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*Section: Agriculture, forestry, fisheries and water management*

**A COMPREHENSIVE ANALYSIS OF LIVE WEIGHT LOSSES AND  
MEAT QUALITY INDICATORS UNDER LOGISTIC STRESS: THE  
EXPERIENCE OF CANADA AND THE EU (2025 - 2026)**

**Kushnerenko V. G.**

*Candidate of Agricultural Sciences, Associate Professor*

*Kherson State Agricultural and Economic University*

*ORCID: 0000-0003-1220-2972*

*e-mail: [kushnerenkovg@gmail.com](mailto:kushnerenkovg@gmail.com)*

**Abstract.** This article presents the results of a comprehensive study on the impact of logistic stress on the quantitative and qualitative indicators of raw meat materials within modern agri-food systems in Canada and the European Union (EU). It was established that during the period 2025 - 2026, the livestock transport stage represents the most critical link in the supply chain, directly determining technological suitability and economic efficiency in meat processing.

Based on the analysis of live weight loss dynamics ("shrinkage"), it was demonstrated that quantitative mass loss can reach up to 12% under prolonged stress exposure (over 24 hours), which is typical for Canadian logistics routes.

The study provides a detailed analysis of the biochemical mechanisms underlying the formation of meat quality defects such as PSE (Pale, Soft, Exudative) and DFD (Dark, Firm, Dry), resulting from disruptions in animal homeostasis. It was found that financial losses associated with technological defects and reduced water-holding capacity of meat are 25.8% higher than direct losses caused by live weight reduction.

According to projected calculations based on wholesale producer prices, total annual losses in the Canadian agricultural sector due to inefficient logistics protocols exceed 2 billion CAD.

The scientific novelty of the study lies in substantiating the identification of the transport stage as a Critical Control Point (CCP) within the food safety management system based on HACCP principles. Key monitoring parameters (transit time, temperature conditions, and pH levels) are defined, enabling the integration of IoT sensor data into digital HACCP frameworks.

A comparative analysis of EU practices demonstrates the effectiveness of strict transport time regulations (up to 8 hours) in minimizing chronic stress in cattle, while also highlighting the risk of acute stress in pigs due to frequent unloading (EFSA Panel on Animal Health and Welfare, 2022).

The practical significance of the study lies in the development of recommendations for modernizing logistics through electrolyte support systems and intelligent climate control technologies, thereby enhancing product quality and export potential.

**Keywords:** HACCP, logistic stress, shrinkage, PSE, DFD, beef, pork, animal welfare, economic losses, Canada, EU.

**Introduction.** The transformation of global food systems in 2025 - 2026 places new demands on the integration of animal welfare standards into the overall framework of food quality and safety management (Grandin, 2014). The issue of live weight loss ("shrinkage") and the deterioration of qualitative characteristics of raw meat due to logistic stress is no longer purely an ethical concern; it has become a critical economic and technological challenge for the meat processing industry.

For countries such as Canada, characterized by significant geographical distances between production and processing centers, as well as for the European Union (EU), with its strict regulatory environment governing livestock transport, minimizing stress is essential for maintaining export potential.

The practical relevance of this issue lies in the need to develop preventive technological solutions based on HACCP principles. In 2026, the logistics stage should be considered the initial phase in the formation of meat's technological properties. Any disruption of animal homeostasis during transport leads to irreversible biochemical changes, particularly the development of PSE (Pale, Soft, Exudative) and DFD (Dark,

Firm, Dry) defects. Thus, identifying logistics as a Critical Control Point (CCP) is an urgent scientific objective that enables the transition from passive loss observation to proactive quality management.

**Problem Statement.** Research into the mechanisms by which pre-slaughter stress affects meat quality occupies a central place in contemporary scientific studies. In previous publications, emphasis was placed on the implementation of innovative technologies for the storage and processing of meat products, where logistics was identified as a stage with a high risk of initiating technological defects. The development of food safety management systems is based on the principles of traceability and control of biochemical quality markers at each stage of the product life cycle (Riapolova & Kushnerenko, 2024).

In international practice as of 2025, a significant contribution to the study of "shrinkage" has been made by specialists from the Beef Cattle Research Council (2025) and the EFSA Panel on Animal Health and Welfare (2022). In particular, studies by Canadian researchers have demonstrated a direct correlation between transit time and the level of muscle glycogen depletion, which is the primary cause of the DFD defect (Schwartzkopf-Genswein et al., 2012).

At the same time, European standards of 2026 (Animal Welfare Regulation) focus on reducing transport duration and implementing intelligent temperature monitoring systems. However, most existing studies consider these aspects in isolation from HACCP systems, thereby creating a scientific gap that this study aims to address.

In particular, there remains a need to establish objective critical limits for the transport stage depending on climatic conditions, ranging from extreme cold stress in the Canadian prairies to heat stress in southern EU countries. Furthermore, a comprehensive comparative analysis of economic losses at wholesale producer prices-taking into account the cumulative effect of "shrinkage" and subsequent technological degradation of raw materials-has not yet been conducted.

This article seeks to fill this gap by proposing a logistics model as a Critical Control Point (CCP) within the overall quality management system (Kushnerenko, 2024; Riapolova & Kushnerenko, 2024).

**Formulation of the task.** The aim of this study is to conduct a comprehensive analysis of quantitative live weight losses and qualitative characteristics of meat products under conditions of logistic stress in 2025-2026 (using the examples of Canada and the EU), as well as to develop scientific and technological recommendations for identifying the transport stage as a Critical Control Point (CCP) within the HACCP system.

To achieve this goal, the following main objectives were identified:

1. Systematize data on the dynamics of live weight loss (“shrinkage”) in beef cattle and pigs depending on the duration of stress exposure.
2. Analyze the mechanisms underlying the occurrence of PSE (Pale, Soft, Exudative) and DFD (Dark, Firm, Dry) defects as technological risks arising from violations of transportation regulations.
3. Calculate and justify the economic losses for the agricultural sector at wholesale producer prices for 2025-2026.
4. Develop a CCP structure for the logistics stage, including the determination of critical limits and monitoring methods within the HACCP plan.

**Results.** Analysis of Technological Parameters of Live Weight Loss (“Shrinkage”)

The transport of farm animals in modern logistics chains during 2025 - 2026 is inevitably accompanied by live weight loss, referred to in scientific literature as “shrinkage.” According to our previous research, this process has a complex etiology and can be divided into two functional components: excretory shrinkage and tissue shrinkage.

- Excretory shrinkage results from the evacuation of gastrointestinal tract contents and bladder, which is a natural physiological response to initial loading stress.

- Tissue shrinkage is associated with the dehydration of soft tissues and the metabolic breakdown of internal reserves (glycogen, fats, and proteins) to maintain homeostasis under conditions of water and feed deprivation during transport.

In Canadian livestock practice, given extreme delivery distances often exceeding 1000 - 1200 km, shrinkage parameters are a key indicator of the technological

suitability of animals for slaughter. Based on the analysis of Beef Cattle Research Council (2025) data, we have systematized the dynamics of these losses for beef cattle. The data presented in Table 1 summarize the relationship between transport duration and live weight loss in beef cattle, based on the Beef Cattle Research Council (2025) data for 2025. Particular attention is given to the progression of shrinkage under prolonged stress exposure. These results provide a basis for assessing technological and economic risks associated with livestock transport.

**Table 1. Technological parameters of cattle live weight loss depending on transit duration (2025 - 2026 forecast)**

| <b>Transit time (hours)</b> | <b>Expected weight loss (%)</b> | <b>Nature of physiological and technological changes</b>                  |
|-----------------------------|---------------------------------|---|
| <b>0 - 2 hours</b>          | 1.0% - 2.0%                     | Predominantly excretory losses; minimal impact on carcass quality.        |
| <b>4 - 8 hours</b>          | 3.0% - 5.0%                     | Onset of tissue dehydration; initiation of glycogenolysis.                |
| <b>12 - 24 hours</b>        | 6.0% - 8.0%                     | Deep metabolic stress; depletion of muscle energy reserves.               |
| <b>Over 24 hours</b>        | 8.0% - 12.0%                    | Critical tissue mass shrinkage; irreversible degradation of meat quality. |

*Note. Developed by the author based on data from the Beef Cattle Research Council (Canada).*

The analysis of the data presented in Table 1 shows that the critical threshold of 5% live weight loss is exceeded after 8 hours of transportation. This finding correlates with EU standards, where an 8-hour limit without rest is established as a regulatory threshold for many categories of livestock (EFSA Panel on Animal Health and Welfare, 2022).

Under Canadian conditions, exceeding the 12-hour interval leads to a transition of losses into the tissue phase, which significantly reduces carcass yield and negatively affects its water-holding capacity.

Particular attention in this study is given to the species-specific response to logistic stress. Pigs demonstrate higher sensitivity to microclimatic conditions within

transport vehicles, which is reflected in the dynamics of their "shrinkage," as presented in Table 2.

**Table 2. Comparative characteristics of mass losses of pigs and cattle in short - and medium-term logistics**

| <b>Animal species</b> | <b>Short distances (up to 4 hours), %</b> | <b>Long trips (8 - 12 hours), %</b> | <b>Main risk factor</b>       |
|-----------------------|---|-------------------------------------|-------------------------------|
| <b>Pigs</b>           | 1.0 - 2.0                                 | 3.0 - 5.0                           | Temperature stress (PSE risk) |
| <b>Cattle</b>         | 2.0 - 3.0                                 | 5.0 - 7.0                           | Time exposure (DFD risk)      |

*Source: Developed by the author based on Schwartzkopf-Genswein et al. (2012) and EFSA (2022)*

It has been established that for pigs, even with a low percentage of shrinkage (1–2%), the risk of technological defects remains high due to rapid post-mortem glycolysis. For cattle, the primary challenge is quantitative mass deficit and dehydration resulting from prolonged transit. As noted by Grandin (2014), the implementation of FWR (Feed, Water, Rest) protocols according to 2025 regulations allows for partial compensation (1.5 - 2.0%) of excretory losses, yet tissue deficit remains a constant factor in the overall economic loss structure.

**Biochemical model of logistic stress: mechanisms of PSE and DFD defect formation**

The biochemical stability of muscle tissue after slaughter is fundamentally dependent on the animal's energy reserves at the moment of slaughter. According to Warriss (2000), the energy status of the musculature determines the rate and extent of pH decline. Riapolova and Kushnerenko (2024) emphasize that logistic stress acts as a powerful catalyst for glycogenolysis, where live weight loss is merely the external manifestation of deep metabolic shifts.

**Mechanism of PSE (Pale, Soft, Exudative) defect formation**

In contemporary pig farming (2025 - 2026), the PSE defect remains a primary technological challenge. It is triggered by acute stress-such as improper loading, aggressive handling, or temperature fluctuations-which aligns with the findings of the

Canadian Meat Council (2025). Physiologically, this leads to an accelerated breakdown of glycogen and the accumulation of lactic acid while the carcass temperature is still high, resulting in protein denaturation.

This physiological reaction, characterized by a rapid drop in pH while the carcass temperature remains high, leads to the denaturation of sarcoplasmic and myofibrillar proteins, which significantly reduces the water-holding capacity of the meat (Warriss, 2000). The technical parameters and quality impacts of this defect, based on Canadian industrial data, are systematized in Table 3.

**Table 3. Technological characteristics of the PSE defect in pork (Canada's experience)**

| <b>Indicator</b>                 | <b>Value for PSE raw material</b> | <b>Standard value</b> | <b>Impact on quality</b>                       |
|----------------------------------|-----------------------------------|-----------------------|--|
| <b>pH level (after 45 min)</b>   | < 5.8                             | 6.3 - 6.6             | Denaturation of sarcoplasmic proteins          |
| <i>Color (L CIELAB system)*</i>  | > 52 (pale)                       | 43 - 48               | Reduction of commercial attractiveness         |
| <b>Exudation (juice loss), %</b> | 6.0 – 10.0%                       | 2.0 - 3.0%            | Reduction of juiciness and final product yield |

*Source: Developed by the author based on Canadian Meat Council (2025)*

It was established that in pigs, even at a low level of shrinkage (1 - 2%), the risk of technological defects remains high due to rapid glycolysis. In contrast, for cattle, the primary issue is quantitative weight loss and dehydration (Beef Cattle Research Council, 2025). The application of FWR (Feed, Water, Rest) protocols in accordance with 2025 regulations allows for partial compensation (1.5 - 2.0%) of excretory losses; however, tissue-related losses remain a persistent factor contributing to economic damage .

The biochemical model of logistic stress and the mechanisms underlying the formation of PSE and DFD defects are centered on the animal's energy status at the moment of slaughter. As noted by Riapolova and Kushnerenko (2024), logistic stress acts as a powerful catalyst for glycogenolysis. Live weight loss, analyzed in the

previous sections, represents only the external manifestation of deeper metabolic disturbances.

#### Mechanism of PSE (Pale, Soft, Exudative) Defect Formation

In pig production during 2025 - 2026, the PSE defect remains a primary technological challenge. It is triggered by acute stress factors such as loading, rough handling, and temperature fluctuations during transport, which is consistent with the animal welfare concerns raised by Grandin (2014).

This physiological reaction leads to rapid glycogen breakdown and lactic acid accumulation while the carcass is still warm, which is the hallmark of the PSE defect. In contrast, prolonged logistic stress, typical for long-distance Canadian routes, leads to a different biochemical outcome-the DFD (Dark, Firm, Dry) defect.

The primary difference lies in the pre-slaughter energy status: while PSE is caused by a sudden post-mortem pH drop, DFD is the result of chronic glycogen depletion during transit, leaving insufficient reserves for normal acidification. The comparative biochemical markers and their technological consequences are systematized in Table 4.

**Table 4. Comparative characteristics of biochemical markers of DFD and normal beef**

| Parameter          | DFD (Dark Cutter)   | Normal beef | Technological consequences       |
|--------------------|---------------------|-------------|----------------------------------|
| Ultimate pH (24 h) | > 6.0               | 5.4 - 5.7   | Risk of microbiological spoilage |
| Consistency        | Firm, sticky        | Elastic     | Disruption of mince structure    |
| Shelf life         | Reduced by 40 - 50% | Standard    | Limitations on vacuum packaging  |

*Source: Developed by the author based on Schwartzkopf-Genswein et al. (2012) and Beef Cattle Research Council (2025)*

In the case of DFD, glycogen reserves are almost completely depleted during transit, a process directly linked to tissue-related “shrinkage.” After slaughter, the amount of lactic acid produced is insufficient to reduce the pH to normal levels. A high pH level (>6.0) represents a critical risk factor within the HACCP system, as it creates

favorable conditions for the development of pathogenic microflora, thereby undermining sanitation measures at the processing enterprise.

#### Implementation of IoT Monitoring as a CCP Tool

To prevent the above-described defects in 2026, intelligent monitoring systems are being actively implemented in Canada and the EU. It is proposed to consider data obtained from IoT (Internet of Things) sensors-specifically temperature, humidity, and levels within transport vehicles-as monitoring parameters for the “Logistics” Critical Control Point (CCP). The automation of data collection enables:

- Determination of the optimal timing for FWR (Feed, Water, Rest) stops to mitigate chronic stress (EFSA, 2022);
- Adjustment of carcass cooling rates based on predicted PSE/DFD risks;
- Minimization of “shrinkage” through the maintenance of optimal microclimatic conditions (Grandin, 2014).

#### Economic Assessment of Agricultural Sector Losses: 2025 - 2026 Model

The calculation of the economic efficiency of logistics chains in livestock production is traditionally based on direct weight losses. However, the author’s methodology incorporates a cumulative negative effect, including the depreciation of raw materials affected by PSE and DFD defects. For the purpose of analytical objectivity, weighted average wholesale prices from the Canadian market as of early 2026 were used, in accordance with the official report of Agriculture and Agri-Food Canada (2026).

**Calculation Methodology.** Total losses (T\_loss) are determined as the sum of losses from quantitative “shrinkage” (L\_g) and qualitative degradation of raw materials

$$(L_j): T_{loss} = L_g + L_j \quad (1)$$

$$L_g = \sum (V_i * S_i * P_{wi})$$

$$L_j = \sum (V_i * Q_i * P_{wi} * D_i)$$

where:  $V_i$  - annual production volume of the i-th type of meat (million tons);

$S_i$  - average shrinkage rate (%);

$P_{wi}$  - wholesale price per unit of weight;

$Q_i$  - proportion of products with quality defects (PSE/DFD);

$D_i$  - discount coefficient (value loss) for non-conforming raw materials.

This methodological approach is consistent with modern studies on meat quality and economic loss assessment under stress conditions (Warriss, 2000; Schwartzkopf-Genswein et al., 2012).

Equation (1) represents the integrated model for assessing total economic losses in the livestock sector, combining both quantitative and qualitative loss components. To determine the practical scale of these losses, a prognostic assessment was conducted based on the current market conditions in Canada, utilizing data from Tridge (2025) and the Canadian Meat Council (2025).

To ensure the validity and practical applicability of the proposed model, a comprehensive economic assessment of losses in the Canadian meat industry was conducted. The analysis integrates both quantitative losses associated with live weight reduction ("shrinkage") and qualitative losses caused by PSE and DFD defects.

The calculations are based on weighted average wholesale prices and production volumes, using official industry data and analytical reports (Agriculture and Agri-Food Canada, 2026; Tridge, 2025).

The summarized results of the economic loss assessment for 2025 - 2026 are presented in Table 5.

**Table 5. Forecasted financial losses of Canada's meat industry (2025 - 2026)**

| <b>Product type</b> | <b>Loss category</b>  | <b>Volume (mln t)</b> | <b>Loss %</b> | <b>Wholesale price (CAD/kg)</b> | <b>Losses (mln CAD)</b> |
|---------------------|-----------------------|-----------------------|---------------|---------------------------------|-------------------------|
| <b>Beef</b>         | Logistics (Shrinkage) | 1.2                   | 4.0%          | 12.50                           | 600.0                   |
|                     | Quality (DFD)         | 1.2                   | 5.0%          | 12.50                           | 750.0                   |
| <b>Pork</b>         | Logistics (Shrinkage) | 2.1                   | 3.3%          | 4.20                            | 293.2                   |
|                     | Quality (PSE)         | 2.1                   | 4.2%          | 4.20                            | 373.2                   |
| <b>TOTAL</b>        |                       | <b>3.3</b>            |               |                                 | <b>2,016.4</b>          |

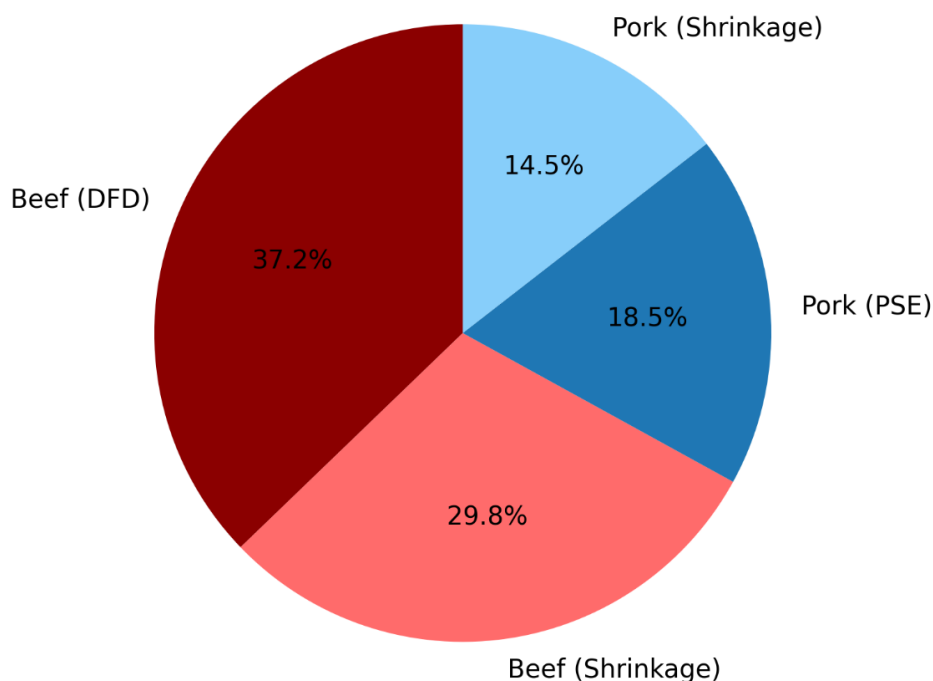
*Source: calculated by the author based on data from Agriculture and Agri-Food Canada.*

The data presented in Table 5 indicate that total projected losses in the Canadian meat industry reach approximately \$2.016 billion CAD. A significant proportion of these losses is attributed not only to direct weight reduction but also to quality degradation of raw materials.

The results confirm that qualitative losses associated with PSE and DFD defects exceed purely quantitative shrinkage losses, highlighting the critical importance of preventive measures during the transportation stage.

To further illustrate the distribution of economic losses, a structural analysis was conducted based on the calculated data and industry statistics (Agriculture and Agri-Food Canada, 2026).

Fig. 1. Total Loss Structure (\$2.016 billion CAD)



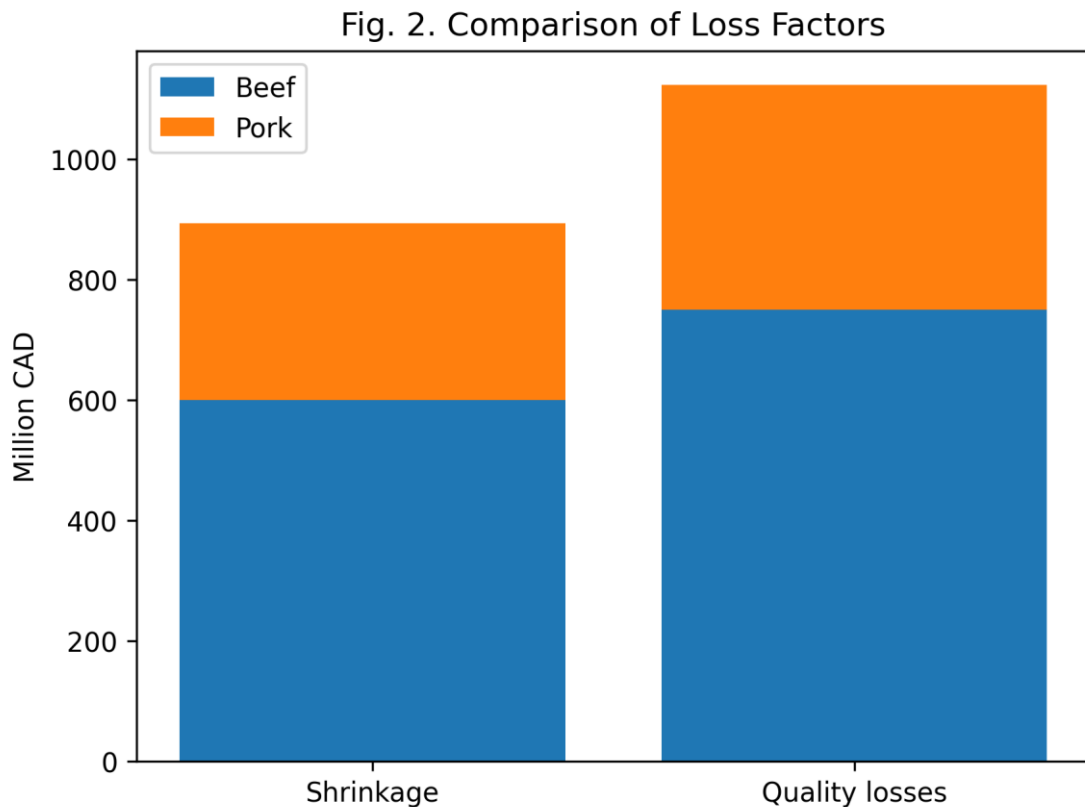
*Figure 1 - Total loss structure in Canada's meat industry (CAD 2.016 billion)*

This distribution reflects the higher economic sensitivity of the beef sector to stress-related losses, which has been previously highlighted in transport and welfare studies (Schwartzkopf-Genswein et al., 2012).

The pork sector (shades of blue) accounts for approximately 33% of total losses. Despite relatively high production volumes, the lower price per kilogram and the

species-specific response to stress result in comparatively lower monetary losses than in the cattle sector.

A comparison of quantitative and qualitative loss components is presented in Figure 2.



*Figure 2 - Comparison of quantitative and qualitative loss components in Canada's meat industry*

The left bar (live weight loss / shrinkage) represents direct losses associated with animal weight reduction, totaling approximately CAD 893 million.

The right bar (quality losses / PSE - DFD) demonstrates significantly higher economic losses, exceeding CAD 1.123 billion, which highlights the dominant impact of quality-related defects on the overall loss structure.

The predominance of quality-related losses emphasizes the importance of pre-slaughter stress control, which is a key focus in both scientific literature and regulatory frameworks (EFSA Panel on Animal Health and Welfare, 2022; Grandin, 2014).

**Conclusions.** Based on the results of a comprehensive analysis of live weight losses and qualitative characteristics of meat products under conditions of logistic stress in 2025 - 2026, the following conclusions can be drawn:

•**Differentiation of logistic impact.** A fundamental difference in the structure of losses between the studied regions has been identified. In Canada, due to extreme transport distances (often exceeding 1000 km), the dominant factor is chronic stress, leading to significant shrinkage (up to 12% of live weight) and the occurrence of DFD defects in cattle (Schwartzkopf-Genswein et al., 2012).

•In contrast, the EU experience demonstrates that strict transport duration limits (e.g., 8-hour intervals) shift the focus toward acute stress during frequent loading and unloading operations, increasing the risk of PSE defects in pork (EFSA Panel on Animal Health and Welfare, 2022).

•Cumulative nature of losses. It has been established that financial losses associated with technological defects (PSE/DFD) consistently exceed losses from live weight reduction by approximately 25.8%.

•Total losses in Canada's agricultural sector are projected at CAD 2.016 billion. In the EU, total losses-particularly those associated with the disposal of non-conforming raw materials with elevated pH - represent a significant destabilizing factor for the implementation of the Farm to Fork strategy.

•HACCP-oriented approach. The necessity of identifying the transport stage as a Critical Control Point (CCP) has been substantiated. The EU experience in 2026 demonstrates the effectiveness of implementing "digital welfare passports," enabling the integration of real-time data on temperature and humidity within transport vehicles directly into the HACCP systems of processing facilities. This approach ensures preventive quality management prior to slaughter. This confirms the relevance of integrating animal welfare parameters into HACCP-based systems, as also emphasized in previous studies (Grandin, 2014).

Prospects and technological convergence. Future development of the livestock sector is associated with the adaptation of European short-chain logistics standards to Canadian territorial conditions through the implementation of mobile slaughter units and IoT-based monitoring systems. Further research will focus on a comparative assessment of safety and quality parameters of traditional meat raw materials and cultivated alternatives.

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