Meat Science 220 (2025) 109689

Contents lists available at ScienceDirect

Meat Science

journal homepage: www.elsevier.com/locate/meatsci

Review

Assessment of pig welfare at slaughterhouse level: A systematic review of animal-based indicators suitable for inclusion in monitoring protocols

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ARTICLE INFO

Keywords:
Pork industry
Pig welfare indicators
Iceberg indicators
Key performance indicators
Artificial intelligence
PRISMA model

ABSTRACT

Pig welfare constitutes a strategic pillar of sustainability within the pork industry. Consequently, there is a need to identify, develop and/or validate indicators for assessing pig wellbeing under commercial conditions. A systematic review following PRISMA guidelines identified 95 pig welfare indicators (PWIs) categorized into physiological, behavioral, health and post-mortem, and product quality. The review evaluated their validity and feasibility (V&F) for use in abattoirs to measure welfare during transport and slaughter. Thirty V&F indicators were found: one physiological (body temperature), 12 behavioral (human-animal relationship, aggression, falling, vocalization, slipping, panting, lying down, sitting, turning back), 13 health and post-mortem (presence of entry points, hernias, body lesions, ear lesions, tail lesions, pericarditis, pneumonia, bursitis, lameness, dead animals, walking and non-walking animals), and four product quality (pH, bruises, body condition, carcass weight). This information might help to identify the factors that affect the risk level of particular pig welfare problems, thereby aiding in the application of risk-based strategies.

1. Introduction

Pig welfare stands as a strategic pillar of sustainability within the pork industry, interlinked with various facets of this concept, such as animal health, productivity, food safety, food quality, bioethics, and production cost efficiency (Velarde et al., 2015). Nonetheless, despite favorable conditions in pre-slaughter operations, pigs are subjected to numerous stressors that frequently trigger pronounced stress responses (Faucitano, 2018). These stressors typically arise from factors such as the withdrawal of feed and/or water, human contact (either known or unknown), handling and herding, social mixing, abrupt fluctuations in micro- and macro-environments, atypical densities, exposure to new environments, and various multisensory stimuli (Miranda-de La Lama, Villarroel, and María, 2014). The impact of these stressors varies depending on the quality of the pre-slaughter conditions, the commercial category of the animals, and notably, their pre-existing health and welfare status, which can affect their fitness during transport, lairage, and slaughter (Machado et al., 2022). In recent decades, there has been a growing movement among citizens, consumers, and NGOs advocating for changes to promote animal welfare throughout rearing, transport, and slaughter (Støier, Larsen, Aaslyng, and Lykke, 2016). Subsequently, farm animal welfare has emerged as a socio-cultural value in contemporary human societies, driven by its bioethical, trade, and food safety implications (Estévez-Moreno et al., 2025).

Consequently, there are currently numerous initiatives aimed at achieving high levels of pig welfare. These initiatives encompass improvements in management practices, the establishment of performance protocols, personnel training, and enhancements in the design of facilities, trucks, and slaughterhouses (Faucitano et al., 2020). Furthermore, there is a growing trend towards the development of protocols and tools for conducting inspections, audits, and/or controls to ensure compliance with governmental or private regulations (i.e., standards, certifications) throughout rearing, transport, and slaughter (EFSA Panel on Animal Health and Welfare (AHAW) et al., 2020). One example is the Welfare Quality® protocols, which prioritize animal-based measures enabling systematic and standardized assessments of farm welfare through the specific training of qualified auditors. Although these protocols are considered reliable and repeatable, their implementation can be costly,

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https://doi.org/10.1016/j.meatsci.2024.109689
Received 27 June 2024; Received in revised form 17 October 2024; Accepted 17 October 2024
Available online 19 October 2024

operationally challenging, and difficult to universally apply (De Luca, Zanardi, Alborali, Ianieri, and Ghidini, 2021). To address these limitations, there is a growing trend in research towards reducing the length of protocols without sacrificing accuracy. This is accomplished by excluding highly correlated indicators, reducing sample sizes, eliminating indicators with low prevalence, and shifting from on-farm assessments to abattoir assessments (Friedrich et al., 2020). Thus, there is a need to develop new protocols that can be directly applied in the slaughterhouse, with specific objectives and targets that can be implemented without compromising operational procedures on the slaughter line and in the chilling room. It is crucial to recognize that rearing, transport, and slaughter systems are dynamic and heavily influenced by production, operational, commercial, and infrastructural conditions unique to each country or region (Sundermann, Bibbal, Holleville, and Salines, 2023).

The World Organization for Animal Health (WOAH, formerly OIE) defines animal welfare as "the physical and mental condition of an animal in relation to the conditions in which it lives or dies" (World Organization for Animal Health (WOAH), 2018). Therefore, welfare assessment can assess an individual's capacity to cope with environmental challenges through a spectrum of animal-based indicators (Blokhuis et al., 2010). However, an indicator proves valuable only if it demonstrates validity, reliability, and feasibility, depending upon the methodology and the objective of the assessment. Additionally, the indicator should be scalable, meaning that measured values can be categorized into two (binary - presence/absence) or more levels associated with increasing or decreasing animal welfare thresholds (Losada-Espinosa et al., 2018). In recent years, 'iceberg' indicators, which can be either indirect or direct, have been developed and validated. These indicators retrospectively describe various aspects that influence the welfare of animals throughout their lives. Analogous to the visible tip of an iceberg reflecting its invisible mass beneath the surface, these indicators unveil aspects of animal welfare that may not always be readily apparent. By combining multiple indicators into one, these indicators maintain variance in animal welfare while facilitating a comprehensive assessment of welfare (Friedrich, Krieter, Kemper, and Czycholl, 2020). Furthermore, there has been a suggestion that key performance indicators (KPIs) employed in industrial process engineering could be adapted to evaluate animal welfare. These KPIs are utilized to measure, compare, and monitor the performance of on-farm, transport, and slaughterhouse processes (Kelly et al., 2011). KPIs facilitate the optimization of operations and provide early warnings of potential animal welfare issues, thereby enabling stakeholders to adjust their decisions and management practices (Van Meensel, Lauwers, and Van Huylenbroeck, 2010). A number of welfare indicators have been validated through specific observational or experimental studies. Given that farm environments, handling, transport, and slaughter induce stress and affect pig welfare, there is a clear need to identify, develop, and validate indicators for assessing pig welfare under commercial conditions. It is therefore essential that these indicators be simple to implement, non-disruptive, and capable of retrospective inference regarding the quality of life of the animals in question. The objective of this paper is to review the current knowledge on PWIs and evaluate their validity and feasibility for use in commercial slaughterhouses.

2. Materials and methods

This systematic review included scientific articles published in indexed journals in English, Spanish, or Portuguese between 1 January 2000 and 30 June 2024. The review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Urrútia et al., 2021), ensuring a systematic approach to the analysis and synthesis of diverse data from an emerging field of research. Prior to commencing the review, the research team developed and agreed upon a protocol.

2.1. Systematic review process by PRISMA guidelines

In accordance with the PRISMA model, the systematic review process to select studies for inclusion in this review comprised four stages: identification, screening, eligibility, and inclusion (Fig. 1). The initial stage involves identifying keywords, followed by the search process in various databases. The databases searched were PubMed, Scopus, and Web of Science. The search terms employed (including titles, abstracts, and keywords) were as follows: abattoir AND pig OR swine AND welfare; lairage AND stun AND slaughter OR abattoir AND "meat quality" AND "pig" OR "swine" AND welfare; AND PUBYEAR >1988. Additionally, a snowball search was conducted to identify further studies by examining the reference lists of relevant studies related to pig welfare indicators that were deemed suitable for full-text review.

A total of 2153 articles were initially identified in the three databases. Additionally, a manual search using similar keywords in other databases resulted in 10 more articles (Google Scholar and Scielo) After removing duplicates, 2163 articles were identified in the initial phase of the systematic review. During the screening phase, 93 duplicate articles were removed, and 1549 articles were excluded based on title, abstract, and keyword analysis. This resulted in 521 eligible articles. Data were extracted from these eligible articles using a spreadsheet (Microsoft Excel), including details such as author(s), year, journal, DOI, aim of the study, methodology, type of research (experimental or retrospective), and the animal welfare indicators tested in the study. At the eligibility stage, the titles, abstracts, and main content of all articles were comprehensively reviewed to ensure they met the inclusion criteria. The following criteria were used to include articles in this study: 1) experimental or observational studies in the pre-slaughter phase; 2) studies utilizing new or known indicators of pig welfare; and 3) studies involving finishing pigs and culled sows. Consequently, 294 articles were excluded because they were based on other species, on-farm studies, or studies not related to pig welfare indicators.

2.2. Articles selected

On completion of the screening process, 227 manuscripts were deemed eligible for inclusion in the systematic review. The list of selected articles is presented below for ease of reference in all tables:

Kobek-Kjeldager et al., 2024[1], Melo et al., 2023[2], Scollo et al., 2023[3], Teixeira et al., 2023[4], Amatucci et al., 2023[5], D'Alessio et al., 2023[6], Ghidini et al., 2023[7], Kobek-Kjeldager et al., 2023[8], Gerster et al., 2022[9], Golightly et al., 2022[10], Helbing et al., 2022 [11], Machado et al., 2022[12], Marti et al., 2022[13], Martin et al., 2022[14], May et al., 2022[15], Moak et al., 2022[16], Piva et al., 2022 [17], Romero et al., 2022[18], Sentamu et al., 2022[19], Valkova et al., 2022[20], Zappaterra et al., 2022[21], Carrascal et al., 2021[22], Cybulski et al., 2021a[23], Cybulski et al., 2021b[24], Ghidini et al., 2021[25], Heinonen et al., 2021[26], Jongman et al., 2021[27], Larson et al., 2021[28], Lechner et al., 2021[29], Teixeira et al., 2021[30], Miranda-de la Lama et al., 2021[31], Pessoa et al., 2021[32], Schaeperkoetter et al., 2021[33], Urrea et al., 2021[34], Vitali et al., 2021a [35], Vitali et al., 2021b[36], Atkinson et al., 2020[37], Blömke et al., 2020[38], Čobanović et al., 2020[39], Driessen et al., 2020a[40], Driessen et al., 2020b[41], Faucitano et al., 2020[42], Flores-Peinado et al., 2020[43], Guardone et al., 2020[44], Jerez-Timaure et al., 2020[45], Ko et al., 2020[46], Lee et al., 2020[47], Li et al., 2020[48], López-Arjona et al., 2020[49], Maisano et al., 2020[50], Nienhaus et al., 2020[51], Sardi, Gastaldo, Borciani, Bertolini, Musi, Garavaldi, et al., 2020[52], Sardi, Gastaldo, Borciani, Bertolini, Musi, Martelli, et al., 2020[53], Teixeira et al., 2020[54], Valros et al., 2020[55], Acevedo-Giraldo et al., 2019[56], Brünger et al., 2019[57], Dalla-Costa et al., 2019a[58], Dalla-Costa et al., 2019b[59], Dalla-Costa et al., 2019c[60], Diana et al., 2019[61], Mantis et al., 2019[62], Marcon et al., 2019[63], Passafaro et al., 2019[64], Vom Brocke et al., 2019[65], Rocha et al., 2019[66], Aboagye et al., 2018[67], Bottacini et al., 2018[68], Carroll

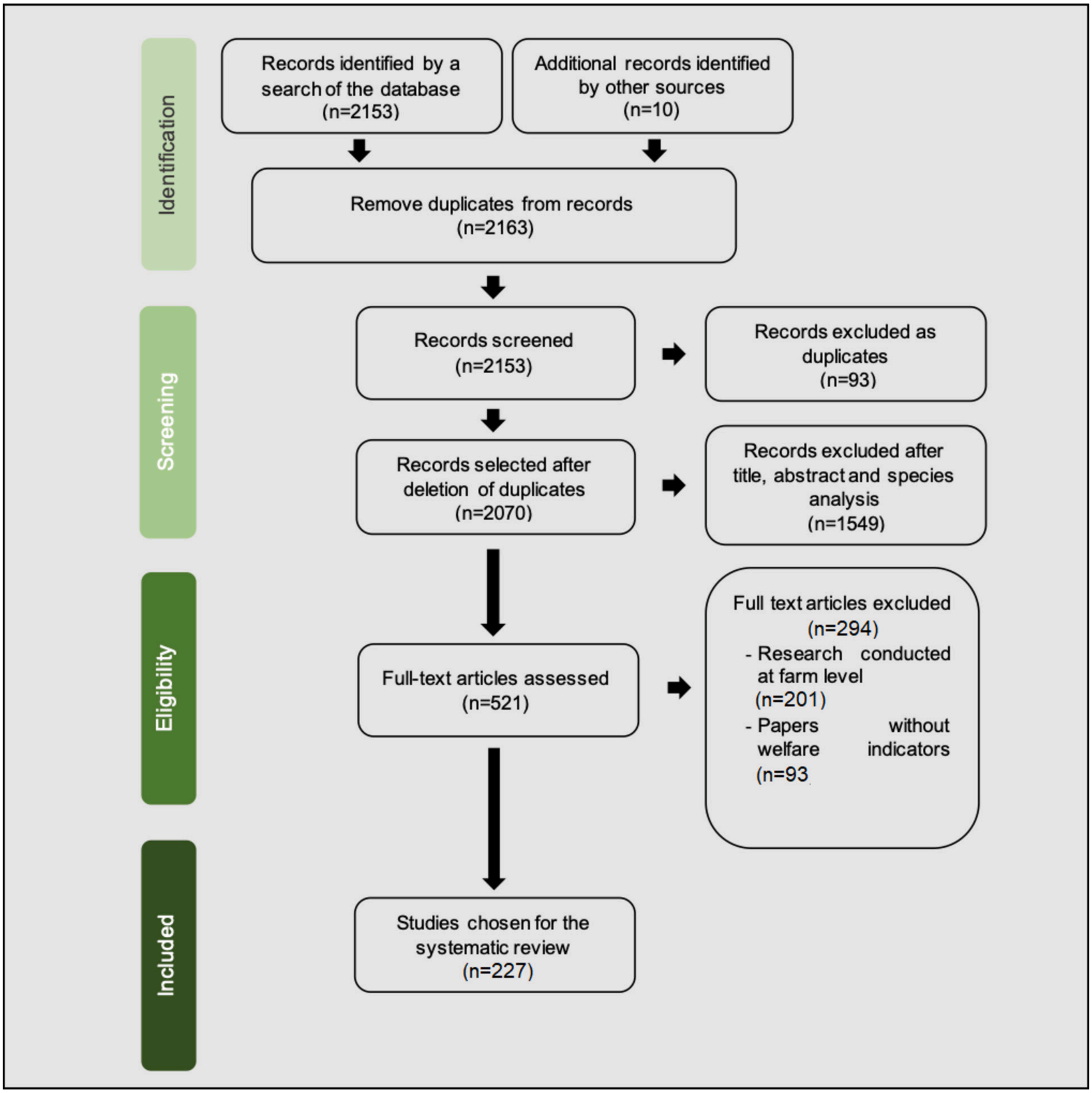

Fig. 1. Flow diagram of literature search and selection processes (adapted from Moher et al., 2009).

et al., 2018a[69], Carroll et al., 2018b[70], Casal et al., 2018[71], Uribe-Corrales et al., 2018[72], Kamenik et al., 2018[73], Mathur et al., 2018[74], Rey-Salgueiro et al., 2018[75], Arduini et al., 2017[76], Correia-Gomes et al., 2017[77], Dalla-Costa et al., 2017[78], Di Martino et al., 2017[79], Díaz et al., 2017[80], Dokmanovic et al., 2017[81], Fertner et al., 2017[82], Herskin et al., 2016[83], Kongsted and Sørensen 2017[84], Pereira et al., 2017[85], Van Staaveren et al., 2017 [86], Vitali et al., 2017[87], Voslarova et al., 2017[88], Wirthgen et al., 2017[89], Sommavilla et al., 2017[90], Barington et al., 2016[91], Carreras et al., 2016[92], Carroll et al., 2016[93], Čobanović et al., 2016 [94], Correia-Gomes et al., 2016[95], Dalla-Costa et al., 2020[96], Dalla-Costa et al., 2016[97], Dalmau et al., 2016[98], Omotosho et al., 2016[99], Rocha et al., 2016[100], Teixeira et al., 2016[101], Van Staaveren et al., 2016[102], Vermeulen et al., 2016[103], Vidal et al., 2016[104], Aguilera-Arango et al., 2015[105], Alban et al., 2015[106], Brandt et al., 2015[107], Dalla-Costa et al., 2015[108], Di Martino et al., 2015[109], Eze et al., 2015[110], Lebret et al., 2015[111], Omotosho et al., 2015[112], Parotat et al., 2016[113], Vermeulen et al., 2015a [114], Vermeulen et al., 2015b[115], Nodari et al., 2014[116], Bolaños-López et al., 2014[117], Correa et al., 2014[118], Dokmanović et al., 2014[119], Estéves et al., 2014[120], González et al., 2014[121], Kephart et al., 2014[122], Nielsen et al., 2014[123], Scheeren et al., 2014[124], Stocchi et al., 2014[125], Teixeira and Boyle, 2014[126], Vial & Reist, 2014[127], Vitali et al., 2014[128], Barington and Jensen, 2013[129], Brandt et al., 2013[130], Correa et al., 2013[131], Fàbrega et al., 2013[132], Fries et al., 2013[133], Gajana et al., 2013[134], Gerritzen et al., 2013[135], Gonzalez et al., 2013[136], Goumon et al., 2013[137], Jerez-Timaure et al., 2013[138], Klauke et al., 2013[139], Llonch et al., 2013[140], Machtolf et al., 2013[141], Piñeiro et al., 2013 [142], Prunier et al., 2013[143], Seshoka et al., 2013[144], Soler et al., 2013[145], Torrey et al., 2013[146], Valros et al., 2013[147], Velazco et al., 2013[148], Weschenfelder et al., 2013a[149], Weschenfelder et al., 2013b[150], Zhen et al., 2013[151], Atkinson et al., 2012[152], García-Celdrán et al., 2012[153], Guàrdia et al., 2012[154], Harley et al., 2012[155], Llonch et al., 2012[156], Ludtke et al., 2012[157], Mota-Rojas et al., 2012[158], Panella-Riera et al., 2012[159], Swaby &

Gregory, 2012[160], Weschenfelder et al., 2012[161], Foury et al., 2011 [162], Pilcher et al., 2011[163], Støier et al., 2011[164], Vogel et al., 2011[165], Becerril-Herrera et al., 2010[166], Chai et al., 2010[167], Correa et al., 2010[168], Dalmau et al., 2010[169], D'Eath et al., 2010 [170], Edwards et al., 2010[171], Kephart et al., 2010[172], Van de Perre et al., 2010[173], Becerril-Herrera et al., 2009[174], Dalmau et al., 2009[175], Guàrdia et al., 2009[176], Hötzel et al., 2009[177], Mota-Rojas et al., 2009[178], Piñeiro et al., 2009[179], Terlouw et al., 2009[180], Gade, 2008[181], Dalla-Costa et al., 2008[182], Haley et al., 2008[183], Lloveras et al., 2008[184], Panella-Riera et al., 2008 [185], Sutherland et al., 2008[186], Gade, et al., 2008[187], Averos et al., 2007[188], Chaloupková et al., 2007[189], Dalla-Costa et al., 2007[190], Fàbrega et al., 2007[191], Foury et al., 2007[192], Gade et al., 2007[193], Nowak et al., 2007[194], Piñeiro et al., 2007[195], Rabaste et al., 2007[196], Van den Berg et al., 2007[197], Jackowiak et al., 2006[198], Lewis and McGlone, 2006[199], Mota-Rojas et al., 2006[200], Scott et al., 2006[201], Smulders et al., 2006[202], Faucitano et al., 2006[203], Brown et al., 2005[204], Cagienard et al., 2005 [205], Hambrecht et al., 2005a[206], Hambrecht et al., 2005b[207], Salajpal et al., 2005[208], Van den Berg et al., 2005[209], Fàbrega et al., 2004[210], Lambooij et al., 2004[211], Valros et al., 2004[212], Franck et al., 2003[213], Kim et al., 2004[214], Warriss et al., 2003 [215], Beattie et al., 2002[216], Fàbrega et al., 2002[217], Hartung et al., 2002[218], Hemsworth et al., 2002[219], Perez et al., 2002a [220],Pérez et al., 2002b[221], Faucitano, 2001[222], Grandin, 2001 [223], Hunter et al., 2001[224], Klont et al., 2001[225], Støier et al., 2001[226], Gispert et al., 2000[227].

2.3. Criteria for selection of pig welfare indicators (PWI)

In order to provide a comprehensive assessment of the welfare problem in question, animal and product quality indicators related to pig welfare were identified. Related indicators assessing the same welfare issue were combined to produce 95 different indicators. Each indicator was then assigned to a measurement category (physiological, behavioral, health and product quality). This classification also included information on the validation phase (transport T; lairage L; pre-slaughter handling PSH; slaughter and bleeding SB), animal sex, trade categories (cull sows CS; finished pigs FP), validity (high H; intermediate I; low L), feasibility of measurement at slaughter (high H; intermediate M; low L), and supporting literature reference (first author and year of publication). The validity and feasibility of each indicator in the slaughterhouse were categorized as high, medium, and low (Table 1) according to the criteria proposed by Losada-Espinosa et al. (2018). Following these criteria, indicators of high validity were those validated in previous research by a considerable number of articles. These indicators demonstrated both internal (i.e., sampling, measures, and procedures) and external (i.e., inferences) validity, making them likely to be considered valid indicators. Indicators of moderate validity were those that did not necessarily indicate poor welfare (i.e., body condition score). Indicators with low validity were proposed, but there was no evidence that they effectively assessed welfare. Indicators deemed to have high feasibility could be reliably recorded in slaughterhouses regardless of the number of animals, available space, or processing line speed. Indicators with medium feasibility required special conditions (i.e., extra space or time) for proper assessment. Indicators with low feasibility could not be routinely assessed in commercial slaughterhouses. In cases where an indicator was defined as having high validity in its original setting but was unlikely to be valid or feasible in a slaughterhouse environment, we considered the possible use of indicators with intermediate validity and high feasibility, or exploring alternative novel technologies.

3. Results

A systematic review of peer-reviewed articles identified 95 indicators of pig welfare, categorized into four main categories: physiological PWI's (7 subcategories: endocrine measure; fear/ excitement index and release of catecholamines; food deprivation index; fasting Indicators; physical effort index; indicators of dehydration and/or hemoconcentration; indicators of inflammatory processes; fear/excitation and emotional reactivity markers), behavioral PWI's (3 subcategories: pre-slaughter behaviors; slaughter behaviors; pain responses), health and post-mortem PWI's (5 subcategories: injuries body and others inflammations; gastrointestinal lesions; cardiac and respiratory lesions; diseases and injuries of the locomotor system; mortality and morbidity), and product quality PWI's (2 subcategories: carcass quality; sensory analysis). Within these categories, they were further subdivided into 17 subcategories. Specifically, 21 physiological indicators, 36 behavioral indicators, 29 health and post-mortem indicators, and 9 product quality indicators were identified. Table 2 provides a comprehensive overview of all physiological indicators. Among the most commonly used indicators in the physiological category are plasma cortisol concentrations (an endocrine measure), glucose (indicative of fear/excitement and catecholamine release), creatine kinase, and lactate (markers of physical effort). Notably, among the eight subcategories that constitute this classification, indicators related to inflammatory processes (haptoglobin, acute phase proteins, alpha-amylase/amyloid A, adrenocorticotropic hormone, and albumin) and anxiety/excitement, as well as indicators measuring emotional reactivity (body temperature, rectal temperature, respiratory rate, and heart rate), accounted for 24 % and 19 % of the total number of indicators, respectively.

Table 3 presents 36 behavioral indicators categorized into three subcategories. Among these, 53 % pertain to behaviors assessed during pre-slaughter (unloading, handling, and lairage), 44 % to behaviors during slaughter, and the remaining 3 % focus on responses to pain. The most frequently used indicators for assessing pig welfare include vocalizations, falling and lying down accounting for 30 %, 27 %, and 25 %, respectively. The corneal reflex and rhythmic breathing are also commonly utilized indicators in the reviewed studies, comprising 21 %. Regarding post-mortem and health indicators (Table 4), five subcategories were identified. Within these, 34 % of the indicators relate to body injuries and other inflammations, 21 % to gastrointestinal injuries,

Table 1
Inclusion criteria for the classification of pig welfare indicators (PWIs) according to their validity and feasibility for possible incorporation into commercial slaughterhouse evaluation protocols.

	Validity	Feasibility
Low	These indicators have a tenuous or indirect relationship to animal welfare. As a result, they are unable to provide a definitive account of the animal's welfare status and frequently necessitate meticulous interpretation.	The measurement of these indicators is often challenging in practice due to the inherent complexity, cost, time, and resource requirements. The lack of accessible tools or methods may also act as a significant barrier to implementation.
Intermediate	They are indicators that can provide valuable information, but are not as precise or direct as high validity indicators. Their effectiveness may depend on the context and interpretation of the data.	The assessment of these indicators is a complex process, yet feasible, requiring additional time, equipment or specialized training to ensure an accurate evaluation.
High	These indicators have been validated in previous research with strong scientific support, which in turn has internal (i.e. sampling, measures and procedures) and external (inference) validity, and have been shown to be effective in assessing welfare.	These indicators are straightforward to quantify in practice and can be evaluated on a regular basis (number of animals, space allowance or speed of the processing line) using relatively uncomplicated and accessible methodologies.

Table 2
The category on physiological indicators of pig welfare is divided into seven subcategories, each of which presents the indicator, the stage of assessment, the commercial category, the validity and feasibility, as well as the supporting references.

Subcategory	PWIs	Pre-slaughter stage	Commercial categories	Validity	Feasibility	References *
Endocrine measure	Plasmatic cortisol concentration	T, L, PSH, SB	FP, CS	H	L	12, 18, 27, 28,31, 33, 48, 49, 46, 52, 56, 58, 59, 66; 67, 70,73, 75, 78, 81, 88, 89 91, 96, 108, 109, 111, 119, 132, 144, 145, 147, 148, 149, 135, 151, 153, 162, 163, 167, 170, 181, 182, 186, 187, 203, 207.
	Corticosterone	SB, PSH	FP	L	L	75.
	Catecholamines	T, L, PSH, SB	FP	L	L	162, 192, 194, 202, 218.
Fear/ Excitement index and release of catecholamines	Glucose	T, L, PSH, SB	FP, CS	H	L	18, 30, 31, 33, 39, 54, 56, 67, 73, 107, 111, 117, 130, 135, 151, 158, 166, 174, 182, 186, 187, 192, 214, 219, 220.
Food deprivation index	B-hydroxybutyrate	T, L, PSH, SB	FP	H	L	56.
Fasting Indicators	Non-esterified fatty acids (NEFA)	T, L, PSH, SB	FP	H	L	18, 56.
Physical effort index	Creatine kinase	T, L, PSH, SB	CS, FP	H	L	16, 30, 31, 34; 52, 54, 56, 67, 90, 92, 97, 107, 111, 118, 130, 131, 135, 150, 151, 162, 167, 170, 187, 186, 187, 192, 211, 214, 215, 216, 226, 227.
	Creatine Phosphokinase	T, L, PSH	FP	I	L	154, 169.
	Lactate	T, L, PSH, SB	CS, FP	H	L	12, 16, 18, 33,34, 30, 39, 42, 54,56, 58, 66; 67, 73, 78, 81, 89, 90, 96, 105, 107, 108, 111, 117, 118, 119, 130, 131, 135, 144, 147, 149, 150, 151, 154, 158, 161, 162, 163, 166, 170, 171, 168, 174, 182, 187, 192, 194, 207, 210, 218, 225, 226, 227.
Indicators of dehydration and/or hemoconcentration	Lactate dehydrogenase	T, L, PSH, SB	FP	I	L	49, 111, 135, 167, 187, 210, 214, 217.
	Total serum protein	T, L, PSH, SB	FP	L	L	56; 67, 107.
	Hematocrit	T, L, PSH, SB	FP			16, 18, 56; 117, 135, 151, 158, 176, 186.
Indicators of inflammatory processes	Haptoglobin	T, L, PSH, SB	FP	H	L	70, 145, 195, 197.
	Acute Phase Proteins (Pig-Map, haptoglobin C-Reactive protein)	T, L, PSH, SB	FP	H	L	139, 142, 150, 153, 161, 179, 195.
	Alpha - Amylase/ Amyloid A	T, L, PSH, SB	FP	I	L	49, 145, 195.
	Adrenocorticotropic hormone ACTH	T, L, PSH, SB	FP	I	L	30, 111, 167.
	Albumin	T, L, PSH	FP	H	L	178, 188.
Fear/excitation and emotional reactivity markers	Body temperature	T, L, PSH, SB	FP	H	H	12, 43, 76, 135, 165, 204.
	Rectal temperature	T, L, PSH	FP	I	M	2, 12, 18, 66.
	Respiratory rate	T, L, PSH, SB	FP	I	M	2, 12.
	Heart rate	T, L, PSH, SB	FP	H	L	14, 18, 66, 118, 131, 135, 137, 165, 168, 182, 182, 199, 204.

Abbreviations: Pre-slaughter stage: transport T; lairage L; pre-slaughter handling PSH; slaughter and bleeding SB. Commercial Category: finishing pigs FP, culled sows CS. Validity/Feasibility: high H, intermediate I; low L; Medium M; Pig welfare indicators PWIs * The authors of each reference can be located in section 2.2.

and 17 % to cardiac and respiratory injuries. Among the documents reviewed, the most frequently used indicators were skin lesions (54 %), percentage of dead animals (16 %), and lameness (15 %). Finally, the product quality category consisted of three subcategories (Table 5): 11 % of the indicators related to carcass quality, 66 % to instrumental meat quality indicators, and the remaining 22 % to sensory indicators. The most commonly employed indicators were pH, water holding capacity, and color, with frequencies of 87 %, 60 %, and 51 %, respectively. Thirty valid and feasible (V&F) indicators were identified across four categories—physiological, behavioral, health and post-mortem, and product quality—to be included in animal welfare protocols or inspections at the slaughterhouse level. Within the physiological indicator category, only one V&F indicator was found: body temperature. In the behavioral category, 12 V&F indicators were identified, including 9 indicators applicable during the pre-slaughter stage (human-animal relationship, aggression, falling, vocalization, slipping, panting, lying down, sitting, turning back) and 3 indicators applicable at slaughter (corneal reflex, rhythmic breathing, vocalization). In the health and post-mortem category, 13 V&F indicators were detected: presence of entry points, hernias, body lesions, ear lesions, tail lesions, pericarditis, pneumonia, bursitis, lameness, dead animals, walking and non-walking animals. Finally, in the product quality category, 4 V&F indicators were identified: pH, bruises, body condition, and carcass weight.

4. Discussion

The slaughter of animals represents a crucial stage in meat production, often shielded from public view behind closed doors (Miranda-de La Lama, Villarroel, and María, 2014). Despite this, it remains a significant concern for consumers and civil society organizations. Consequently, public policies and private standards continually evolve to meet societal expectations and optimize animal welfare inspections or audits in slaughterhouses (Sundermann, Bibbal, Holleville, and Salines, 2023). Accurate and systematically collected data are essential to describe

Table 3
The category on behavioral indicators of pig welfare is divided into seven subcategories, each of which presents the indicator, the stage of assessment, the commercial category, the validity and feasibility, as well as the supporting references.

Subcategory	PWIs	Pre-slaughter	Commercial categories	Validity	Feasibility	References *
Pre-slaughter behaviors	Human-Animal interactions	T, L, PSH	FP	H	H	21, 42, 151, 218, 219.
	Aggression	T, L, PSH	FP, CS	H	H	1, 8, 126, 135, 170, 181,187, 202.
	Fall	T, L, PSH, SB	FP, CS	H	H	39, 52, 72, 98, 100, 103, 107, 111, 121, 122, 125, 130, 146, 161, 168, 169, 175.
	Vocalization	T, L, PSH	FP, CS	H	H	21, 42, 72, 89, 97, 98, 100, 103, 115, 121, 122, 125, 146, 164, 171, 168, 189.
	Slip	T, L, PSH	FP, CS	H	H	21, 39, 52, 79, 98, 100, 103, 121, 122, 130, 169, 175, 196.
	Drink	T, L, PSH	FP	I	M	90, 201.
	Exploring	T, L, PSH	FP, CS	I	H	10, 56.
	Panting	T, L, PSH, SB	FP, CS	H	H	15, 21, 37, 39, 72, 103, 140, 152, 156, 173, 175.
	Huddling	T, L, PSH	FP	I	H	21, 39, 72, 86.
	Jam	T, L, PSH, SB	FP	H	M	152, 171.
	Lying down	T, L, PSH, SB	FP, CS	H	H	10, 34, 78, 83, 90, 97, 107, 109, 130, 137, 146, 177, 180, 187, 196, 200, 201, 221.
	Open-mouth breathing	T, L, PSH	FP	I	H	163, 172.
	Overlaps	T, L, PSH	FP	I	H	21, 52, 107, 146, 153, 161, 168.
	Reluctance to move	T, L, PSH	FP	I	H	100, 107, 171.
	Seated	T, L, PSH, SB	FP, CS	H	H	34, 56, 78, 97, 130, 137, 146, 187, 221.
	Sniffing	T, L, PSH	FP, CS	I	H	56, 182.
	Standing	T, L, PSH, SB	FP, CS	I	H	1, 10, 34, 56, 78, 107, 126, 136, 146, 177, 187, 196, 200, 201.
	Turning back	T, L, PSH, SB	FP, CS	H	H	21, 29, 33, 42, 100, 107, 115, 146, 168, 169, 198.
	Walking	T, L, PSH	FP	I	H	56, 78, 180, 225.
Slaughter behaviors	Positive blink reflex	SB	FP	I	H	121, 125.
	Cessations of breathing	SB	FP	I	H	13, 19.
	Convulsion	SB	FP, CS	I	H	15, 19, 27, 196.
	Corneal reflex	SB	FP, CS	H	H	15 19, 22, 27, 37, 113, 125, 135, 140, 152, 156, 165, 185, 194, 218.
	Loss of posture	SB	FP	I	M	27, 121, 116.
	Crawl	SB	FP	I	M	27
	Jumping	SB	FP	I	H	29
	Opening mouth	SB	FP	I	M	15, 113.
	Palpebral reflex	SB	FP, CS	H	M	194
	Pupil reflex	SB	FP	I	H	125
	Rhythmic breathing	SB	FP, CS	H	H	27, 37, 98, 116, 125, 140, 156, 165, 173.
	Vocalization	SB	FP, CS	H	H	19, 27, 33, 113, 116,121, 125, 140, 156.
	Righting reflex	SB	FP	H	M	15, 113, 116,121.
	Sensitivity reflex	SB	FP	I	H	22
	Spontaneous natural eye blinking	SB	FP	I	H	224
Pain responses	Responding to prick on the nasal septum.	SB	FP, CS	I	H	194
	Responding to hot water	SB		I	H	113

Abbreviations: Pre-slaughter stage: transport T; lairage L; pre-slaughter handling PSH; slaughter and bleeding SB. Commercial Category: finishing pigs FP, culled sows CS. Validity/Feasibility: high H, intermediate I; low L; Medium M; Pig welfare indicators PWIs * The authors of each reference can be located in section 2.2.

health hazards effectively and aid in planning, implementing, and evaluating risk reduction measures (Hoinville et al., 2013). In this context, our review focused on identifying Pig Welfare Indicators (PWIs) used in international research, particularly under commercial conditions, and assessing their validity and feasibility to promote their adoption in slaughterhouses. We identified a total of 95 indicators, from which 29 were determined to be both valid and feasible for inclusion in animal welfare assessment systems at the slaughterhouse level.

4.1. Physiological indicators

The term "stress" is frequently defined as the physiological state that an animal enters when confronted with challenges that impede its ability to adapt to environmental or physical constraints (Broom, 1988). Accordingly, the prevailing methodology for investigating stress and animal welfare entails the utilization of physiological indices that are employed to gauge activity within the hypothalamic-pituitary-adrenal (HPA) axis, either directly or indirectly. The conventional method for assessing stress typically involves the measurement of glucocorticoid hormones (such as cortisol or corticosterone) in blood plasma. However, in order to mitigate the stress induced by blood sampling, alternative methods have been developed, including the measurement of corticosteroids in saliva, urine, or faeces (Mormède et al., 2007; Russell et al., 2012). Despite its variability and short half-life, cortisol has been widely used to validate other welfare indicators (Acevedo-Giraldo, Sánchez, and Romero, 2020). Elevated cortisol levels have been observed in animals with tail injuries and ear bites (Smulders, Verbeke, Mormede, & Geers, 2006). However, it is important to note that cortisol levels are known to fluctuate based on factors such as the time of day and food intake.

The assessment of long-term or chronic stress necessitates the collection of repeated samples over an extended period of time. In this context, hair cortisol measurement offers several advantages over traditional methods. Hair samples can be collected non-invasively,

Table 4
The category on health and pre-slaughter indicators of pig welfare is divided into seven subcategories, each of which presents the indicator, the stage of assessment, the commercial category, the validity and feasibility, as well as the supporting references.

Subcategory	PWIs	Observation	Commercial categories	Validity	Feasibility	References *
Injuries body and others inflammations	Abscesses	SB	FP, CS	H	H	25, 36, 44, 55, 65, 82, 84, 97, 101, 106, 110, 127, 197, 198.
	Hernia	SB	FP	H	H	4, 12, 32, 54, 59, 84, 106.
	Foot lesions	SB	FP	I	H	186, 201.
	Skin lesions	SB	FP, CS	H	H	5, 4, 10,19, 25, 26, 30, 34, 36, 39, 41, 42, 54, 59, 60, 68, 69, 72, 78, 79, 81 84, 85, 86, 87, 89, 92, 93, 94, 98, 104, 107, 111, 119, 122, 123, 124, 126, 130, 131, 132, 136, 143, 150, 153, 157, 162, 170, 176, 178, 180, 187, 191, 201, 202, 221, 222.
	Ear lesions	SB	FP	H	H	4, 54, 38, 60, 202, 205.
	Tail lesions	SB	FP, CS	H	H	5, 6, 3, 4, 9, 17, 26, 36, 47, 54, 55, 57,60,101, 102, 126, 147, 155, 197, 201, 202, 205, 212, 224.
	Skin discoloration		FP, CS	I	H	21, 163, 172.
	Dermatitis		FP	I	H	25, 50, 77, 104.
	Presence of dirtiness		FP	H	M	25, 50, 202.
	Erysipelas		FP	H	M	44.
	Erythema		FP	I	H	120.
	Ham defects		FP	I	M	35.
Gastrointestinal lesions	Gastric ulcers		FP	H	M	3,7, 11, 23, 24, 112, 99, 112, 160, 197, 209.
	Enteritis		FP	H	M	44.
	Peritonitis	SB	FP	I	H	36, 44, 65, 95, 104.
	Jaundice		FP	H	M	35.
	Milk spot liver		FP	I	H	35, 39, 44, 51, 77, 84.
	Rectal prolapse	SB	FP	I	H	4, 59.
Cardiac and respiratory lesions	Pericarditis		FP, CS	H	H	39, 51, 74, 77, 80, 95, 101.
	Pleuropneumonia		FP	I	H	19, 110.
	Pneumonia		FP, CS	H	H	25, 32, 39, 44, 51, 74, 80, 95, 101, 110, 133, 197.
	Pleurisy		FP, CS	I	H	25, 44, 51, 64, 80, 95, 101, 102, 106, 110, 197.
	Pleuritis		FP	I	M	74.
Diseases and injuries of the locomotor system	Lameness	T, L, PSH	FP, CS	H	H	7, 10, 21, 25, 32, 50, 54, 69, 79, 80, 103, 169, 172, 175, 197, 198, 201.
	Arthritis	SB	FP	I	M	84, 198.
	Bursitis	SB	FP, CS	H	H	4, 19, 32, 50, 54, 68, 84, 86, 201.
Mortality and morbidity*	DOA	T, L, PSH	FP, CS	H	H	12, 13, 18, 20, 44, 51,60, 64, 88, 128, 131, 163, 175, 183, 186, 195, 201, 217.
	NANI	T, L, PSH	FP, CS	H	H	12, 18, 60. 131,163, 186.
	NAI	T, L, PSH	FP, CS	H	H	12,17, 60, 163.

Abbreviations: Pre-slaughter stage: transport T; lairage L; pre-slaughter handling PSH; slaughter and bleeding SB. Commercial Category: finishing pigs FP, culled sows CS. Validity/Feasibility: high H, intermediate I; low L; Medium M; Pig welfare indicators PWIs * The authors of each reference can be located in section 2.2.

Table 5
The category on product quality indicators of pig welfare is divided into seven subcategories, each of which presents the indicator, the stage of assessment, the commercial category, the validity and feasibility, as well as the supporting references.

Subcategory	PWIs	Observation	Commercial categories	Validity	Feasibility	References *
Carcass quality	Bruises		FP, CS	H	H	6, 19, 34, 45, 42, 59, 67, 68, 69, 91, 93, 124, 126, 129, 131,149, 159, 161, 196, 200, 203.
	pH		FP, CS	H	H	4, 2, 15, 16, 19, 31, 28, 34, 37, 39, 40, 42, 45, 48, 51, 54, 56, 58, 59, 62, 63, 71, 75, 78, 81, 89, 94, 96,100, 103, 111, 114, 115, 118, 119, 124, 130, 131, 134, 136, 138, 139, 147, 149, 150, 151, 156, 157, 159, 161, 162, 165, 167, 168, 170, 173, 174, 180, 181, 184, 185, 187, 189, 190, 191, 194, 200, 206, 208, 210, 211, 213, 214, 216, 217, 219, 220, 225, 226, 227.
	Water- holding capacity		FP, CS	H	L	2, 19, 28, 34 39, 40, 42, 45, 48, 51, 54, 56, 58, 59, 62, 63, 71, 75, 78, 81, 89, 96, 100, 111, 118, 119, 124, 131, 134, 138, 139, 144, 147, 149, 150, 151, 156, 157, 161, 165, 167, 168, 170, 180, 184, 185, 200, 203, 207, 208, 210, 2121 216, 217, 218, 226
	Texture		FP, CS	H	L	51, 63, 78, 134, 184, 185.
	Meat temperature		FP, CS	L	M	4, 40, 59, 94, 103, 130, 131, 134, 138, 144, 147, 149, 151, 187, 225
	Color		FP, CS	H	L	19, 28, 54 34, 39, 40, 42, 48, 51, 54, 56, 63, 71, 75, 78, 81, 100, 111, 119, 131, 134, 138, 139, 147, 148, 150, 151, 156, 157, 161, 165, 168, 170, 184, 185, 190, 200, 206, 208, 210, 213, 216, 225, 226.
	Carcass weight	PSH, SB	FP, CS	H	H	5, 19, 27, 34, 39, 48, 54, 59; 71, 80, 89, 138, 139, 141, 147, 151, 176, 192, 216, 220.
Sensory analysis	Tenderness		FP	H	No applicable	51, 71, 185.
	Odor			H	No applicable	52, 71.

Abbreviations: Pre-slaughter stage: transport T; lairage L; pre-slaughter handling PSH; slaughter and bleeding SB. Commercial Category: finishing pigs FP, culled sows CS. Validity/Feasibility: high H, intermediate I; low L.; Medium M; Pig welfare indicators PWIs * The authors of each reference can be located in section 2.2.

simplifying transport and storage, and they provide a reflection of long-term cortisol levels without the need for multiple samplings (Bacci et al., 2014; Burnett et al., 2015; Martelli et al., 2014). The concentration of cortisol in hair samples is indicative of the concentration of cortisol in the blood, and thus enables the hair to provide information on changes in cortisol levels over time. This renders it an appropriate biomatrix for monitoring the welfare and health of animals that are exposed to environmental and physiological stressors throughout their lives (Ghassemi Nejad, Ghaffari, Ataallahi, Jo, and Lee, 2022). When interpreting cortisol levels in hair, methodological aspects such as the use of the shave-reshave method or the hair color should be considered, to properly interpret the results with regards to the stressors that may be reflected. Other physiological indicators used in pigs include corticosterone (Rey-Salgueiro et al., 2018), glucose, lactate, and lactate dehydrogenase levels (López-Arjona et al., 2020), plasma creatine kinase activity (Brandt et al., 2013), B-hydroxybutyrate, and non-esterified fatty acids (Acevedo-Giraldo et al., 2020), as well as haptoglobin and acute phase proteins (García-Celdrán et al., 2012; Klauke et al., 2013; Piñeiro et al., 2013; Soler et al., 2013), which have been identified as potential indicators. However, incorporating these indicators into welfare measurement protocols at the slaughterhouse level is often impractical due to the high economic and operational costs involved.

The detection of the thermal status of pigs is dependent on two principal methodologies: invasive techniques for the measurement of internal body temperature (which serves as a reference point) and remote techniques for the assessment of thermal radiation emitted from the pig's body. One noteworthy example is infrared temperature measurement (IRT), which has the potential for implementation as an automated monitoring system at the slaughterhouse level (Barbosa-Pereira et al., 2019). Pigs are particularly susceptible to abrupt alterations in ambient temperature, as observed during transportation and pre-slaughter procedures (Miranda-de la Lama et al., 2021). It has been demonstrated that in circumstances characterized by stress, the body temperature of an animal may rise to a maximum of 41.0 °C (Gariepy et al., 1989). This phenomenon occurs as a result of the activation of the sympathetic pathway of the autonomic nervous system, which has the potential to alter the thermoregulatory set point and serve as an indicator of animal welfare. Accordingly, elevated body temperature may indicate stress or injury in pigs (Sapkota et al., 2016), as well as serve for disease diagnosis and health monitoring (Zhang et al., 2019). Teixeira, Boyle, and Enríquez-Hidalgo (2020) reported that pigs with tail lesions exhibited higher body temperatures than those without lesions, which is likely due to underlying inflammatory and infectious processes.

Another physiological indicator identified in our study is heart rate, which serves as an indirect measure of autonomic function and can indicate stress in pigs (Von Borell et al., 2007). Detecting abnormalities in heart rate and rhythm not only signals stress but also serves as a valuable diagnostic tool for heart disease. Increases in breathing and heart rate can be associated with pain, fear, anxiety, and panic (Barbosa-Pereira et al., 2019). Correa et al. (2014) observed higher heart rates in animals that exhibited more slips, falls, and vocalizations during loading and unloading operations. Additionally, introducing pigs to new surroundings and environments has been shown to affect heart rate (Lewis et al., 2008; Rocha et al., 2019). Continuous heart rate monitoring provides a valuable tool for research, allowing non-invasive assessment of the animal's physiological state. Although there are experimental sensors that can be implanted in animals to monitor body temperature and heart rate, their application in slaughterhouse settings is currently impractical (Brandt & Aaslyng, 2015).

4.2. Behavioral indicators

At the slaughterhouse level, behavior represents one of the most commonly utilized groups of indicators in reviewed studies for assessing animal welfare (Vitali et al., 2021). This is because pig behavior results from complex interactions involving phylogeny (such as breed and temperament) and ontogeny (including behavioral development, experiences, and social interactions), as well as environmental conditions during pre-slaughter operations (such as handling and human-animal interactions). The quality of lairage and other factors influencing physiological status, mental states, and biological functioning have been extensively studied (Zappaterra et al., 2022). However, behavioral assessment requires observations from the moment pigs leave the farm until they are stunned or bled (Brandt & Aaslyng, 2015). Consequently, under commercial conditions, behavioral assessment is impractical due to its time-consuming nature, the need for specialized training, and potential disruptions to abattoir operations. Recently, automated behavioral analysis (ABA) has been proposed using various tools and methods such as machine learning, machine vision, unsupervised learning, and deep learning. However, current ABA capabilities still struggle to fully transition from qualitative recognition of behaviors by human experts to quantitative descriptions used by machines. Moreover, detecting behaviors is complicated by differences in data collection methods between ethologists and the information required for training algorithms in machine systems (Siegford et al., 2023).

During pre-slaughter operations, which include unloading, transportation to resting pens, and subsequent transportation to stunning, animals often display abrupt behavioral changes. These changes can serve as early indicators of stress, health issues, fitness problems during transport, or deficiencies in management (Terlouw et al., 2021). Several authors agree that measuring behavioral frequency or latency is valuable for assessing operational quality in terms of animal welfare within slaughterhouses (Sardi et al., 2020a). The most frequently observed behaviors in our systematic review were aggression, falling, slipping, panting, huddling, non-ambulatory animals, overlapping animals, sitting animals, animals turning back, and vocalizations. It is clear that conditions during animal unloading prior to slaughter significantly influence their subsequent behavior. Additionally, factors such as fasting and poor lairage conditions (such as inadequate ventilation, lack of cooling showers on hot days, limited access to drinking water, environmental noise, and dirty or poorly maintained facilities) can also lead to noticeable changes in pig behavior, preventing their ability to rest after transport. This can lead to increased reactivity to handling and aggression (Dokmanovic et al., 2017). Another critical consideration is the impact of heat stress, which can result from the extreme conditions experienced during transport and within the abattoir, often with limited infrastructure to mitigate it. Indicators of heat stress include fatigue, panting, stereotypic behaviors, and animals sitting (Atkinson et al., 2020; Brandt et al., 2013; Zappaterra et al., 2022).

It is also important to consider that the facilities available and the handling of animals by stockmen prior to slaughter will directly influence animal behavior (Applebaum, MacLean, and McDonald, 2021; Grandin, 2017). The development of positive human-animal relationships (HAR) can mitigate the occurrence of fear and stress in animals, which are crucial factors in the evaluation of animal welfare (Pol et al., 2021). However, the quality of human-animal relationships (HAR) is influenced by a number of factors, including the working conditions, quality of life, health and safety of the workers, as well as their knowledge and experience (Pastrana-Camacho et al., 2023). Operators lacking experience, competence, or responsibility may inflict pain and suffering on animals and, in some instances, may cause electrothermal injuries due to the improper use of electrical devices employed to handle and stun animals prior to slaughter (Miranda-de la Lama, 2024). The tests employed to evaluate animal fear within the context of human-animal relationships (HAR) can be classified into three principal categories: The assessment of reactions to the presence of a stationary person, the assessment of reactions to a moving person, and the assessment of reactions to handling are the three categories of tests used to assess animal fear in the human-animal relationship (Lensink et al., 2001; Wilhelmsson et al., 2023). Therefore, the implementation of proper management strategies that promote positive interactions can significantly enhance the quality of life of pigs, thereby optimizing production outcomes.

Stunning is defined as an intentionally induced physical, chemical, or electrical process that causes painless loss of consciousness and sensation, including any method that results in instantaneous death (EFSA Panel on Animal Health and Welfare (AHAW) et al., 2020). In our review, the most commonly observed indicators were convulsions, corneal reflexes, rhythmic breathing, and vocalizations. It is important to note that these indicators should not be considered independently but rather as interdependent measures that collectively indicate a timely and effective loss of consciousness. Moreover, the implementation of these protocols should be integrated as key performance indicators (KPIs) to measure, compare, and monitor the effectiveness of these processes. However, these protocols cannot always be consistently implemented due to operational constraints or lack of staff. Recently, there has been an initiative to integrate machine learning into stunning and exsanguination processes through the use of video cameras. Machine learning algorithms enable computers to learn from data and predict certain behavioral indicators (Amalraj et al., 2024; Grandin, 2021). Implementing protocols and good practices in slaughterhouses, analyzing behavioral data obtained, and providing staff training are crucial for evaluating and continuously improving slaughterhouse operations, particularly when using sensitive behavioral indicators. In this context, Grandin (2010) proposes a monitoring protocol that utilizes available slaughterhouse resources and animal-based measures. This protocol includes efficiency recording, percentage of insensitivity, incidents of falls, vocalizations, and is designed to be easily implemented and reproducible in high-production settings.

4.3. Health and post-mortem indicators

Post-mortem inspections have the potential to identify diseases and certain welfare conditions that may not be apparent during ante-mortem inspections upon the animal's arrival at the slaughterhouse (Vial & Reist, 2014). These inspections not only reveal the conditions under which animals were handled, transported, and slaughtered, but also provide insights into their breeding (Grandin, 2017). From the 30 indicators identified in our review, 18 have the potential to be integrated into slaughterhouse-level protocols. One advantage of incorporating these indicators into slaughterhouse animal welfare protocols, compared to other categories like behavior or physiology, is that veterinarians and operators are already familiar with conducting these types of assessments, thereby minimizing disruption to slaughterhouse operations and maintaining operational efficiency. Moreover, these indicators are less likely to be disregarded by veterinarians and operators because they are perceived as more tangible compared to behavioral indicators. Some of these indicators reveal suffering and poor handling during the pre-slaughter period, such as animal mortality and morbidity, skin discoloration (indicative of fatigue), and lameness. These four indicators upon arrival at the slaughterhouse result from inadequate fitness of animals for transport and handling. It is not uncommon for animals to exhibit undiagnosed or underestimated subclinical ailments during pre-transport inspections. In addition to rough handling, poorly designed or maintained facilities can contribute to increased mortality and morbidity rates (Machado et al., 2022).

At the slaughterhouse level, lameness is a crucial iceberg indicator of pig welfare, signaling pain or discomfort due to locomotor disorders induced by injuries to bones, joints, skin, or muscles (EFSA, 2020). These injuries can stem from nutritional deficiencies, inadequate housing conditions, falls, entrapment, overcrowding, and rough handling (Grandin, 2017). Currently, lameness assessment relies on subjective visual systems that assign a numerical grade based on the severity of the condition. Common scales typically range between three to five categories. For instance, Welfare Quality proposes three thresholds: normal ambulation, typical lameness, and severe lameness, where the animal cannot support its weight or move (Welfare Quality Network, 2009). The primary challenge in lameness assessment lies in the requirement for optimal conditions (such as clean concrete floors), specialized observer training, and ensuring consistency among different observers. However, these visual scoring systems have limited reliability, prompting the proposal of automated lameness detection systems, though these have yet to be fully validated (Nalon et al., 2013). Additionally, according to Dalmau et al. (2010), assessing lameness in slaughterhouses is complicated by the limited ability to simultaneously measure multiple indicators. This becomes critical when considering other behavioral indicators at the time of assessment (such as reluctance to move, slipping, falling, and fear) observed from the unloading dock to the lairage pen. An alternative to visually assessing lameness is post-mortem examination for indicators like overgrowth, heel lesions, toe cracks, sidewall cracks, white line defects, and heel-to-toe junction issues (heel-sole interface) (Nalon et al., 2013). However, no studies or protocols evaluating these lesions were identified at the slaughterhouse level, despite their validation in cattle (Bautista-Fernández et al., 2021).

In this context, veterinary inspection plays a strategic role in quality management, welfare monitoring, and ensuring food safety for consumers. These assessments provide retrospective insights into the animal's quality of life throughout its rearing cycle and pre-slaughter processing stages (Losada-Espinosa et al., 2018). Several studies have suggested that the presence of abscesses, hernias, dermatitis, bursitis, foot lesions, tail lesions, ear lesions, and body lesions in the abattoir may indicate poor health and welfare in pigs (Driessen, Van Beirendonck, and Buyse, 2020a; Teixeira, Salazar, Larraín, and Boyle, 2023). Specially, body, tail, and ear lesions are considered "iceberg indicators" because they are associated with animal welfare concerns and can indicate suboptimal on-farm management, transportation, and lairage conditions, among other factors (Van Staaveren et al., 2017). The presence of defects by handling on the carcass poses a significant economic challenge for the pork industry due to increased meat loss during processing, necessitating the removal of surrounding areas affected by lesions (Harley et al., 2014).

Our findings indicate an increasing utilization of organ lesions as iceberg indicators in a growing number of recently published articles. This trend connects routine post-mortem inspection processes for detecting zoonotic diseases in slaughter systems worldwide with a retrospective assessment of "quality of life" emerging from animal welfare sciences (Dalmau, Temple, Rodriguez, Llonch, and Velarde, 2009). The most commonly identified indicators in our systematic review include peritonitis, pericarditis, pneumonia, pleuritic, and gastric ulcers. Gastric ulcers are influenced by nutritional factors and prolonged fasting periods in pigs (Swaby & Gregory, 2012). However, the assessment of gastric ulcers in slaughterhouses can present significant hygiene challenges. There is a high risk of cross-contamination during inspection, which can compromise the safety of the carcasses, although in some EU countries ulcers are grounds for condemnation (Alban et al., 2022). The high incidence of pneumonia and pericarditis is associated with stressful environmental conditions such as overcrowding, poor management, sudden temperature fluctuations, or inadequate ventilation in pig facilities. These conditions can contribute to the accumulation of gases and particles in the air, predisposing pigs to various respiratory ailments (Ghidini et al., 2021). Animals afflicted with pleurisy, pneumonia, pleuropneumonia, and pericarditis often exhibit lower average daily weight gain, reduced growth rates, decreased feed digestibility, higher morbidity and mortality rates, and increased veterinary and medication costs (Teixeira, Salazar, Larraín, and Boyle, 2023). Moreover, the presence of pathological lesions correlates with pH alterations and a higher incidence of dark meat (Čobanović et al., 2016). Consequently, inspecting internal organs at slaughterhouses can enhance pig welfare standards by providing feedback to farmers, enabling them to implement necessary interventions to improve health and overall animal welfare.

4.4. Product quality indicators

Several meat quality indicators can offer insights into the welfare of pigs throughout their lifetime (Grandin, 2017). Our findings highlight nine indicators related to meat quality, with four meeting feasibility and reliability criteria for potential incorporation into animal welfare monitoring protocols at slaughterhouses. Among these indicators, pH, bruises/scratches, body condition, and carcass weight have been identified (Čobanović et al., 2020; Driessen et al., 2020a). Meat pH is widely used as an instrumental indicator in studies assessing the impact of pre-slaughter handling. It reflects the balance between metabolic pathways and energy reserves in muscle tissue (Miranda-de la Lama et al., 2021). Quality defects in pork, such as pale, soft, and exudative (PSE) and dark, firm, and dry (DFD) pork, are determined by parameters including muscle pH, color, and water holding capacity. These parameters are influenced by the amount of muscle glycogen present at slaughter and the subsequent rate and extent of glycolysis in muscle tissue (D'Souza and Matthews, 2024). Pre-slaughter processes encompass various operations that can affect these factors, highlighting their significance in evaluating pork quality. Among these parameters, pH measurement is relatively straightforward compared to assessing color and water holding capacity at the commercial level. Therefore, pH serves as a pivotal reference point in meat quality assessment. In many slaughterhouses, meat pH is systematically monitored, reflecting its importance in quality control (Klauke et al., 2013).

Recording bruises and scratches on carcasses at the slaughterhouse holds considerable potential for monitoring welfare issues in pigs. This practice provides valuable insights into the efficiency and safety of slaughterhouse operations, pinpointing areas for enhancement (Correia-Gomes et al., 2016). Bruises are regarded as iceberg indicators, revealing underlying issues such as the use of electric prods, protruding objects, rough edges, falls, and social mixing (Jerez-Timaure et al., 2020; Urrea et al., 2021). These lesions become more visible during scalding and depilation, aiding in visual assessment (Carroll et al., 2016). Finally, assessing the nutritional status of animals includes measurements of live body condition and carcass weight. While neither indicator directly reflects the animal's current starvation status, they do provide insights into its historical nutritional condition. Weight loss can be influenced by various factors including social hierarchy, inadequate feeding practices, stress, or chronic diseases. Moreover, research has shown that pre-slaughter stress and fatigue can adversely affect meat quality and occasionally lead to carcass weight reduction. Pigs typically start losing weight at a rate of around 0.2 % or 0.25 kg/h in response to stressful conditions such as fasting periods or suboptimal pre-slaughter management (Faucitano et al., 2010). Prolonged fasting exceeding 24 h has been associated with greater weight loss (Acevedo-Giraldo et al., 2020). Furthermore, pigs with tail lesions have been observed to experience increased weight loss (Teixeira, Salazar, Larraín, and Boyle, 2023).

4.5. Artificial intelligence (AI)

At present, there is a growing interest among stakeholders in the meat chain in developing and implementing a cost-effective solution for the assessment and improvement of pig welfare at the slaughterhouse level through automated processes. In the European Union, an initiative known as AWISH has been developed, which employs automated monitoring (using sensors and AI algorithms) based on complementary animal-based indicators to obtain a retrospective overview from farm to slaughter. Furthermore, additional data from other sources, including slaughterhouse data, antibiotic use, farm data, and so forth, can be employed to enhance the measurements taken at the slaughterhouse (for more information, see https://www.awish-project.eu/about/). This initiative draws inspiration from a number of previous studies conducted in various species, which have demonstrated the value of such measurements. Studies conducted in slaughterhouses have evaluated injuries to the ears and tails of pigs (Brünger, Dippel, Koch, and Veit, 2019a; Blömke, Volkmann, and Kemper, 2020a) and foot pad injuries in broiler chickens using automated camera systems. Furthermore, abnormal behavior and lameness in pigs have been evaluated on farms through the utilization of automated systems (Silvera et al., 2017; Benjamin and Yik, 2019). The integration of artificial intelligence (AI) and 'iceberg' indicators in the assessment of animal welfare in slaughter plants has the potential to transform the industry, ensuring higher and more consistent standards of animal welfare while optimizing operational efficiency. The rationale for replacing manual monitoring with AI-supported systems is primarily based on the premise that human observers may become fatigued or inattentive due to prolonged periods of work or the rapid pace of inspection lines. This issue is often addressed through the deployment of multiple personnel, with assessments distributed among them. However, this approach may introduce inconsistencies due to potential discrepancies between observers (Blömke, Volkmann, and Kemper, 2020a). In this context, the implementation of AI has the advantage of enabling the use of a real-time computer vision system to perform the same assessments that are currently carried out by humans.

In pigs, a methodology has been proposed and validated for the detection of lesions in carcasses during slaughter. This methodology employs convolutional neural network (CNN) models for the capture of dorsal and lateral views. The CNN models comprise a primary model for body detection, a secondary model for carcass section detection, a model for head position classification, and a 'Detection Manager' module. The module is responsible for storing the various detections made by the models and selecting the final detections based on queues, thresholds and scheduling for each channel (Ferri et al., 2024). The results demonstrated that the model exhibited an accuracy of 0.937, a precision of 1, a recall of 0.915, and an F1 score of 0.955. The results were evaluated by human observers, who determined that 92.5 % of the image detections and missing images were accurate. Furthermore, 6.25 % of the positions were undetected, while 1.25 % of the detections resulted in images that were in incorrect or cropped positions. Nevertheless, the capture of images at the exact moment a pig carcass passes in front of the camera of a computer vision system is still constrained by technical limitations, including the varying sizes of pigs, the conditions of pigs in the production line, the variable times for a pig to enter the camera's field of view, and the influence of environmental variability and occlusion (Oliveira et al., 2021). Some of these systems are capable of recognizing individual animals through the use of facial recognition software (Grandin, 2021). Furthermore, cameras equipped with computer vision technology have the potential to be utilized for the continuous monitoring of abnormal animal behavior (Amalraj et al., 2024). Furthermore, the integration of audio detection and processing algorithms is crucial for the analysis of anomalous vocalizations, such as cries or groans. However, such equipment must be calibrated, and once calibrated, its performance can be compared to visual assessments conducted by highly trained personnel (Alsaaod et al., 2019). Additionally, the potential for data collection via mobile phones and computers merits consideration, particularly in low- and middle-income countries where the integration of automatic detection systems may not be feasible (Klingström et al., 2024).

5. Conclusions

This systematic review identifies valid and feasibility indicators for assessing pig welfare at slaughterhouses, such as body temperature, pH, bruises, human-animal interactions, and various health and post-mortem issues. Nevertheless, some of these indicators still require careful systematization in order to be implemented on a commercial scale (i.e. body temperature and human-animal interactions). Differences in the prevalence of these indicators can offer valuable retrospective insights into animal welfare conditions. Additionally, they provide data on how effectively different production systems maintain acceptable animal welfare standards. However, incorporating these measurements into routine operations requires a cost assessment. The training of inspectors and standardization of injury records are also essential. Therefore, consistent surveillance systems, prolonged data collection, and the concurrent measurement of multiple indicators are essential. As an integrated information system, evaluating these indicators can offer a comprehensive overview of the animals' rearing, fattening, and slaughtering processes, contributing significantly to the control of various animal health and welfare challenges. These findings warrant further research to enhance efficient and sustainable pig production practices.

Author declaration template

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

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

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

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

Consent form declaration

We wish to confirm that this study was based on a systematic literature review conducted by the co-authors of this manuscript and did not involve the collection of data from human subjects. Therefore, no informed consent was required for this study.

CRediT authorship contribution statement

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

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal. Relationships that could have appeared to influence the study reported in this paper.

Acknowledgements

This study was funded by the Spanish Ministry of Industry, Trade and Tourism (Innovative Business Clusters; Project OPTICARN, AEI 2022/2054). Thanks to the Santander Bank and the University of Zaragoza for the Latin American Scholarship PhD Programme of Nancy F. Huanca-Marca from National University of San Marcos (UNMSM) of Peru.

Data availability

Data will be made available on request.

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