

Lairage behavior, carcass lesions, blood biomarkers, and meat quality in pigs transported over two distances across season

ANA Maria BRIDI

ambridi@uel.br

Universidade Estadual de Londrina <https://orcid.org/0000-0002-0110-5037>

Giovanna Lima Silva

Universidade Estadual de Londrina

Natalia Nami Ogawa Simizu

Universidade Estadual de Londrina

Daniela Kaiser Terto

Universidade Estadual de Londrina

Natalia Alves Ferreira

Universidade Estadual de Londrina

Karina Keller Marques da Costa Flaiban

Universidade Estadual de Londrina

Caio Abércio da Silva

Universidade Estadual de Londrina

Rafael Humberto Carvalho

Universidade Estadual de Londrina

Research Article

Keywords: carcass lesions, meat color, blood lactate, serum albumin, water-holding capacity

Posted Date: September 17th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10471338/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

This study aimed to evaluate lairage behavior, carcass lesions, blood biomarkers, and meat quality in pigs transported over two distances (28 ± 10 km and 112 ± 24 km) during two seasons (winter and summer). A total of 256 surgically castrated male pigs were evaluated under commercial slaughter conditions. Behavioral observations were conducted in 10 pens in winter and 8 pens in summer. Pigs transported during summer spent 20.4% more time drinking than those transported in winter (6.5% vs. 5.4% of lairage time). Regardless of distance or season, pigs spent more time standing during the first hour and lying down during the second and third hours ($p < 0.05$), with a 45% increase in lying behavior from the first to the second hour. Serum albumin was 4.40 g/dL in pigs transported 28 ± 10 km during summer, 3.6% higher than those transported 112 ± 24 km (4.27 g/dL). Glucose concentration was 16% higher in pigs transported 112 ± 24 km (131 mg/dL) compared to 28 ± 10 km (109 mg/dL), independent of season. Blood lactate concentration was 73% higher in summer (7.07 mmol/L) than in winter (4.14 mmol/L). Pigs transported over shorter distances had lower Semimembranosus muscle pH at 24 h (5.77 vs. 5.81; 0.7% lower). Pigs transported in the summer had higher drip loss (2.78% vs. 2.34%; +18.8%), greater redness (a^* : 5.44 vs. 3.12; +74%) and more severe carcass lesions (2.12 vs. 1.30; +63%) compared to winter. Pigs transported during summer exhibited physiological and meat quality responses indicative of increased pre-slaughter stress and dehydration, resulting in greater carcass damage and reduced meat quality.

1 Introduction

Pig transport is a complex step in the pork production chain, during which multiple factors may act simultaneously to intensify discomfort or stress, including handling practices, vehicle design, animal distribution within vehicle compartments, environmental conditions, travel distance, stocking density, and driving conditions, with direct implications for animal welfare (Faucitano and Goumon 2018).

Within pre-slaughter management, transport is energetically demanding and is associated with the occurrence of fatigued pigs (NANI; non-ambulatory, non-injured) and injured pigs (NAI; non-ambulatory, injured) (Faucitano and Lambooij 2019). This phase can disrupt homeostasis, resulting in direct consequences for animal health and physical performance (Fazio et al. 2018; Rizzo et al. 2017). Moreover, environmental change, mixing of groups, adverse conditions, unfamiliar odors, and human-animal interactions are thought to increase stress and compromise animal welfare, carcass yield, and meat quality (Ison et al. 2018)

Rising demand for pork has expanded trade and increased the transport of live pigs over longer distances (Miranda-de la Lama et al. 2014). Consequently, longer journeys may expose animals to varying levels of stress, ranging from thermal discomfort and fatigue to death (Voslarova et al. 2017). Extreme ambient temperatures are among the main risk factors during transport to slaughterhouses and may increase transport-related deaths, the occurrence of injured or fatigued pigs, and skin lesions, particularly when microclimatic conditions fall outside the thermoneutral range for pigs (Machado et al.

2021). Long-distance transport can also result in substantial body weight losses, mainly due to dehydration associated with restricted access to water during the journey (Machado et al. 2016). In contrast, short transport distances have been associated with a higher incidence of PSE (pale, soft, exudative) meat and with increased risk of losses, as pigs may have less time to recover from loading stress (Werner et al. 2007).

Considering the impact of pre-slaughter transport on animal welfare and on meat and carcass quality, this study evaluated the effects of different transport distances from the farm to the slaughterhouse on behavioral and physiological responses and carcass quality under commercial slaughter conditions across two seasons.

2 Materials and Methods

All experimental procedures performed in this study were approved by the Animal Use Ethics Committee (CEUA) of the State University of Londrina (UEL), under protocol no. 043.2023.

2.1 Study location and animals

Data were collected from 256 surgically castrated male pigs with an average slaughter body weight of 130 ± 3.9 kg. The pigs were processed at a commercial slaughterhouse under Federal Inspection Service (SIF) located in the state of Paraná, Brazil (latitude: -24.7922, longitude: -50.0117; 24° 47' 32" S, 50° 0' 42" W), during two seasons (winter and summer). Animals were selected in advance by identifying batches transported over distances < 50 km for treatment 1 and > 90 km for treatment 2. To enable carcass identification in the chilling room, pigs were tattooed on the shoulder region immediately after unloading, indicating the respective treatment.

The evaluated batches were transported to the slaughterhouse in the morning using two-deck transport vehicles. All trucks were fitted with shade cloths to reduce direct solar radiation exposure. The transport vehicles operated at a loading density of 235 kg/m². Upon arrival, all animals were unloaded using a rattle paddle and moved in groups of 14 pigs to the holding pens without the use of aversive handling. The average fasting time of the evaluated batches was 12 h.

The slaughterhouse used mobile unloading ramps aligned with the height of the truck floor. The average waiting time for unloading was 20 min. Each pen had three nipple drinkers installed on the side wall, and pigs had free access to water throughout the lairage period.

Holding pens measured 9 m², with a stocking density of 216.16 kg/m². Environmental enrichment was provided by a hanging metal chain positioned above each pen. During lairage, pigs were showered using overhead water sprinklers to remove body dirt. After 3 h of rest, animals were moved to slaughter.

Pigs were driven from the holding pens to the stunning area in groups of 14. At the entrance to stunning, animals were subdivided into smaller groups of six pigs and guided into the CO₂ stunning chamber,

where they remained for at least 2 min at a minimum concentration of 85% CO₂. After stunning, animals were exsanguinated by making an approximately 5 cm incision to sever the carotid arteries and jugular veins in the mid-neck region (thoracic inlet area), ensuring bleeding and death.

2.2 Treatments and experimental design

The study used a completely randomized design in a 2 × 2 factorial arrangement. Treatments consisted of two transport distances (28 ± 10 km and 112 ± 24 km) evaluated in two seasons (winter and summer).

A total of 10 lairage pens were observed during winter (five pens per transport distance) and eight pens during summer (four pens per transport distance). Data collection took place from July to December, with winter data collected in July and summer data collected in December. In both seasons, only two pens were observed per day (one per transport distance), resulting in five consecutive experimental days in winter and four consecutive experimental days in summer.

2.3 Environmental variables

A data logger (HOBO Ware® - Onset Computer Corporation, Bourne, MA, USA) was used to monitor environmental variables, including temperature and relative humidity, throughout the study period. The device was installed above the lairage pens. The recorder was programmed to register temperature (T) and relative humidity (RH) at 5-min intervals from the beginning of unloading until slaughter. Data were subsequently extracted using HOBO ware software.

Based on T and RH values, the mean temperature-humidity index (THI) was calculated according to the following formula: $THI = (1.8 \times T + 32) - [(0.55 - 0.0055 \times RH) \times ((1.8 \times T - 26))]$ (Weschenfelder et al. 2013), where T is expressed in °C and RH in %.

2.4 Lairage pen behavior

Behavior during lairage was recorded continuously for 3 h (180 min) by a panel of trained observers, with an intra-observer reliability coefficient of 0.98. Observers were strategically positioned on a platform above the pens to ensure complete and simultaneous visualization of all animals. Observations of each pen began as soon as the pen reached its stocking capacity (14 pigs per pen) and the gate was closed.

Scan sampling at 5-min intervals was used to record the number of pigs lying, standing, sitting, or adopting other postures, whereas continuous observation was performed to record drinking and fighting behaviors (Table 1). Drinking time was defined as any occurrence of a pig placing its mouth around the drinker regardless of duration. A new drinking bout was recorded if the pig's mouth remained away from the drinker for at least 5 s. For fighting behavior, the sequence was required to last at least 2 s with no interruption longer than 10 s. If the interval between events exceeded 10 s, it was considered a new fight. If a third pig joined the interaction, a new fighting event was recorded.

Table 1

Operational definitions of behaviors evaluated during the lairage period at the slaughterhouse.

Behavior	Description
Standing	The pig is supported in a vertical position using three or four extended legs, with the abdomen not in contact with the floor.
Lying	The pig is not using any limbs to support its body and may have full contact with the floor either lying laterally on the floor or partially on another pig.
Sitting	The pig is supported by one or two forelimbs, while the hind limbs do not support the body, and the hindquarters part of the animal is in contact with the floor or another lying pig.
Other posture	The pig is not in any of the previously defined postures, including situations in which it is neither standing, sitting, nor lying
Drinking water	Pigs place their mouth around the drinker for any duration (a new drinking event is recorded if the animal remains away from the drinker for at least 5 s).
Fighting	Animals displaying aggressive or intense competitive behaviors toward other pigs, whether reciprocal or not, occurring suddenly or persistently.
Latency to drink	Period, measured for each pen, from the moment the lairage pen was filled and the gate was closed until the first pig initiated drinking.
Latency to lie down	Period, measured for each pen, from the moment the lairage pen was filled and the gate was closed until at least 50% of the pigs were lying.
Adapted from Vero et al. (2023).	

For postural behavior, the mean percentage of pigs standing, lying, sitting, and in other postures was calculated. Data were analyzed for the entire 3-h period and separately for the first, second, and third hours. Latency to lie down was calculated as the time (min) from the start of lairage until at least 50% of pigs were lying.

Drinking behavior during lairage was analyzed based on the number of drinking bouts per pen and the percentage of time spent drinking. Drinking latency was calculated as the time (min) from pen closure until the first pig in the pen reached the drinker and initiated drinking. Fighting behavior was analyzed based on the percentage of time spent fighting and the total number of fight events. Drinking and fighting data were analyzed for the entire 3-h observation period.

2.5 Blood collection

Blood was collected at the bleeding channel using a plastic cup and transferred to 4-mL Firslab® vacuum tubes containing fluoride and ethylenediaminetetraacetic acid (EDTA) for lactate and glucose analyses, and to tubes containing a clot activator for albumin analysis. Tubes were gently inverted eight times immediately after collection to ensure homogenization. The samples were stored in a polystyrene cooler containing reusable ice packs (Gelox®) and transported to the laboratory. To obtain serum and

plasma, samples were centrifuged at 3,000 rpm for 10 min. Serum and plasma were transferred to Eppendorf® tubes and stored at – 20°C until biochemical analyses.

Serum samples were analyzed using the Dimension® LDI Flex® reagent cartridge and Albumina-PP (Analisa®) for albumin determination. Plasma samples were assessed using the Siemens/Dimension Gluc Ver Flex method and Dimension LA–Lactic Acid for glucose and lactate, respectively. All analyses were performed using a Siemens Dimension Xpand Plus analyzer (Siemens Healthcare Diagnostics Inc., USA).

2.6 Carcass and meat quality

Carcass lesions were assessed by a single trained investigator in the chilling room 24 h after *post mortem* using a five-point photographic scale (ranging from 1 = no lesions to 5 = severe lesions) (MLC 1985).

Color, pH, and water-holding capacity were measured 24 h post slaughter. These parameters were assessed in the cold room at an average cold temperature of 4°C. Ultimate pH (pH_{24h}) was determined using a Testo 205® digital pH meter (Testo AG, Lenzkirch, Germany), previously calibrated at room temperature with two buffer solutions, acidic (pH 4) and basic (pH 7). pH was measured in the ham region (*Semimembranosus muscle*).

Water-holding capacity was assessed following the method described by Kauffman et al. (1986). A superficial cut was made in the ham region to allow surface oxygenation of the area for 10 min. After this period, the plastic was removed and filter paper (Whatman® Grade 1, 125 mm diameter) was applied to the ham surface for 3 s using anatomical forceps. The filter paper was compared with a photographic standard scale of moisture loss (score 0–5). This comparison was performed by a single observer to avoid inter-observer variation. Drip loss percentage was subsequently estimated using the following equation: % drip loss = 1.8 + 1.4 (filter paper score).

Color was evaluated using a portable Minolta CR-10® device (Konica Minolta, Inc., Osaka, Japan) with illuminant D65, a 10° observer angle, and an 8.0 mm aperture (CIE 1978). Measurements were taken at three different points on the sample surface, and the mean value was calculated. Results were expressed using the CIELAB color space (L*, a*, b*).

2.7 Statistical analysis

The experimental design was completely randomized in a 2 × 2 factorial arrangement. The factors analyzed were two transport distances (28 ± 10 and 112 ± 24 km) and two seasons (winter and summer), with transport time between journeys included as a covariate. The lairage pen was considered the experimental unit.

Behavioral data, carcass and meat quality traits, and blood parameters were analyzed using Statistica software (version 2010). The effects of the experimental factors were assessed using the general linear model (GLM) procedure, with the model fitted to include main effects and their interaction. Model

assumptions were evaluated prior to analysis, including residual normality and homogeneity of variances.

3 Results

3.1 Environmental variables

During winter, the mean air temperature in the lairage facilities at the slaughterhouse was 19.54°C (range: 4.74 to 27.95°C), with a mean relative humidity of 55.24% (ranging from 34.56 to 95.61%) and a mean temperature-humidity index (THI) of 62.17. In contrast, during summer, the mean temperature was 26.98°C (range: 17.25 to 34.60°C), with a mean relative humidity of 47.22% (range: 18.30 to 79.77%) and a mean THI of 68.31.

3.2 Lairage pen behavior

No interaction between transport distance and season was observed for any behavioral variables. However, pigs transported over shorter distances ($p = 0.034$) and during summer ($p = 0.013$) showed a shorter latency to drink water. During summer, pigs also spent a greater proportion of time drinking water (Table 2).

Table 2
Effects of transport distance and season on drinking behavior, fighting, and latency variables of pigs during lairage at the slaughterhouse.

	Distance		Season		SD	p-value		
	28 ± 10 km	112 ± 24 km	Winter	Summer		TD	SEA	DTxSEA
Latency to drink water (min)	2.44	5.37	5.11	2.37	2.24	0.034	0.013	0.280
Time spent drinking (% of total lairage time)	4.90	4.20	5.40	6.50	4.33	0.447	< 0.001	0.511
Drinking episodes (n per pen)	31.33	47.12	36.11	41.75	23.94	0.433	0.677	0.859
Latency to lie down (min)	22.40	24.50	30.3	11.81	16.79	0.781	0.048	0.254
Time spent fighting (% of total lairage time)	3.07	3.81	3.60	3.21	5.33	0.779	0.904	0.632
Fighting episodes (n per pen)	11.77	8.37	8.44	12.12	8.63	0.908	0.539	0.631
Min: minutes; %: percentage of total lairage time; n: mean number of episodes per pen; SD: standard deviation. TD: transport distance; SEA: season; TD × SEA: interaction between transport distance and season. The lairage pen was considered the experimental unit.								

Time spent fighting and the number of fighting events in the lairage pens were not affected by transport distance or season. However, pigs transported during winter showed a longer latency to lie down ($p = 0.048$) after arriving in the lairage pens (Table 2).

Transport distance and season, as well as their interaction, did not affect postural behaviors during the entire 3-h lairage period ($p > 0.05$) (Table 3). However, when postures were analyzed separately by hour, a consistent behavioral pattern was observed across groups, indicating a natural transition from standing to lying over time (Fig. 1).

Table 3

Mean number of pigs per pen observed in each postural behavior during lairage according to transport distance and season.

	Distance		Season		SD	p-value		
	28 ± 10 km	112 ± 24 km	Winter	Summer		DT	SEA	DT x SEA
Behavior								
Standing (n pigs per pen)	7.80	7.00	6.50	7.00	3.14	0.320	0.817	0.253
Sitting (n pigs per pen)	1.20	1.25	1.25	0.75	0.65	0.121	0.464	0.718
Lying (n pigs per pen)	5.00	6.00	6.25	6.00	3.32	0.214	0.935	0.272
Other posture (n pigs per pen)	0	0.20	0	0.10	0.15	0.334	0.133	0.176
n: number of pigs per pen; SD: standard deviation. TD: transport distance; SEA: season; TD × SEA: interaction between transport distance and season.								
The lairage pen was considered the experimental unit.								

Regarding lying behavior across hours, no difference was observed between the second and third hours. Only the first hour differed among treatments, during which pigs remained standing for a longer period in both summer and winter. A similar pattern was observed for lying behavior, with a higher number of pigs lying during the second and third hours compared with the first hour.

3.3 Stress biomarkers

Blood lactate at slaughter was higher in pigs transported during summer (7.07 and 7.56 mmol/L for short and long distances, respectively) than in those transported during winter (4.14 and 4.20 mmol/L for short and long distances, respectively) ($p < 0.0001$) (Fig. 2), across both transport distances.

There was an interaction between season and transport time for plasma glucose concentration. Pigs transported for 28 ± 10 km during winter showed lower glucose concentration (100.9 mg/dL). Regardless of season, pigs transported for 112 ± 24 km showed higher plasma glucose values (125.1 and 120.1 mg/dL in winter and summer, respectively) ($p = 0.045629$). Glucose concentration in pigs transported for 28 ± 10 km during summer (115.2 mg/dL) did not differ from the other treatments (Fig. 3).

Blood albumin concentration did not differ between pigs transported during winter across the two distances analyzed (4.12 and 4.21 g/dL for short and long distances, respectively). However, during summer, pigs transported for 28 km showed higher blood albumin concentration at slaughter (4.40 g/dL) than pigs transported for 112 km (4.27 g/dL) (Fig. 4).

3.4 Carcass and meat quality

The interaction between transport distance and season did not affect any of the carcass or meat quality parameters evaluated ($p > 0.05$) (Table 4). However, season had a significant effect on carcass lesion scores ($p < 0.0001$), with higher lesion scores observed in carcasses from pigs transported in summer (2.12 ± 0.39) compared with winter (1.30 ± 0.55). Transport distance also influenced Semimembranosus muscle $\text{pH}_{24\text{h}}$ ($p = 0.0065$), with pigs transported for 112 km showing higher $\text{pH}_{24\text{h}}$ values.

Table 4

Effects of transport distance and season on carcass lesion score and meat quality traits of the *Semimembranosus* muscle in pigs.

	Distance		Season		SD	p-value		
	28 ± 10 km	112 ± 24 km	Winter	Summer		TD	SEA	DTxSEA
Carcass lesion score (5-point photographic scale)	1.67	1.72	1.30	2.12	0.01	0.726	< 0.001	0.768
Final pH ($\text{pH}_{24\text{h}}$)	5.77	5.81	5.80	5.78	0.04	0.006	0.269	0.218
L* (lightness)	44.1	43.96	44.14	43.81	0.16	0.492	0.203	0.962
a* (redness)	4.01	4.45	3.12	5.44	0.17	0.951	0.000	0.351
b* (yellowness)	11.86	11.84	12.02	11.67	0.20	0.052	0.306	0.145
Drip loss (% of muscle weight)	2.39	2.71	2.34	2.78	0.09	0.174	0.004	0.164
Values are expressed as means ± SD. SD: standard deviation. TD: transport distance; SEA: season; TD × SEA: interaction between transport distance and season. The lairage pen was considered the experimental unit.								

Season affected a* values ($p < 0.0001$), indicating that meat was redder in summer (5.44 ± 2.86) than in winter (3.12 ± 1.30). Drip loss percentage ($p = 0.0042$) was also influenced by season, with higher values in carcasses from pigs transported in summer (2.78 ± 1.55) compared with winter (2.34 ± 1.01).

4 Discussion

4.1 Environmental variables

Temperature and humidity variations inside vehicle compartments have been shown to affect pigs' thermal comfort and physiological responses. In the present study, the recorded temperature values were outside the range recommended by the European Commission to ensure thermal comfort in pigs during transport for slaughter, which is between 10 and 28°C (European Commission 2019). During both

summer and winter, temperatures were recorded below 10°C or above 28°C, which likely exposed the animals to considerable thermal stress during certain periods, either due to cold stress in winter or heat stress in summer, thereby impairing the animals' ability to maintain homeostasis.

The temperature-humidity index (THI) remained within levels considered to be within the thermal comfort range ($\text{THI} < 75$). However, at certain moments during the lairage period, relative humidity exceeded the threshold of 88%, a level that may impair evaporative cooling mechanisms in pigs. These conditions may lead to reduced activity, increased respiration and heart rate, and greater contact with cold and wet surfaces, thereby increasing the risk of mortality (Rioja-Lang et al. 2019; Ruis and Bracke 2021). Peterson et al. (2017) reported that inadequate ventilation and high temperature gradients within transport vehicles increased mortality and fatigue in pigs upon arrival at the slaughterhouse.

4.2 Lairage pen behavior

Behavioral observations during lairage provide insight into pigs' recovery after transportation. Pigs transported during summer sought water sooner and spent more time drinking. Increased water consumption under heat stress conditions represents a physiological response aimed at thermoregulation, as evaporative cooling and panting increase water loss. Conversely, reduced drinking time during lairage may be associated with a higher degree of fatigue upon arrival at the slaughterhouse (Urrea et al. 2021). According to Kobek-Kjeldager et al. (2023), pigs subjected to longer journeys and high temperatures tend to rest more, drink less water, and show reduced exploratory behavior, reflecting stress and muscular fatigue. Therefore, the present findings suggest that heat stress during summer was not sufficiently severe to suppress water-seeking behavior, as pigs were able to access drinkers and rehydrate after transport.

Transport distance and season did not affect the time pigs spent fighting or the number of fighting episodes in the lairage pens at the slaughterhouse. The conditions implemented in the lairage pens, characterized by handling pigs in small groups, may have been effective in limiting aggressive behaviors during lairage by avoiding the mixing of unfamiliar groups. This strategy, by modulating pig interactions through subdivision into smaller groups, likely contributed to reducing social conflicts and aggressive encounters among animals. Such an approach may be considered promising for improving pig welfare during pre-slaughter resting periods, as it promotes a more stable social environment and minimizes the potential risks associated with aggressive interactions (Faucitano and Goumon 2018).

During winter, pigs showed a longer latency to lie down during lairage. When pigs lie on a cold floor, the thermal gradient between the warm body and the cold surface promotes rapid heat transfer from the body to the floor via thermal conduction. This process increases body heat loss, potentially reducing peripheral temperature and causing thermal discomfort or even hypothermia if the animal is unable to compensate metabolically for heat loss. To minimize heat loss, pigs tend to remain standing or seek drier and more insulated areas, thereby reducing the body surface area in contact with the floor and decreasing conductive heat loss.

Pigs spent more time standing during the first hour and more time lying during the second and third hours of lairage, regardless of the transport treatments applied. This pattern suggests the existence of a common behavioral response, largely independent of transport conditions or season, reinforcing the understanding of the temporal dynamics of lairage behavior in pigs. Typically, pigs spend the initial hour exploring the new environment and subsequently remain lying for most of the resting period, even under different transport conditions. In contrast, pigs in a state of exhaustion tend to remain lying throughout lairage (Brandt and Aaslyng 2015; Dalla Costa et al. 2016; Fox et al. 2014; Urrea et al. 2021).

It is also important to note that pigs spend more time resting than exploring the environment. This reflects a species-typical behavioral pattern, in which exploratory behavior is the second most frequently observed activity in growing–finishing pigs, while lying and/or sleeping represents the most prevalent behavior (Martínez-Macipe et al. 2020; Ocepek et al. 2020).

4.3 Stress biomarkers

Increases in plasma cortisol and glucose concentrations are considered reliable indicators of the intensity of the stress response during transport, whereas blood lactate is a well-established indicator of animal fatigue. Chronic stimulation associated with prolonged stress activates the hypothalamic–pituitary–adrenal (HPA) axis, triggering the release of corticotropin-releasing hormone by the hypothalamus, adrenocorticotrophic hormone (ACTH) by the pituitary gland, and cortisol by the adrenal cortex (Loudon et al. 2019). The release of cortisol into the bloodstream promotes catabolic processes in peripheral tissues, such as glycogenolysis, proteolysis, and lipolysis, while stimulating anabolic activity in the liver, including gluconeogenesis and protein synthesis. This metabolic response increases blood glucose levels to provide the energy required to cope with stress (Day 2000).

Pigs transported over short distances during winter showed lower blood glucose concentrations, consistent with previous studies reporting higher glucose levels in pigs subjected to longer transport durations (Becerril-Herrera et al. 2010; Mota-Rojas et al. 2006). These findings reinforce the role of transport duration as a relevant factor influencing the metabolic stress response.

Pigs transported during summer exhibited higher blood lactate concentrations. Elevated blood lactate levels in pigs are generally associated with muscular fatigue, which may have been exacerbated by heat stress during specific stages of pre-slaughter handling (Martínez-Rodríguez et al. 2015; Mota-Rojas et al. 2012; Roldan-Santiago et al. 2013). Muscular fatigue increases oxygen demand, leading to a shift toward anaerobic glycolysis for adenosine triphosphate (ATP) production and, consequently, to increased lactate accumulation in the bloodstream. There is evidence that both hot and cold temperature conditions represent physiological challenges for pigs during transport and lairage (Torrey et al. 2013). Similar findings were reported by Huanca-Marca et al. (2025), who observed that shorter pre-slaughter logistics (< 3.5 h) were associated with higher plasma cortisol and lactate levels in market pigs, indicating that the initial stages of transport and handling are particularly stressful. Elevated blood lactate concentrations may, in turn, negatively affect meat quality, resulting in tougher meat and increased shear force (Antonelo et al. 2006).

Total plasma protein and albumin concentrations are indicators of protein homeostasis, and both typically increase under dehydration. Considering plasma albumin concentrations, dehydration is regarded as the primary cause of elevated albumin levels (hyperalbuminemia) (Carr 1998; Mersmann and Pond 2001). On average, all pigs in the present study exhibited elevated albumin concentrations compared with the physiological reference range for the species (1.80–3.30 g/dL) (Kaneko et al. 2008). These values therefore indicate that, regardless of transport conditions and season, all animals experienced some degree of dehydration at slaughter.

4.4 Carcass and meat quality

The incidence of skin lesions observed in this study reflects the intensity of physical interactions among animals and the handling conditions during loading, unloading, and lairage at the slaughterhouse. All experimental treatments resulted in carcasses presenting lesions. Transport increases stress and agitation in pigs, mainly due to prolonged exposure to uncomfortable conditions and abrupt temperature changes during the journey. Pre-slaughter stress may lead to abnormal behaviors, such as aggression among pigs, excessive vocalization, and disorganized movement in lairage pens, negatively affecting animal welfare (Peres 2014) and potentially increasing both the number and severity of carcass lesions.

In addition, a higher incidence of carcass lesions may be associated with the mixing of batches at the farm, which can increase the frequency of confrontations among animals. Previous studies have reported a higher incidence of fighting in pigs that were previously mixed (Barton Gade 2008). Pigs are highly social animals with a natural preference for living in groups with a clearly defined hierarchical structure. Consequently, disruptions to these social arrangements can trigger aggressive behaviors during competition for resources such as feed, water, or rest areas. These competitive interactions may result in injuries and adverse physiological responses, thereby compromising animal welfare (Gimsa et al. 2018).

In the present study, pigs exhibited a higher degree of carcass lesions during summer. Similarly, Barton Gade (2008) reported increased aggressive behavior in pigs transported during summer, particularly under high ambient temperatures, where thermal discomfort exacerbates aggressiveness. Furthermore, the prevalence of carcass lesions can be considered an indicator of pre-slaughter stress.

Pigs transported over longer distances showed higher pH_{24h} values. Long-distance transport has been described as physically, metabolically, and emotionally demanding for pigs (Garrido-Izard et al. 2019). Thermal stress is one of the main factors that may exacerbate the effects of long-distance transport on pig health and welfare, and in combination with transport-related stress, may contribute to higher ultimate pH values (Garrido-Izard et al. 2019). Final muscle pH plays a key role by interacting with the isoelectric point of myofibrillar proteins, influencing not only their physical integrity and light dispersion on the muscle surface, but also product stability during storage.

Pigs slaughtered during summer showed higher drip loss values. Although ultimate pH was not affected, pigs slaughtered in summer exhibited more aggressive behavior and higher blood lactate

concentrations. These factors may have led to a more pronounced decline in pH during the first hour *post mortem*, resulting in degradation of myofibrillar and sarcoplasmic proteins and damage to cell membranes, ultimately increasing water loss from the meat (Choe et al. 2015). Čobanović et al. (2020) observed that pigs slaughtered in summer exhibited lower pH, higher thawing loss, increased L* and b* values, and a higher occurrence of pale, soft, and exudative meat.

5 Conclusion

Transport distance and season did not influence pigs' behavior in the lairage pens, as animals exhibited similar postural patterns across the different observation periods. However, regardless of season or transport distance, pigs showed biochemical changes in blood indicative of pre-slaughter stress and dehydration. In contrast, pigs transported during summer exhibited a higher incidence of carcass lesions and more pronounced blood alterations, resulting in meat with reduced water-holding capacity and compromised quality attributes.

Declarations

Acknowledgments

The authors thank MEC/SESu/FNDE for the scholarship granted to the first author and CAPES for providing scholarships to the graduate students involved in this study.

Statement of Animal Rights

The animal study was approved by the Comissão de Ética no Uso de Animais of the State University of Londrina (UEL), under protocol number 043.2023. All procedures were conducted in accordance with local legislation and institutional requirements. Written informed consent was obtained from the owners for the participation of their animals in this study.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Funding

This project was funded by PAS–HUTec (Programa de Prestação de Serviços da Fazenda-Escola). The funders had no role in the study design, data collection, analysis, or interpretation, the writing of the manuscript, or the decision to submit the article for publication.

Competing Interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author contributions

BRIDI AM: Conceptualization, methodology, resources, project administration, data curation, formal analysis, writing—original draft, writing—review and editing. SILVA GL: the acquisition, analysis, or interpretation of data, writing—original draft, writing. SIMIZU NNO: the acquisition, analysis, interpretation of data, writing—review. TERTO DK: the acquisition, analysis, interpretation of data, writing—review. FERREIRA NA: the acquisition, analysis, interpretation of data, writing—review. FLAIBAN, KKMC: Methodology, supervision, formal analysis, writing—review. SILVA CA: Validation, formal analysis, supervision, writing—review. CARVALHO RH: Supervision, data curation, formal analysis, writing—review.

Data Availability

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics Approval

The animal study was approved by the Comissão de Ética no Uso de Animais of the State University of Londrina (UEL), under protocol number 043.2023. All procedures were conducted in accordance with local legislation and institutional requirements. Written informed consent was obtained from the owners for the participation of their animals in this study.

References

1. Antonelo D, Gómez J, Cônsolo N, Beline M, Colnago L, Schilling W, Zhang X, Suman S, Gerrard D, Balieiro J and Silva S (2020) Metabolites and metabolic pathways correlated with beef tenderness. *Meat Muscle Biol* 4:1. <https://doi.org/10.22175/mmb.10854>
2. Barton Gade P (2008) Effect of rearing system and mixing at loading on transport and lairage behaviour and meat quality: comparison of outdoor and conventionally raised pigs. *Animal* 2:902–911. <https://doi.org/10.1017/S1751731108002000>
3. Becerril-Herrera M, Alonso-Spilsbury M, Trujillo-Ortega ME, Guerrero-Legarreta I, Ramírez-Necoechea R, Roldan-Santiago P, Pérez-Soto M, Soní-Guillermo E and Mota-Rojas D (2010) Changes in blood constituents of swine transported for 8 or 16 h to an abattoir. *Meat Sci* 86:945–948. <https://doi.org/10.1016/j.meatsci.2010.07.021>
4. Brandt P and Aaslyng MD (2015) Welfare measurements of finishing pigs on the day of slaughter: a review. *Meat Sci* 103:13–23. <https://doi.org/10.1016/j.meatsci.2014.12.004>
5. Carr J (1998) Garth pig stockmanship standards. 5M Enterprises Limited, Sheffield.
6. Choe JH, Choi MH, Ryu YC, Go GW, Choi YM, Lee SH, Lim KS, Lee EA, Kang JH, Hong KC and Kim BC (2015) Estimation of pork quality traits using exsanguination blood and postmortem muscle metabolites. *Asian-Australas J Anim Sci* 28:862–869. <https://doi.org/10.5713/ajas.14.0768>

7. Commission Internationale de l'Eclairage (1978) Recommendations on uniform colour spaces, colour difference equations, psychometric colour terms. Supplement No. 2 to CIE Publication No. 15 (E-1.3.1) 1971. Bureau Central de la CIE, Paris.
8. Čobanović N, Stajković S, Blagojević B, Betić N, Dimitrijević M, Vasilev D and Karabasil N (2020) The effects of season on health, welfare, and carcass and meat quality of slaughter pigs. *Int J Biometeorol* 64:1899–1909. <https://doi.org/10.1007/s00484-020-01977-y>
9. Dalla Costa FA, Devillers N, Paranhos da Costa MJR and Faucitano L (2016) Effects of applying preslaughter feed withdrawal at the abattoir on behaviour, blood parameters and meat quality in pigs. *Meat Sci* 119:89–94. <https://doi.org/10.1016/j.meatsci.2016.03.033>
10. Day MJ (2000) Biology of lymphocytes and plasma cells. In: Feldman BF, Zinkl JG and Jain NC (eds) *Schalm's Veterinary Hematology*. Williams & Wilkins, Philadelphia, pp 240–246.
11. European Commission (2019) Transport guide: extreme temperatures – pigs. EU Platform on Animal Welfare.
12. Faucitano L and Goumon S (2018) Transport of pigs to slaughter and associated handling. In: Špinko M (ed) *Advances in Pig Welfare*. Woodhead Publishing, pp 261–293. <https://doi.org/10.1016/C2015-0-05682-9>
13. Faucitano L and Lambooij E (2019) Transport of pigs. In: Grandin TA (ed) *Livestock Transport and Handling*. CAB International, Wallingford, UK, pp 307–327.
14. Fazio F, Arfuso F, Rizzo M, Giannetto C, Giudice E, Zanghì E and Piccione G (2018) Livestock handling and road transport influence some oxidative stress parameters in ewes. *J Vet Behav* 26:5–10. <https://doi.org/10.1016/j.jveb.2018.03.010>
15. Fox J, Widowski T, Torrey S, Nannoni E, Bergeron R, Gonyou HW, Brown JA, Crowe T, Mainau E and Faucitano L (2014) Water sprinkling market pigs in a stationary trailer. I. Effects on pig behaviour, gastrointestinal tract temperature and trailer microclimate. *Livest Sci* 160:113–123. <https://doi.org/10.1016/j.livsci.2013.12.019>
16. Garrido-Izard M, Correa EC, Requejo JM, Villarroel M and Diezma B (2019) Phase space analysis of pig ear skin temperature during air and road transport. *Appl Sci* 9:5527. <https://doi.org/10.3390/app9245527>
17. Gimsa U, Tuchscherer M and Kanitz E (2018) Psychosocial stress and immunity—what can we learn from pig studies? *Front Behav Neurosci* 12:64. <https://doi.org/10.3389/fnbeh.2018.00064>
18. Gonçalves Vero J, Devillers N, Bridi AM, Moak KAT, Aboagye G, Agostinis Ferreira G, Genova JL, Conte S and Faucitano L (2023) Transport of pigs of two market weights at two space allowances: effects on behaviour, blood parameters, and meat quality under summer and winter conditions. *Animals* 13:2767. <https://doi.org/10.3390/ani13172767>
19. Huanca-Marca NF, Estévez-Moreno LX, Pastrana-Camacho A, Piñeiro M, María GA and Miranda-de la Lama CG (2025) Effects of pre-slaughter logistics duration on stress responses and coping profiles in commercial finishing pigs. *Res Vet Sci* 193:105796. <https://doi.org/10.1016/j.rvsc.2025.105796>

20. Ison SH, Bates RO, Ernst CW, Steibel JP and Siegford JM (2018) Housing, ease of handling and minimising inter-pig aggression at mixing for nursery to finishing pigs as reported in a survey of North American pork producers. *Appl Anim Behav Sci* 205:59–66.
<https://doi.org/10.1016/j.applanim.2018.05.004>
21. Kaneko JJ, Harvey JW and Bruss ML (2008) *Clinical biochemistry of domestic animals*. 6th edn. Academic Press, New York.
22. Kauffman RG, Eikelenboom G, van der Wal PG, Merkus G and Zaar M (1986) The use of filter paper to estimate drip loss of porcine musculature. *Meat Sci* 18:191–200. [https://doi.org/10.1016/0309-1740\(86\)90033-8](https://doi.org/10.1016/0309-1740(86)90033-8)
23. Kobek-Kjeldager C, Jensen LD, Foldager L, Thodberg K, Schrøder-Petersen DL and Herskin MS (2023) Effects of journey duration and temperature during pre-slaughter transport on behaviour of cull sows in lairage. *Res Vet Sci* 164:105016. <https://doi.org/10.1016/j.rvsc.2023.105016>
24. Loudon KMW, Tarr G, Pethick DW, Lean IJ, Polkinghorne R, Mason M, Dunshea FR, Gardner GE and McGilchrist P (2019) The use of biochemical measurements to identify pre-slaughter stress in pasture-finished beef cattle. *Animals* 9:503. <https://doi.org/10.3390/ani9080503>
25. Machado ST, Nääs IA, Mollo Neto M, Vendrametto O and Reis JGM (2016) Effect of transportation distance on weight losses in pigs from dehydration. *Eng Agric* 36:1229–1238.
<https://doi.org/10.1590/1809-4430-Eng.Agric.v36n6p1229-1238/2016>
26. Machado NAF, Martin JE, Barbosa-Filho JAD, Dias CTS, Pinheiro DG, de Oliveira KPL and Souza-Junior JBF (2021) Identification of trailer heat zones and associated heat stress in weaner pigs transported by road in tropical climates. *J Therm. Biol* 97:102882.
<https://doi.org/10.1016/j.jtherbio.2021.102882>
27. Martínez-Macipe M, Mainau E, Manteca X and Dalmau A (2020) Environmental and management factors affecting the time budgets of free-ranging Iberian pigs reared in Spain. *Animals* 10:798.
<https://doi.org/10.3390/ani10050798>
28. Martínez-Rodríguez R, Roldan-Santiago P, Orozco-Gregorio H, Trujillo-Ortega ME, Mora-Medina P, González-Lozano M, Sánchez-Hernández M, Bonilla-Jaime H, García-Herrera R, Hernández-Trujillo E and Mota-Rojas D (2015) Physiological responses and blood gas exchange following long-distance transport of piglets weaned at different ages over unpaved or paved roads. *Livest Sci* 172:69–78.
<https://doi.org/10.1016/j.livsci.2014.12.013>
29. Mersmann HJ and Pond WG (2001) Hematology and blood serum constituents. In: Pond WG and Mersmann HJ (eds) *Biology of the Domestic Pig*. Cornell University Press, Ithaca, NY.
30. Miranda-de la Lama GC, Villarroel M and María GA (2014) Livestock transport from the perspective of the pre-slaughter logistic chain: a review. *Meat Sci* 98:9–20.
<https://doi.org/10.1016/j.meatsci.2014.04.005>
31. MLC (1985) Concern at ringside damage in pigs. *Meat and Marketing Technical Notes*. Meat and Livestock Commission, Milton Keynes, UK, pp 14–16.

32. Mota-Rojas D, Becerril M, Lemus C, Sánchez P, González M, Olmos SA, Ramírez R and Alonso-Spilsbury M (2006) Effects of mid-summer transport duration on pre- and post-slaughter performance and pork quality in Mexico. *Meat Sci* 73:404–412.
<https://doi.org/10.1016/j.meatsci.2005.11.012>
33. Mota-Rojas D, Becerril-Herrera M, Roldan-Santiago P, Alonso-Spilsbury M, Flores-Peinado S, Ramírez-Necoechea R, Ramírez-Telles JA, Mora-Medina P, Pérez M, Molina E, Soní E and Trujillo-Ortega ME (2012) Effects of long-distance transportation and CO₂ stunning on critical blood values in pigs. *Meat Sci* 90:893–898. <https://doi.org/10.1016/j.meatsci.2011.11.027>
34. Ocepek M, Goold CM, Busančić M and Aarnink AJA (2020) Maize silage as enrichment material improves the welfare of growing-finishing pigs in environmentally friendly pens. *Appl Anim Behav Sci* 230:105043. <https://doi.org/10.1016/j.applanim.2020.105043>
35. Peres LM, Bridi AM, Silva CA, Andreo N, Tarsitano M and Stivaletti ELT (2014) Effect of low or high stress in pre-slaughter handling on pig carcass and meat quality. *Rev Bras Zootec* 43:385–390. <https://doi.org/10.1590/S1516-35982014000700004>
36. Peterson E, Remmenga M, Hagerman AD and Akkina JE (2017) Use of temperature, humidity, and slaughter condemnation data to predict increases in transport losses in three classes of swine and resulting foregone revenue. *Front Vet Sci* 4:67. <https://doi.org/10.3389/fvets.2017.00067>
37. Rioja-Lang FC, Brown JA and Brockhoff EJ (2019) A review of swine transportation research on priority welfare issues: a Canadian perspective. *Front Vet Sci* 6:36. <https://doi.org/10.3389/fvets.2019.00036>
38. Rizzo M, Arfuso F, Giannetto C, Giudice E, Longo F, Di Pietro S and Piccione G (2017) Cortisol levels and leukocyte population values in transported and exercised horses after acupuncture needle stimulation. *J Vet Behav* 18:56–61. <https://doi.org/10.1016/j.jveb.2016.12.006>
39. Roldan-Santiago P, Martinez-Rodriguez R, Yanez-Pizana A, Trujillo-Ortega ME, Sanchez-Hernandez M, Perez-Pedraza E and Mota-Rojas D (2013) Stressor factors in the transport of weaned piglets: a review. *Vet Med* 58:241–251. <https://doi.org/10.17221/6805-VETMED>
40. Ruis AAW and Bracke MBM (2021) Review of climate control and space allowance during transport of pigs. European Reference Centre for Animal Welfare (EURCAW-Pigs).
41. Torrey S, Bergeron R, Faucitano L, Widowski T, Lewis N, Crowe T, Correa JA, Brown J, Hayne S and Gonyou HW (2013) Transportation of market-weight pigs. II. Effect of season and location within truck on behavior during an eight-hour transport. *J Anim Sci* 91:2872–2878. <https://doi.org/10.2527/jas.2012-6006>
42. Urrea VM, Bridi AM, Ceballos MC, Paranhos da Costa MJR and Faucitano L (2021) Behavior, blood stress indicators, skin lesions, and meat quality in pigs transported to slaughter at different loading densities. *J Anim Sci* 99:skab119. <https://doi.org/10.1093/jas/skab119>
43. Gonçalves VJ, Devillers N, Bridi AM, Moak KAT, Aboagye G, Agostinis FG, Genova JL, Conte S, Faucitano L. (2023) Transport of Pigs of Two Market Weights at Two Space Allowances: Effects on

44. Voslarova E, Vecerek V, Passantino A, Chloupek P and Bedanova I (2017) Transport losses in finisher pigs: impact of transport distance and season of the year. *Asian-Australas J Anim Sci* 30:119–124. <https://doi.org/10.5713/ajas.16.0265>
45. Werner C, Reiners K and Wicke M (2007) Short as well as long transport duration can affect the welfare of slaughter pigs. *Anim Welf* 16:385–389. <https://doi.org/10.1017/S0962728600027202>
46. Weschenfelder AV, Torrey S, Devillers N, Crowe T, Bassols A, Saco Y, Piñeiro M, Saucier L and Faucitano L (2013) Effects of trailer design on animal welfare parameters and carcass and meat quality of three Pietrain crosses being transported over a short distance. *Livest Sci* 157:234–244. <https://doi.org/10.1016/j.livsci.2013.07.004>

Figures

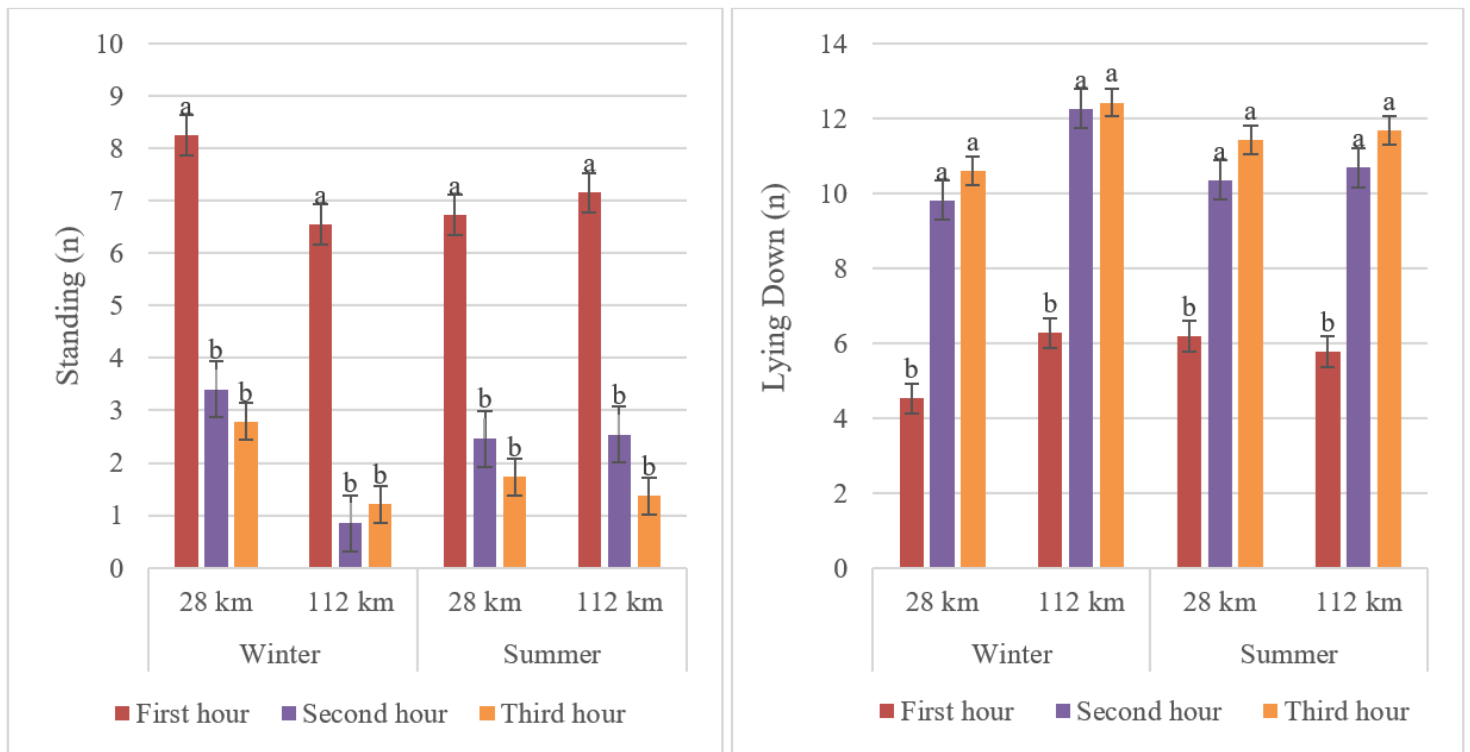


Figure 1

Interaction effects of transport distance and season on postural behavior of pigs during lairage. Mean values ($\pm$ standard deviation of the mean) of the proportion of pigs standing (a) and lying (b) during the first, second, and third hours of lairage for pigs transported over short (28 ± 10 km) and long (112 ± 24 km) distances in winter and summer. Different lowercase letters (a, b) indicate significant differences among treatments within the same hour ($p < 0.05$; Tukey's post hoc test).

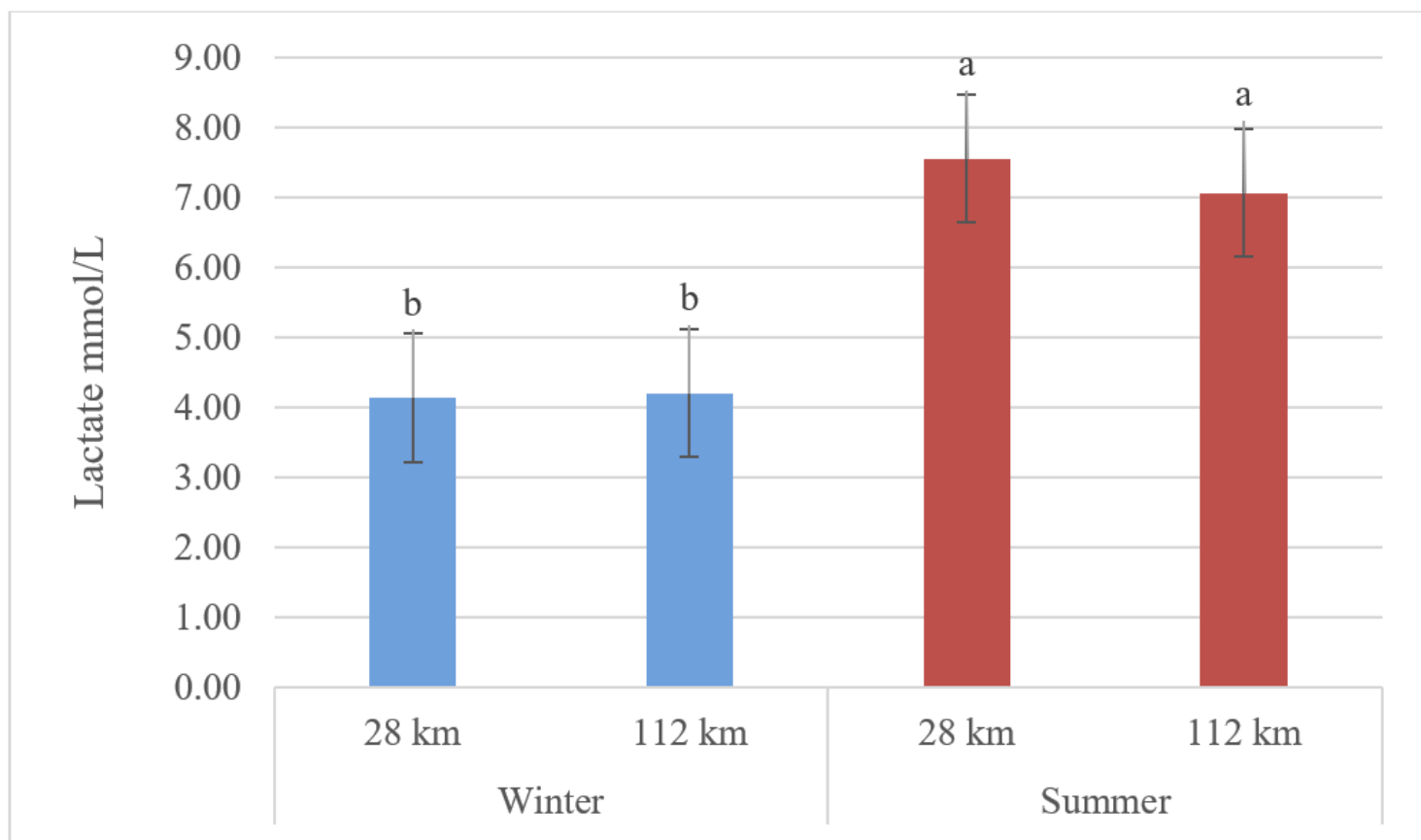


Figure 2

Interaction effects of transport distance and season on blood lactate concentration of pigs at slaughter. Mean blood lactate concentrations (mmol/L; $\pm$ standard deviation of the mean) of pigs transported over short (28 ± 10 km) and long (112 ± 24 km) distances during winter and summer. Different lowercase letters (a, b) indicate significant differences among treatments ($p < 0.05$; Tukey's post hoc test).

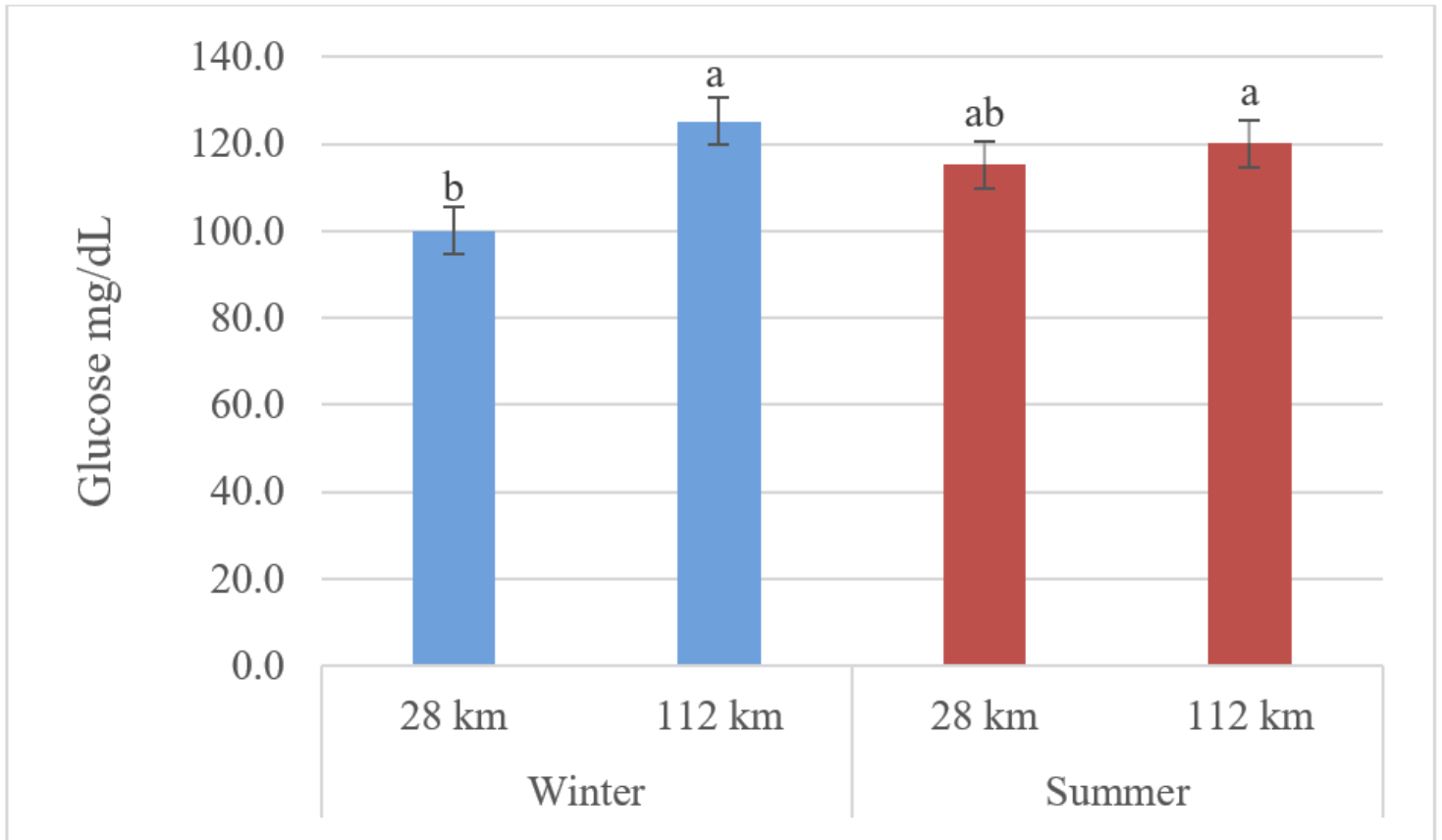


Figure 3

Interaction effects of transport distance and season on blood glucose concentration of pigs at slaughter. Mean blood glucose concentrations (mg/dL; $\pm$ standard deviation of the mean) of pigs transported over short (28 ± 10 km) and long (112 ± 24 km) distances during winter and summer. Different lowercase letters (a, b) indicate significant differences among treatments ($p < 0.05$; Tukey's post hoc test).

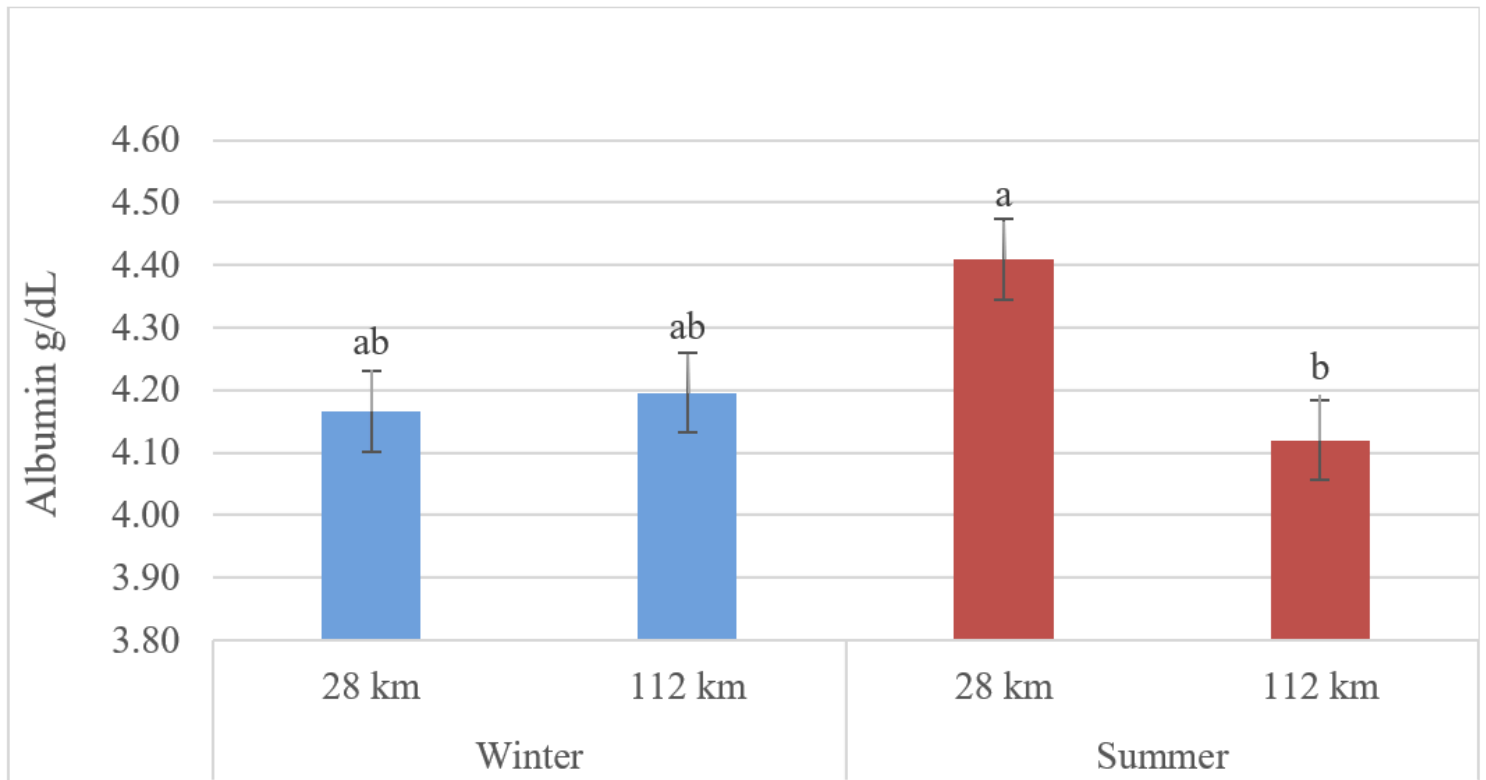


Figure 4

Interaction effects of transport distance and season on blood albumin concentration of pigs at slaughter. Mean blood albumin concentrations (g/dL; $\pm$ standard deviation of the mean) of pigs transported over short (28 ± 10 km) and long (112 ± 24 km) distances during winter and summer. Different lowercase letters (a, b) indicate significant differences among treatments ($p < 0.05$; Tukey's post hoc test).