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Animal Welfare Status and Meat Quality Attributes of Finishing Pigs Across Diverse Farm Production Scales

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ABSTRACT

The intensification of pig production in developing countries raises concerns about animal welfare and its impact on pork quality, as well as industry sustainability and product value. This study aimed to evaluate the welfare status and post-slaughter meat quality of finishing pigs across different production scales in Vietnam. A cross-sectional survey of 45 farms (small, medium, and large-scale) was conducted using the Welfare Quality® framework (four principles and twelve assessment criteria). Subsequently, 18 crossbred pigs were slaughtered to analyze *Longissimus dorsi* quality (10th-15th ribs), including pH, color, chemical composition, and fatty acid profiles. Results indicated that the good feeding principle scored significantly higher in large-scale farms (LF: 80.28) compared to medium (MF: 67.89) and small-scale farms (SF: 59.95) ($p<0.001$). Conversely, the good health principle recorded the lowest scores across all scales (LF at 7.80, MF at 7.51, and SF at 7.74; $p<0.01$). Acceptable levels were obtained for appropriate behavior and environmental comfort (40-60 points). While pH remained similar across groups, meat from LF pigs exhibited significantly lighter color, higher protein content, and increased drip loss ($p<0.01$). Notably, the proportion of unsaturated fatty acids and the UFA/SFA ratio (unsaturated fatty acids/saturated fatty acids) were greater in pigs raised on the LF, suggesting a favorable lipid composition. Briefly, large-scale production systems demonstrated enhanced animal welfare and beneficial meat quality traits, indicating that improved housing management and nutritional strategies contribute to more sustainable and higher-quality pork production.

Keywords: animal welfare; fatty acid profile; finishing pigs; large-scale farm; longissimus dorsi

INTRODUCTION

In Vietnam, large-scale pig farms are leading the adoption of innovations and progressing through initial digital transformation stages. This transition is expected to reshape the livestock sector by reducing the dominance of disease-vulnerable smallholder farms, promoting sustainable and biosecure production (Qui *et al*., 2025; Zhu *et al*., 2023). Technological applications such as microclimate monitoring (Gao *et al*., 2022) and artificial intelligence (AI) are increasingly integrated to ensure optimal housing, detect abnormal behaviors, monitor health parameters (Balthazar *et al*., 2025; Reza *et al*., 2025), enable early disease detection (Bordignon *et al*., 2025; Reza *et al*., 2025), and facilitate rapid outbreak response. Furthermore, automation minimizes human-animal interaction, limiting pathogen transmission and mitigating stress caused by frequent human presence in intensive settings (Bossert & Coeckelbergh, 2024; Williams *et al*., 2024).

Despite these advances, the rapid adoption of digital systems raises concerns regarding animal welfare (freedom from hunger and thirst, freedom from discomfort, freedom from pain, injury or disease, freedom to express normal behavior, and freedom from fear and distress) in intensive pig production globally (Herlin *et al*., 2021). Overemphasis on productivity can increase stress (Karaer *et al*., 2023; Michielon *et al*., 2024), adversely affecting physiological balance and ultimately compromising pork quality (Gagaoua *et al*., 2025; Ogawa *et al*., 2024). Studies show animal welfare improvements have a nonlinear relationship with productivity (Morgado *et al*., 2023), depending on the degree of enhancement and linked to the animal's physiological responses (Riesner *et al*., 2025).

Restricted space allowance is a major welfare issue, escalating competition for resources (Camp *et al*., 2021; Chidgey, 2024), elevating aggression, and promoting skin lesions and lameness (Camp *et al*., 2021; Vermeer *et al*., 2017). Gilts, in particular, may sustain more severe injuries than mixed-sex groups (Angela *et al.*, 2023) due to factors like higher growth rates (He *et al.*, 2019).

Stress, whether from an adverse environment or management, activates neural and endocrine pathways (Lee *et al.*, 2024). While acute stress causes increased blood cortisol and abnormal behavior (Lee *et al.*, 2024), chronic stress exerts long-term physiological impacts, including suppressed immune function and altered lipid metabolism (Lomax *et al.*, 2013). Cholesterol is central as a precursor (Salisbury *et al.*, 2023; Zhang *et al.*, 2019) for steroid/reproductive hormones (testosterone, estradiol, and cortisol steroid hormones (testosterone, estradiol, cortisol), vitamin D, and bile acids (Celso & Elise, 2024; Ma *et al.*, 2024), essential for homeostasis, reproductive function, and lipid metabolism. Prolonged stress is linked to reduced lymphocyte count and altered monocyte quality (Maydych *et al.*, 2017), leading to impaired immune function (Alotiby, 2024; Dhabhar, 2014). Consequently, growth indicators such as average daily gain (ADG) are reduced (Rodrigues *et al.*, 2024; Silpa *et al.*, 2025), and slaughter age is delayed (Hultgren *et al.*, 2022; Terlouw & Gagaoua, 2023).

Given these challenges, achieving a balance between production efficiency and animal welfare is critical for the modern pig industry. Especially in rapidly digitalizing Vietnam, integrating welfare assessment into management is essential for sustainable development and improved meat quality. Therefore, the present study was designed to evaluate the welfare status (good feeding, good housing, good health, and appropriate behavior) of finishing pigs (aged 124 - 156 days) and assess post-slaughter meat quality indicators across farms of different production scales.

MATERIALS AND METHODS

Study Site and Farm Classification

The study was conducted from October 2024 to October 2025 across 45 pig farms in Dong Nai Province, Vietnam. Farms were categorized into three distinct scales according to the Law on Animal Husbandry (Government of Vietnam, 2020) and sow-unit equivalents: small-scale (SF, 10-30 units, equivalent to approximately 100 sows), medium-scale (MF, 30-300 units, equivalent to approximately 100-500 sows), and large-scale (LF, over 300 units, equivalent to over 500 sows). Prior to data collection, farm managers were interviewed to ensure only healthy herds, free from recent disease outbreaks, were included in the assessment.

Experimental Design

The study was conducted using a completely randomized design (CRD), with farm scale as the main experimental factor. For the welfare assessment component, 45 farms (N = 15 per scale) were evaluated, with each farm serving as an experimental unit. For meat quality evaluation, 18 finishing pigs (crossbred PDLY; balanced for sex: 3 barrows and 3 gilts per scale) were randomly selected for slaughter. A total of 36 *Longissimus dorsi* (LD) muscle samples (two per pig) were collected. Statistical analyses for meat quality were based on six biological replicates per treatment group.

Assessment Protocol For Finishing Pigs

The welfare assessment of growing-finishing pigs was conducted based on the Welfare Quality® assessment protocol for pigs (2009). Prior to data collection, preliminary interviews were performed with farm managers to exclude farms with disease outbreaks or health issues that could bias the welfare assessment. Subsequently, pens and observation areas were selected randomly. The Welfare Quality® framework evaluates animal welfare using four main principles, namely good feeding (GF), good housing (GHs), good health (GHt), and appropriate behavior (B) (Table 1). Each principle encompasses specific criteria designed to assess distinct aspects of animal welfare while avoiding overlap or double-counting (Table 2).

Each criterion was scored on a 0-100 point scale according to the detailed standards described in the guidelines of Welfare Quality® (2009). The mean score for each criterion was used to calculate the corresponding principal score, which reflects the overall welfare level of growing-finishing pigs according to the following classification: 0-20 points means not classified; > 20-60 points means acceptable; > 60-80 points means enhanced; and > 80-100 points means excellent.

Ethical Approval

The present study, which involved field investigation and post-slaughter sampling of growing-finishing pigs, was conducted in accordance with the animal welfare and ethical guidelines of the Animal

Table 1. Main principles and definitions of the Welfare Quality® framework

Principle	Detailed definition
Good feeding (GF)	Animals should not suffer from prolonged hunger or thirst; they must have access to an appropriate diet and an adequate clean water supply.
Good housing (GH)	Animals should have sufficient space to move freely, with an environment that maintains comfortable thermal conditions.
Good health (GHt)	Animals should be free from injuries, diseases, and pain caused by management and husbandry procedures such as castration, ear tagging, tail docking, etc.
Appropriate behaviour (B)	Animals should be able to express normal and social behaviors, be handled gently, and avoid negative emotional states such as fear, etc.

Note: Source: Welfare Quality®, 2009.

Table 2. List of 12 criteria used in the Welfare Quality® Assessment protocol for growing-finishing pigs

Principle	Criteria	Measure for growing and finishing pigs
Good feeding	1. Absence of prolonged hunger	Body condition score (BCS)
	2. Absence of prolonged thirst	Water supply (nipple drinker)
Good housing	3. Comfort around resting	Bursitis and absence of manure on the body
	4. Thermal comfort	Shivering, panting, and huddling
	5. Ease of movement	Space allowance
Good health	6. Absence of injuries	Lameness, wounds on the body and tail biting
	7. Absence of disease	Mortality, coughing, skin condition, hernia, and rectal prolapse
	8. Absence of pain induced by management procedures	Castration, ear tagging, and tail docking
Appropriate behaviour	9. Expression of social behaviour	Social interaction
	10. Expression of other behaviour	Exploratory behaviour
	11. Good human-animal relationship	Avoidance distance (fear of humans)
	12. Positive emotional state	Qualitative behaviour assessment (QBA)

Note: Source: Welfare Quality®, 2009.

Ethics Committees, Nong Lam University, Ho Chi Minh City, Vietnam (AEC - NLU). The committee confirmed that no ethics approvals were required because only commercial post-slaughter samples were used in the current study.

Meat Quality Evaluation

Slaughtering process. Six crossbred pigs (three barrows and three gilts) per treatment, with an average final body weight of 103.2 ± 1.4 kg, were slaughtered under standardized commercial conditions. Prior to transport to the slaughterhouse, pigs were fasted for 8 h on the farm with *ad libitum* access to water in accordance with animal welfare requirements for pre-slaughter management described in Council Regulation (EC) No 1099/2009. At the slaughterhouse, pigs were stunned using electrical shock (voltage ≥ 200 V; frequency 50–60 Hz; duration ≥ 3 seconds), followed by exsanguination, scalding, and depilation.

Carcasses were then transferred to the processing line for inspection and removal of by-products (front feet, head, and any contaminated tissues). A total of 36 longissimus dorsi (LD) muscle samples were collected between the 10^{th} and 15^{th} ribs, with individual sample weights ranging from 1.5-2.5 kg. All samples were vacuum-packed and stored at 4 °C for subsequent determination of meat quality parameters, including pH value, color, water-holding capacity, chemical composition, and fatty acid profiles.

Measurement of meat quality variables. pH value: LD muscle samples (36 samples, approximately 120 g each) were vacuum-packed and stored at 2–4 °C. The pH value was measured using a portable meat pH meter (HI9816, Hanna Instruments, Italy) at 45 minutes, 24 h, and 48 h after the slaughter. For each sample, five readings were taken at different points, and the mean value was recorded as the final pH.

Meat color: Meat color was determined at 24 and 48 h after slaughter using a CR-300 Chroma Meter (Minolta Co., Osaka, Japan). Five readings per sample were taken at different points, and the mean values for L* (lightness), a* (redness), and b* (yellowness) were calculated to represent meat color parameters.

Water-holding capacity (WHC) traits: The ability of meat to retain water was assessed through drip loss and cooking loss measurements.

For drip loss, samples (36 samples, 120 g/sample) were vacuum-packed, stored at 2–4 °C for 24 and 48 h, blotted dry, and reweighed. Drip loss (%) was calculated as the difference in sample weight before and after storage (Honikel, 1997).

For cooking loss, samples (36 samples, 120 g/sample) were cooked in a water bath at 75 °C for 60 min until reaching an internal temperature of 70 °C. Cooking loss (%) was expressed as the difference in sample weight before and after cooking (Honikel, 1997)

Chemical composition and fatty acid profiles: LD muscle samples (36 samples, approximately 120 g each) were vacuum-packed, stored at 2–4 °C, and analyzed at the UP-Science Laboratory (1B Quarter, An Phu, Thuan An, Binh Duong, Vietnam). Crude protein, lipid, phosphorus, zinc, and iron were quantified using standard analytical procedures according to ISO 5983-1:2005, ISO 1443:1973, ISO 23776:2021, and ISO 6869:2000, respectively, while fatty acid profiles were determined according to ISO 12966-2:2017. Moisture content was quantified using a standard oven-drying technique. Intramuscular fat (IMF) was determined in duplicate by Soxhlet extraction according to Horwitz & Latimer (2012). Fatty acid composition of LT samples was analyzed based on the method described by Zhang *et al.* (2019). The average value of duplicate measurements was used for all subsequent analyses.

Statistical Analysis

Analyzed using GraphPad Prism 8.3 (GraphPad Software Inc., San Diego, CA, USA). Each farm was treated as the experimental unit for all analyses, whereas the LD muscle sample was considered the experimental unit for meat quality measurements. A completely randomized design (CRD) with one experimental factor (farm scale) was applied. Analysis of variance (one-way ANOVA) was performed to compare animal welfare scores and meat quality indicators. All data were expressed as the mean. Results were considered significantly different at p<0.05 and, when there was a significant effect, values were compared with a Tukey's multiple range post hoc test.

RESULTS

Animal Welfare

The assessment outcomes of animal welfare demonstrated noticeable differences in welfare performance among the three farm scales (p<0.05; Figure 1). Large-scale farms (LF) showed the highest mean scores for absence of prolonged thirst, thermal comfort, and human-animal relationship, whereas medium-scale farms (MF) had intermediate scores and small-scale farms (SF) exhibited the lowest values. In contrast, the absence of the prolonged hunger criterion was greatest in SF (73.69 points), followed by MF (64.12 points) and LF (56.48 points). The remaining indicators, including comfort around resting, ease of movement, absence of injuries, and expression of social behavior, *showed* mean scores ranging from 50 to 90 points, reflecting moderate to favorable welfare levels. For the absence of disease and absence of pain induced by management procedures, average scores were consistently low (approximately 8 points) across all farm scales. This result was mainly associated with routine piglet management practices, such as teeth clipping and tail docking. No significant differences were observed among farm scales.

The principles of good feeding and appropriate behavior were within an acceptable to enhanced range across all three farm scales (Figure 2). In contrast, the remaining welfare principles showed significant differences among the three treatments (p<0.05). Meanwhile, the good health principle remained very low across all farm scales and was classified as "not classified.". Overall, an increasing trend in welfare performance with farm scale was particularly evident for the good housing principle in growing-finishing pigs.

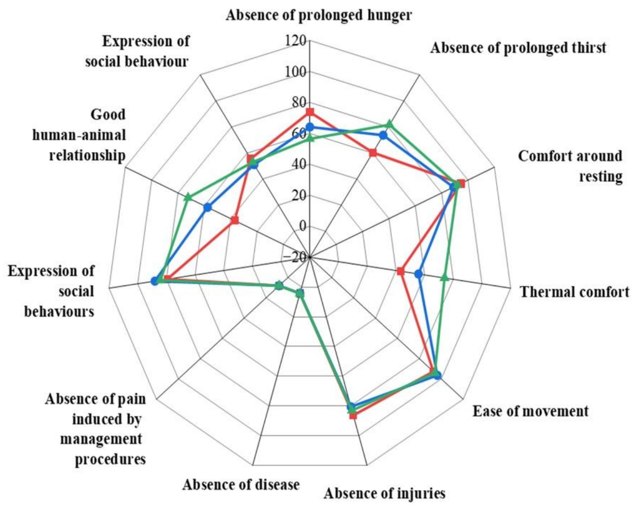

Figure 1. Welfare scores of growing-finishing pigs assessed across three farm scales. Note: small-scale farm; medium-scale farms; large-scale farms.

Meat Quality Indicators

pH value. No significant differences were observed in the pH value of pork among the three farm scales at 45 minutes post-slaughter (Figure 3). However, at 24 hours after slaughter, pigs from large-scale farms (LF) exhibited a higher mean pH value (5.61) compared with those from MF (5.55) and SF (5.54) farms (p<0.01). The final pH values measured across the three scales were 5.57 (SF), 5.63 (MF), and 5.61 (LF), with a significant difference (p<0.01). These results indicate that carcasses from pigs raised on large-scale farms tended to maintain a slightly higher pH value, possibly reflecting better regulation of postmortem muscle glycolysis and reduced pre-slaughter stress compared to smaller-scale operations.

Meat color. At 24 hours post-slaughter, the lightness (L*) of pork from MF (57.23) was significantly higher (p<0.01; Table 3) than that from SF (54.62) and LF

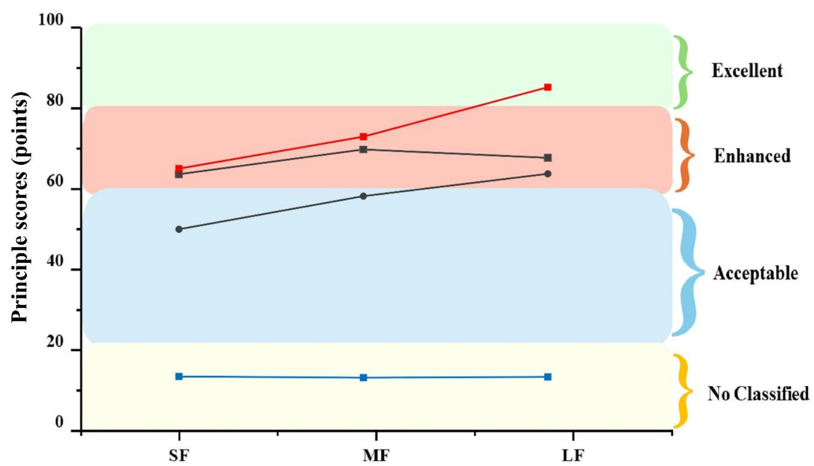

Figure 2. Comparison of animal welfare principles across three farm scales. Note: Good feeding; Appropriate behaviour; Good housing; Good health; SF= small-scale farm; MF= medium-scale farm; LF= large-scale farm.

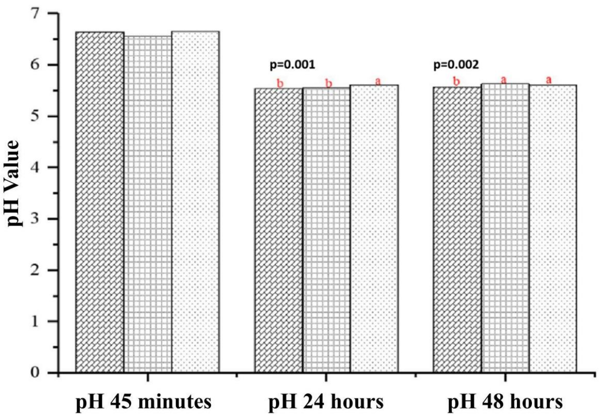

Figure 3. pH value of pork at 45 minutes, 24 and 48 hours after slaughter at various farm scales. Note: small-scale farm; medium-scale farm; large-scale farm. Means in the same row with different superscripts differ significantly (p<0.05).

(51.31). The redness (a*) value increased with farm scale, being lowest in MF (14.05), intermediate in SF (15.07), and highest in LF (16.33) (p<0.01). Conversely, the yellowness (b*) value was greatest in MF (7.93), followed by LF (7.10) and SF (7.04) (p<0.01).

At 48 hours post-slaughter, the L* value in MF (58.54) remained significantly higher (p<0.01; Table 3) than those in LF (53.83) and SF (54.26). According to Warner et al. (1997), pork with an L* value above 50 is considered lighter-colored, whereas values below 42 indicate darker-colored meat; thus, all treatments fell within the normal color range (> 50). The a* value at 48 hours was significantly affected by farm scale (p<0.01), ranging from 12.68 (MF) to 15.53 (LF). In addition, the b* value in the MF (8.65) was higher than that in the SF (8.03) (p=0.012), suggesting a slightly more yellow hue in meat from medium-scale farms.

Water-holding capacity. At 24 hours post-slaughter, drip loss did not differ significantly among the three farm scales (Table 4). However, cooking loss in pork from medium-scale farms (33.63%) was significantly higher (p<0.05) than that from SF (30.25%) and large-scale farms (29.00%). At 48 hours post-slaughter, the percentage of drip loss increased with farm scale, being lowest in SF (1.38%) and highest in MF (2.10%) and LF (2.00%) (p<0.01). Similarly, cooking loss values were higher in MF (32.98%) and LF (32.59%) compared with SF (27.40%) (p<0.05). Overall, pork from medium-scale and large-scale farms exhibited slightly greater water loss during storage and cooking, and a slightly lower water-holding capacity than pork from small-scale farms.

Chemical composition and the profile of fatty acids. The predominant fatty acids identified in pork samples were palmitic acid (C16:0), stearic acid (C18:0), and oleic acid (C18:1), which together accounted for the majority of total fatty acids across all farm scales (Table 6). The proportion of saturated fatty acids (SFA) was highest in SF (41.48%), followed by MF (39.27%) and LF (39.01%), but the differences were not significant (p>0.05). Conversely, the concentration of polyunsaturated fatty acids (PUFA), particularly linoleic acid (C18:2), linolenic acid (C18:3), and arachidonic acid (C20:4), tended to increase in pork from MF and LF (p<0.05). Similarly, the UFA/SFA ratio increased slightly with farm scale, from 1.38 in SF to 1.57 in LF, although the difference was not

Table 3. Pork color traits at 24 and 48 h post-slaughter across three different farm scales

Indicators	Farm scale			SEM	p-value
	SF	MF	LF		
24 hours post-slaughter					
L*	54.62^{b}	57.23^{a}	51.31^{c}	0.307	< 0.01
a*	15.07^{b}	14.05^{c}	16.33^{a}	0.188	< 0.01
b*	7.04^{b}	7.93^{a}	7.10^{b}	0.161	< 0.01
48 hours post-slaughter					
L*	54.26^{b}	58.54^{a}	53.83^{b}	0.210	< 0.01
a*	14.52^{b}	12.68^{c}	15.53^{a}	0.090	< 0.01
b*	8.03^{b}	8.65^{a}	8.48ab	0.149	0.012

Note: Means in the same row with different superscripts differ significantly (p<0.05). SF= small-scale farm; MF=medium-scale farm; LF=large-scale farm; L*= lightness; a*= redness; b*= yellowness; SEM=standard error of means.

Table 4. Drip loss and cooking loss of pork across three different farm scales

Indicators	Farm scale			SEM	p-value
	SF	MF	LF		
24 hours post-slaughter					
Drip loss (%)	1.42	1.42	1.44	0.135	0.997
Cooking loss (%)	29.00^{b}	33.63^{a}	30.25^{ab}	1.189	0.045
48 hours post-slaughter					
Drip loss (%)	1.38^{b}	2.10^{a}	2.00^{a}	0.125	0.003
Cooking loss (%)	27.40^{b}	32.98^{a}	32.59^{a}	0.013	0.019

Note: Means in the same row with different superscripts differ significantly (p<0.05). SF= small-scale farm; MF= medium-scale farm; LF= large-scale farm; SEM=standard error of means.

Table 5. Chemical composition of pork across three different farm scales

Indicators	Farm scale			SEM	p-value
	SF	MF	LF		
Crude protein (g/100g)	20.21	20.80	20.70	0.574	0.820
Lipid (g/100g)	6.65	7.85	8.45	2.891	0.910
P (mg/kg)	2029.5	2227.5	2250.0	135.8	0.527
Zn (mg/kg)	15.90	17.75	21.45	1.167	0.092
Fe (mg/kg)	7.58[b]	12.27[ab]	20.40[a]	1.157	0.021

Note: Means in the same row with different superscripts differ significantly ($p<0.05$). SF= small-scale farm; MF= medium-scale farm; LF= large-scale farm; SEM=standard error of means.

Table 6. Fatty acid profile of pork across three different farm scales

Fatty acids	Farm scale			SEM	p-value
	SF	MF	LF		
Caprylic (C10:1)	0.11	0.10	0.05	0.029	0.416
Undecanoic (C12:0)	0.01[b]	0.26[a]	0.21[ab]	0.023	0.034
Myristic (C14:0)	1.46	1.70	1.60	0.066	0.172
Palmitic (C16:0)	26.21[a]	24.22[b]	23.69[b]	0.267	0.014
Palmitoleic (C16:1)	3.55	2.90	2.39	0.348	0.208
Stearic (C18:0)	14.66	12.25	12.82	0.559	0.109
Cis - Oleic (C18:1)	42.29	40.54	40.76	1.582	0.722
Linoleic (C18: 2)	7.78[b]	13.00[a]	14.14[a]	0.313	0.001
Linolenic (C18:3)	0.24[b]	0.53[a]	0.48[ab]	0.044	0.035
Eicosadiennoic (C20:2)	0.32	0.38	0.74	0.093	0.089
Arachidonic (C20:4)	1.56[c]	2.27[b]	3.07[a]	0.101	0.004
Docosatetraenoic (C22:4)	0.30[b]	0.39[b]	0.55[a]	0.021	0.007
Docosapentaenoic (C22:5)	0.15[b]	0.30[ab]	0.35[a]	0.028	0.029
Omega 3	0.32[b]	0.75[a]	0.68[a]	0.051	0.017
Omega 6	10.29	15.15	15.53	2.548	0.389
Omega 9	38.56	37.68	37.56	1.527	0.884
SFA	41.48	39.27	39.01	1.219	0.405
MUFA	46.78	44.39	44.24	1.606	0.532
PUFA	10.51	16.34	16.76	2.211	0.230
UFA/SFA ratio	1.38	1.55	1.57	0.068	0.258

Note: Means in the same row with different superscripts differ significantly ($p<0.05$). SF= small-scale farm; MF= medium-scale farm; LF= large-scale farm; SEM= standard error of means. SFA= saturated fatty acids; MUFA= monounsaturated fatty acids; PUFA= polyunsaturated fatty acids; UFA= unsaturated fatty acids.

statistically significant. Overall, pork from larger-scale farms showed a trend toward a higher proportion of unsaturated fatty acids, suggesting a potentially more favorable lipid profile, even though most differences among farm scales were not significant.

DISCUSSION

Restricted space allowance in most commercial pig production systems and industrial limits the animals' ability to move freely and express natural behaviors. In the present study, the average space provided for finishing pigs (126-154 days old) ranged between 0.4 and 0.6 m² per pig (Gonçalves Vero et al., 2023), which is considerably lower than the recommended standard of 0.8-1.2 m² per pig established by welfare guidelines (Kim *et al.*, 2016). Such confinement conditions can increase competition for space, feed, and water resources, leading to heightened stress and aggressive interactions among pigs.

One common management practice contributing to welfare challenges is regrouping, particularly during the transition from the nursery to the growing-finishing stage (Coutellier *et al.*, 2007). Pigs originating from different litters are frequently mixed according to similar age or body weight (Angela *et al.*, 2023), which often provokes fighting behavior as animals attempt to establish new social hierarchies (Clavell-Sansalvador *et al.*, 2024). These confrontations may result in skin lesions (Clavell-Sansalvador *et al.*, 2024), leg and hoof injuries (Boyle *et al.*, 2022), and negative emotional states, such as fear or avoidance of human contact (Lecorps *et al.*, 2020), which can be observed through behavioral changes within pens.

Furthermore, several painful husbandry and management procedures are still routinely implemented across farms of all sizes, probably due to preventive measures. Among these, tail docking remains a common practice to mitigate the risk of tail biting (Valros, 2024) during the growing-finishing period (D'eath *et al.*, 2014). However, findings from this study demonstrated that this management intervention contributed to one of the lowest welfare scores under the criterion "absence of pain induced by management procedures." This outcome reinforces concerns that routine invasive practices can adversely affect animal welfare, emphasizing the need for refinement or replacement with less painful alternatives.

In recent years, many large-scale pig production systems have adopted modernized, biosecure housing models to reduce the risk of infectious diseases such as African Swine Fever (ASF). One common innovation is the implementation of zero-discharge slatted floor systems (Butucel *et al.*, 2022; Witkowska & Ponieważ, 2022), which aim to minimize water usage and wastewater generation. These systems help maintain lower humidity levels within barns (Han *et al.*, 2024; Mosquera *et al.*, 2019) and effectively limit the proliferation of pathogenic microorganisms, including bacteria and fungi that thrive in moist environments (Cheng *et al.*, 2024; Haq *et al.*, 2024). However, despite their biosecurity advantages, such systems may pose potential welfare challenges. In addition, the accumulation of manure or urine on the animals' bodies, due to infrequent washing or inadequate drainage, can cause pigs to develop skin irritations or diseases and dermatological disorders/ coughing symptoms (Chen *et al.*, 2024; Duniere *et al.*, 2024). Thus, these factors may be associated with the relatively low scores observed for the "absence of disease" criterion in large-scale farms.

Nutritional management also plays a crucial role in maintaining welfare outcomes across production scales. Understanding the nutrient requirements of pigs at different growth stages allows farms to maintain relatively consistent body condition scores (BCS) (3.5-4.5 points per maximum of 5) in finishing herds (Moniruzzaman *et al.*, 2023; Song *et al.*, 2025). Additionally, most large-scale farms ensure sufficient nipple drinkers that provide continuous and unrestricted access (*ad libitum*) to clean water. Therefore, the "good housing" principle consistently achieved higher ratings, reaching the enhanced welfare level across scales. Furthermore, large-scale farms are also more likely to invest in modern housing designs, such as enclosed housing systems (EHS), which provide improved environmental control compared with conventional indoor housing (IHS) (Delsart *et al.*, 2020). For example, Song *et al.* (2011) reported that the EHS facilities maintained summer temperatures between 24.8 and 29.1 °C, while conventional barns exhibited wider fluctuations (up to 7.6 °C) with peaks of 32.3 °C. Such temperature stability is essential for maintaining animal comfort and productivity.

Moreover, most large-scale pig farms operate under integrated commercial or contract farming models, where companies collaborate with farmers through structured production and marketing agreements (Thawee *et al.*, 2024). In contrast, small-scale farms often lack comprehensive feed planning (Thawee *et al.*, 2024), resulting in inconsistent feed quality or occasional shortages (Thawee *et al.*, 2024). Many large-scale farms have established contracts with feed mills, supported by silo storage and automated feeding systems, ensuring both feed consistency and efficiency (Miller *et al.*, 2023; Thawee *et al.*, 2024). As a result, pigs raised under large-scale systems may exhibit minor differences in chemical composition and nutritional value compared with those from smaller farms.

From a meat science perspective, stress-induced physiological changes affect muscle glycogen reserves, which play a key role in post-mortem glycolysis and meat quality. Depletion of glycogen prior to slaughter limits lactic acid production, leading to high ultimate pH and the development of dark, firm, and dry (DFD) meat (Kiyimba *et al*., 2024; Terlouw *et al*., 2021). In contrast, acute pre-slaughter stress accelerates glycolysis, causing rapid glycogen breakdown and excessive lactic acid accumulation while carcass temperature remains high, resulting in protein denaturation, reduced water-holding capacity, and the formation of pale, soft, and exudative (PSE) meat (Ma *et al*., 2022; Michelle *et al*., 2024; Ogawa *et al*., 2024). Numerous studies have demonstrated the antimicrobial and antioxidative properties of plant-derived compounds, which can enhance gut health, immunity, and overall growth performance. The incorporation of herbal extracts not only supports disease resistance but also contributes to improved meat quality indicators, particularly in terms of lipid profile. In fact, the antimicrobial ability of various herbal extracts has been well-documented in numerous studies (Hemeg *et al.*, 2020), primarily due to the natural bioactive compounds present in plants, which contribute to improved animal health (Njimoh *et al.*, 2015) and reduced disease incidence (Alem, 2024; Guo *et al.*, 2024). Phytogenic additives play an important role as natural antioxidants, helping to reduce oxidative stress and improve meat quality (Orzuna-Orzuna *et al*., 2024; Orlowski *et al*., 2018). These bioactive compounds are associated with increased proportions of unsaturated fatty acids (such as linoleic, linolenic, and arachidonic acids) and a higher UFA/SFA ratio, aligning with the growing consumer preference for healthier, nutritionally balanced pork products.

CONCLUSION

The assessment results indicated that large-scale pig farms achieve higher standards in animal welfare principles, specifically regarding feeding and housing management, compared to medium and small-scale farms. However, health status and behavioral indicators remain relatively consistent across all production scales. In terms of meat quality, while large-scale farming influences certain quality traits, the overall differences in chemical composition and water retention properties among the scales are not substantial. These findings suggest that although large-scale production systems may provide relatively more consistent environmental management and feeding practices, their potential advantages in meat quality were limited under the conditions of the present study.

CONFLICT OF INTEREST

We certify that there is no conflict of interest with any financial, personal, or other relationships with other people or organizations related to the material discussed in the manuscript.

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DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) used ChatGPT in order to improve the readability and language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

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