M., Spariosu, K., Stanković, S. D., & Karabasil, N. (2025). Relationship between skin lesion severity and physiometabolic blood profile, microbial counts and carcass and meat quality characteristics in slaughtered pigs. *Meat Science, 229*, Article 109923. https://doi.org/10.1016/j.meatsci.2025.109923

Corrales, N. U., Ramírez, J. F. N., & Villegas, S. H. (2018). Swine welfare at slaughterhouses in Valle de Aburrá (Colombia). *Veterinary and Animal Science, 6*, 50–55. https://doi.org/10.1016/j.vas.2018.07.006

Dalla-Costa, F. A., Lopes, L. S., & Dalla Costa, O. A. (2017). Effects of the truck suspension system on animal welfare, carcass and meat quality traits in pigs. *Animals, 7*(1), 5.

Dalla-Costa, O. A., Faucitano, L., Coldebella, A., Ludke, J. V., Peloso, J. V., Dalla-Roza, D., & Da Costa, M. P. (2007). Effects of the season of the year, truck type and location on truck on skin bruises and meat quality in pigs. *Livestock Science, 107*(1), 29–36. https://doi.org/10.1016/j.livsci.2006.08.015

Dalmau, A., Fabrega, E., Manteca, X., & Velarde, A. (2014). Health and welfare management of pigs based on slaughter line records. *Journal of Dairy, Veterinary & Animal Research, 1*(3), Article 00016. https://doi.org/10.15406/jdvar.2014.01.00016

De Carvalho, V. C., De Alencar, I., Neto, M. M., & De Souza, S. R. L. (2009). Measurement of pig claw pressure distribution. *Biosystems Engineering, 103*(3), 357–363. https://doi.org/10.1016/j.biosystemseng.2009.04.010

D'Eath, R. B., Turner, S. P., Kurt, E., Evans, G., Thölking, L., Looft, H., & Mormède, P. (2010). Pigs' aggressive temperament affects pre-slaughter mixing aggression, stress and meat quality. *Animal, 4*(4), 604–616. https://doi.org/10.1017/S1751731109991406

Dohoo, I., Martin, W., & Stryn, H. (2012). *Methods in Epidemiologic Research. 2012.* Charlottetown, Prince Edward Island, Canada: VER Inc.

Dokmanović, M., Velarde, A., Tomović, V., Glamočlija, N., Marković, R., Janjić, J., & Baltić, M.Ž. (2014). The effects of lairage time and handling procedure prior to slaughter on stress and meat quality parameters in pigs. *Meat Science, 98*(2), 220–226. https://doi.org/10.1016/j.meatsci.2014.06.003

Driessen, B., Van Beirendonck, S., & Buyse, J. (2020a). The impact of grouping on skin lesions and meat quality of pig carcasses. *Animals, 10*(4), 544. https://doi.org/10.3390/ani10040544

Driessen, B., Van Beirendonck, S., & Buyse, J. (2020b). Effects of transport and lairage on the skin damage of pig carcasses. *Animals, 10*(4), 575. https://doi.org/10.3390/ani10040575

EFSA Panel on Animal Health and Welfare (AHAW), Nielsen, S. S., Alvarez, J., Bicout, D. J., Calistri, P., Canali, E., & Herskin, M. (2022a). Welfare of pigs during transport. *EFSA Journal, 20*(9), Article e07445. https://doi.org/10.2903/j.efsa.2022.7445

EFSA Panel on Animal Health and Welfare (AHAW), Nielsen, S. S., Alvarez, J., Bicout, D. J., Calistri, P., Canali, E., & Spoolder, H. (2022b). Welfare of pigs on farm. *EFSA Journal, 20*(8), Article e07421. https://doi.org/10.2903/j.efsa.2022.7421

EFSA Panel on Animal Health and Welfare (AHAW), Nielsen, S. S., Alvarez, J., Bicout, D. J., Calistri, P., Depner, K., & Velarde, A. (2020). Welfare of pigs at slaughter. *EFSA Journal, 18*(6), Article e06148. https://doi.org/10.2903/j.efsa.2020.6148

Fàbrega, E., Puigvert, X., Soler, J., Tibau, J., & Dalmau, A. (2013). Effect of on farm mixing and slaughter strategy on behaviour, welfare and productivity in duroc finished entire male pigs. *Applied Animal Behaviour Science, 143*(1), 31–39. https://doi.org/10.1016/j.applanim.2012.11.006

Faucitano, L. (2001). Causes of skin damage to pig carcasses. *Canadian Journal of Animal Science, 81*(1), 39–45. https://doi.org/10.4141/A00-031

Faucitano, L. (2010). Invited review: Effects of lairage and slaughter conditions on animal welfare and pork quality. *Canadian Journal of Animal Science, 90*(4), 461–469. https://doi.org/10.4141/cjas10020

Ferguson, D. M., & Warner, R. D. (2008). Have we underestimated the impact of pre-slaughter stress on meat quality in ruminants? *Meat Science, 80*(1), 12–19. https://doi.org/10.1016/j.meatsci.2008.05.004

Fitzgerald, R. F., Stalder, K. J., Karriker, L. A., Sadler, L. J., Hill, H. T., Kaisand, J., & Johnson, A. K. (2012). The effect of hoof abnormalities on sow behavior and performance. *Livestock Science, 145*(1–3), 230–238. https://doi.org/10.1016/j.livsci.2012.02.009

Fredriksen, B., Lium, B. M., Marka, C. H., Mosveen, B., & Nafstad, O. (2008). Entire male pigs in farrow-to-finish pens—Effects on animal welfare. *Applied Animal Behaviour Science, 110*(3–4), 258–268. https://doi.org/10.1016/j.applanim.2007.04.007

Gonzalez-Ramiro, H., López-Jara, A., Cambra, J. M., Gonzalez-Plaza, A., Garcia-Canovas, M., Lopez-Arjona, M., & Parrilla, I. (2025). Severe claw lesions in pregnant sows reduce prolificacy and increase litter heterogeneity. *Porcine Health Management, 11*(1), 52. https://doi.org/10.1186/s40813-025-00462-5

Gregory, N. G. (2007). *Animal welfare and meat production* (2nd ed.). Wallingford, UK: CABI Publishing.

Guàrdia, M. D., Estany, J., Balasch, S., Oliver, M. A., Gispert, M., & Diestre, A. (2005). Risk assessment of DFD meat due to pre-slaughter conditions in pigs. *Meat Science, 70*(4), 709–716. https://doi.org/10.1016/j.meatsci.2005.03.007

Guàrdia, M. D., Estany, J., Balasch, S., Oliver, M. A., Gispert, M., & Diestre, A. (2009). Risk assessment of skin damage due to pre-slaughter conditions and RYR1 gene in pigs. *Meat Science, 81*(4), 745–751. https://doi.org/10.1016/j.meatsci.2008.11.020

Harris, T. L., & Flaherty, E. G. (2010). *Bruises and skin lesions. Child abuse and neglect: Diagnosis, treatment, and evidence* (1st ed., pp. 239–251). Elsevier Saunders. St. Louis (Mo).

Heinonen, M., Pluym, L., Maes, D., Olstad, K., & Zoric, M. (2024). Lameness in Pigs. In *Production diseases in farm animals: Pathophysiology, prophylaxis and health management* (pp. 405–450). Cham: Springer International Publishing.

Hernández, R. O., Romero, M. H., & Sánchez, J. A. (2023). Assessment of slaughterhouse-based measures as animal welfare indicators in fattening pigs. *Frontiers in Animal Science, 4*, Article 1064933. https://doi.org/10.3389/fanim.2023.1064933

Huanca-Marca, N. F., Estévez-Moreno, L. X., Losada-Espinosa, N. L., & Miranda-de la Lama, G. C. (2025). Assessment of pig welfare at slaughterhouse level: A systematic review of animal-based indicators suitable for inclusion in monitoring protocols. *Meat Science, 220*, Article 109689. https://doi.org/10.1016/j.meatsci.2024.109689

Huanca-Marca, N. F., Estévez-Moreno, L. X., Pastrana-Camacho, A., Piñeiro, M., María, G. A., & Miranda-de la Lama, G. C. (2025). Effects of pre-slaughter logistics duration on stress responses and coping profiles in commercial finishing pigs. *Research in Veterinary Science, 193*, Article 105796. https://doi.org/10.1016/j.rvsc.2025.105796

Institute Technique du Porc. (1996). *Notation des hématomes Sur couenne: Porcs vivant ou carcasse*. Rennes, France: Institute Technique du Porc.

Instituto de Hidrología. (2025). *Meteorología y Estudios Ambientales (IDEAM)*. Colombia: Tiempo y clima. http://www.ideam.gov.co/web/tiempo-y-clima/clima.

Instituto Geográfico Agustín Codazzi. IGAC. (2023). Vías de Colombia [conjunto de datos geoespaciales]. Datos Abiertos Colombia https://www.datos.gov.co/dataset/Via/xt96-k9m4.

Kilbride, A. M. Y., Gillman, C., Ossent, P., & Green, L. (2009). Impact of flooring on the health and welfare of pigs. *In Practice, 31*(8), 390–395. https://doi.org/10.1136/inpract.31.8.390

Kongsted, H., & Sørensen, J. T. (2017). Lesions found at routine meat inspection on finishing pigs are associated with production system. *The Veterinary Journal, 223*, 21–26. https://doi.org/10.1016/j.tvjl.2017.04.01

Kschonek, J., Deters, K., Miller, M., Reinmold, J., Twele, L., Emmerich, I., & Beilage, E. G. (2025). Part II: Understanding pain in pigs—Pain assessment in pigs with spontaneously occurring diseases or injuries. *Porcine Health Management, 11*(1), 13. https://doi.org/10.1186/s40813-025-00420-1

Lee, J., Kang, D., & Shim, K. (2023). Effect of lairage time prior to slaughter on stress in pigs: A path analysis. *Porcine Health Management, 9*(1), 55. https://doi.org/10.1186/s40813-023-00350-w

Ljungberg, D., Gebresenbet, G., & Aradom, S. (2007). Logistics chain of animal transport and abattoir operations. *Biosystems Engineering, 96*(2), 267–277. https://doi.org/10.1016/j.biosystemseng.2006.11.003

Machado-Reyes, L. F., Estévez-Moreno, L. X., & Miranda-de La Lama, G. C. (2025). Design, validation, and implementation of animal welfare assessment protocol in an emerging market country: The case of poultry farming in Colombia. In A. Garcia, A. K. Johnson, & A. J. Aguiriano (Eds.), *National and international animal welfare auditing standards* (pp. 264–285). Netherlands: Wageningen Academic. https://doi.org/10.1163/9789004750593_14.

Maisano, A. M., Luini, M., Vitale, N., Nodari, S. R., Scali, F., Alborali, G. L., & Vezzoli, F. (2020). Animal-based measures on fattening heavy pigs at the slaughterhouse and the association with animal welfare at the farm level: A preliminary study. *Animal, 14*(1), 108–118. https://doi.org/10.1017/S1751731119001320

Mashood, Q., Wallenbeck, A., Eriksson, S., Johansson, A. M., Karlsson, A. H., & Segerkvist, K. A. (2025). Prevalence and severity of pale, soft, and exudative (PSE)-like zones in crossbred pigs (Yorkshire × Hampshire): Insights into season, gender, slaughter weight and technological meat traits. *Livestock Science, 295*, Article 105690. https://doi.org/10.1016/j.livsci.2025.105690

Ministerio de Transporte. MT. (2022). *(11 de febrero). Resolución 20223040006915 de 2022: Por la cual se adopta el manual de Procedimientos Para el transporte, manejo y movilización de animales en pie y se dictan otras disposiciones [Resolución 6915 de 2022]*. ICA: Diario Oficial.

Miranda-de la Lama, G. C. (2024). Electro-thermal injuries in ruminants caused by electrical equipment during pre-slaughter operations: Forensic case reports from an animal welfare science perspective. *Forensic Science International, 356*, Article 111936. https://doi.org/10.1016/j.forsciint.2024.111936

Miranda-De la Lama, G. C., Bermejo-Poza, R., Formoso-Rafferty, N., Mitchell, M., Barreiro, P., & Villarroel, M. (2021). Long-distance transport of finisher pigs in the Iberian peninsula: Effects of season on thermal and enthalpy conditions, welfare indicators and meat pH. *Animals, 11*(8), 2410. https://doi.org/10.3390/ani11082410

Miranda-de La Lama, G. C., Estévez-Moreno, L. X., Johnson, A. K., & Aguiriano, A. J. (2025). Introduction: International livestock animal welfare policies and standards: An OverviewIn: Garcia. In *National and international animal welfare auditing standards* (pp. 264–285). Netherlands: Wageningen Academic. https://doi.org/10.1163/9789004750593_2.

Miranda-de La Lama, G. C., Rodríguez-Palomares, M., Cruz-Monterrosa, R. G., Rayas-Amor, A. A., Pinheiro, R. S. B., Galindo, F. M., & Villarroel, M. (2018). Long-distance transport of hair lambs: Effect of location in pot-belly trailers on thermo-physiology, welfare and meat quality. *Tropical Animal Health and Production, 50*(2), 327–336.

Miranda-de La Lama, Rodríguez-Palomares, M., Cruz-Monterrosa, R. G., Rayas-Amor, A. A., Pinheiro, R. S. B., … Villarroel, M. (2018). Long-distance transport of hair lambs: Effect of location in pot-belly trailers on thermo-physiology, welfare and meat quality. *Tropical Animal Health and Production, 50*(2), 327–336.

Nielsen, E. O., Nielsen, N. C., & Friis, N. F. (2001). Mycoplasma hyosynoviae arthritis in grower-finisher pigs. *Journal of Veterinary Medicine Series A, 48*(8), 475–486. https://doi.org/10.1046/j.1439-0442.2001.00378.x

Paranhos da Costa, M. J., Huertas, S. M., & Gallo, C. (2024). Handling and transport of cattle and pigs in South America. In *Livestock handling and transport* (pp. 213–241). GB: CABI. https://doi.org/10.1079/9781800625136.0010.

Randall, J. M., & Bradshaw, R. H. (1998). Vehicle motion and motion sickness in pigs. *Animal Science, 66*(1), 239–245. https://doi.org/10.1017/S1357729800009012

Rodríguez-Realpe, C. (2024). *Logistics challenges in Latin America and the Caribbean: The case of Colombia*. Bachelor's thesis. Finland: Metropolia University of Applied Sciences. Available at: https://www.theseus.fi/bitstream/10024/858083/2/Rodriguez_Carolina.pdf.

Roppa, L., Duarte, M. E., & Kim, S. W. (2024). Pig production in Latin America. *Animal Bioscience, 37*(4), 786. https://doi.org/10.5713/ab.23.0453

Rosero, O., & Lukešová, D. (2008). Food and perspectives on pig production system in Colombia. *Agricultura Tropica et Subtropica, 41*(3), 122–127.

Schrøder-Petersen, D. L., Støier, S., & Hansen, C. (2025). The benefits and societal importance of pig welfare in slaughterhouses: A narrative review. *Meat Science*. https://doi.org/10.1016/j.meatsci.2025.110004

Teixeira, D. L., & Boyle, L. A. (2014). A comparison of the impact of behaviours performed by entire male and female pigs prior to slaughter on skin lesion scores of the carcass. *Livestock Science, 170*, 142–149. https://doi.org/10.1016/j.livsci.2014.09.026

Thodberg, K., Gould, L. M., Støier, S., Anneberg, I., Thomsen, P. T., & Herskin, M. S. (2020). Experiences and opinions of Danish livestock drivers transporting sows regarding fitness for transport and management choices relevant for animal welfare. *Translational Animal Science, 4*(2), 1070–1081. https://doi.org/10.1093/tas/txaa015

Trujillo-Díaz, J., Díaz-Piraquive, F. N., Herrera, M. M., & Gómez Acero, J. (2021). Identification of pig farm practices in the central Andean region of Colombia. *Ciencia y Tecnología Agropecuaria, 22*(2). https://doi.org/10.21930/rcta.vol22_num2_art:1535

Valros, A., & Heinonen, M. (2015). Save the pig tail. *Porcine Health Management, 1*(1), 2. https://doi.org/10.1186/2055-5660-1-2

Valros, A., Välimäki, E., Nordgren, H., Vugts, J., Fàbrega, E., & Heinonen, M. (2020). Intact tails as a welfare indicator in finishing pigs? Scoring of tail lesions and defining intact tails in undocked pigs at the abattoir. *Frontiers in Veterinary Science, 7*, 405. https://doi.org/10.3389/fvets.2020.00405

Van Staaveren, N., Teixeira, D. L., Hanlon, A., & Boyle, L. A. (2015). The effect of mixing entire male pigs prior to transport to slaughter on behaviour, welfare and carcass lesions. *PLoS One, 10*(4), Article e0122841. https://doi.org/10.1371/journal.pone.0122841

Vanheukelom, V., Van Beirendonck, S., Van Thielen, J., & Driessen, B. (2012). Behavior, production results and meat quality of intact boars and gilts housed in unmixed groups: A comparative study. *Applied Animal Behaviour Science, 142*(3–4), 154–159. https://doi.org/10.1016/j.applanim.2012.10.004

Varón-Álvarez, L. J., Romero, M. H., & Sánchez, J. A. (2014). Caracterización de las contusiones cutáneas e identificación de factores de riesgo durante el manejo presacrificio de cerdos comerciales. *Archivos de Medicina Veterinaria, 46*(1), 93–101. https://doi.org/10.4067/S0301-732X2014000100013

Wang, L., & Li, D. (2024). Current status, challenges and prospects for pig production in Asia. *Animal Bioscience, 37*(4), 742. https://doi.org/10.5713/ab.23.0303

Werner, C., Reiners, K., & Wicke, M. (2007). Short as well as long transport duration can affect the welfare of slaughter pigs. *Animal Welfare, 16*(3), 385–389. https://doi.org/10.1017/S0962728600027202

Zhu, X., Wang, J., Zhao, Y., Zhang, Z., Yan, L., Xue, Y., … Aleri, J. (2023). Prevalence, distribution, and risk factors of bovine tuberculosis in dairy cattle in Central China. *Preventive Veterinary Medicine, 213*, Article 105887. https://doi.org/10.1016/j.prevetmed.2023.105887