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Research Paper

Technologies for automatic assessment of pig welfare using animal-based indicators in the slaughterhouse: a review

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ABSTRACT

Most meat-producing species end their life at the slaughterhouse. Here, animals are gathered from diverse farms, allowing for extensive data collection, including on welfare status. Assessing animal welfare requires reliable indicators, particularly those that are animal-based. Automated welfare evaluation offers a continuous, objective, and consistent approach for monitoring large numbers of animals, eliminating human bias and fatigue associated with high-speed production lines, and decreasing farm visits. This review aims to identify animal-based welfare indicators for pigs that can be automatically measured at slaughterhouses and to examine commercially available Precision Livestock Farming (PLF) technologies used at the slaughterhouse, including prototypes and on-farm technologies that can be adapted and applied to slaughterhouses. A three-step methodology is used: first a systematic literature search, followed by a comprehensible commercial search, and finally an expert consultation survey to confirm that all technologies were identified. A total of 16 technologies for slaughterhouse applications and 71 technologies for on-farm use were identified. Among the on-farm technologies, 52 were deemed feasible for slaughterhouse implementation, while 19 were considered unsuitable due to mismatches with slaughterhouse purposes, such as feeding behaviour or heat detection. The results also highlight the need to address automated welfare assessment during the transport phase to ensure thorough understanding and continuous monitoring of animal welfare across the entire production chain. While automated systems for monitoring pig welfare show significant potential, challenges in practical implementation and widespread adoption remain, requiring collaboration between researchers, industry stakeholders, and technology developers to fully realise their potential.

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1. Introduction

Pig husbandry is considered one of the largest and most intensified animal production systems. Domestic animals, including pigs, are sentient beings capable of experiencing emotions such as pain, pleasure, and fear. As such, there is growing social awareness of our moral responsibility to minimise animal suffering (Reimert et al., 2023) throughout the entire production chain, including at slaughterhouses. This awareness has recently been mirrored by increased public concern for animal welfare, as highlighted in the latest Eurobarometer (2023).

Pigs, like any other meat-producing species, will end their productive life at the slaughterhouse. The slaughterhouse represents a crucial place where animals from diverse origins gather, facilitating extensive data collection, including information on the welfare status of the animals. Monitoring welfare at the slaughterhouse allows a large amount of information to be centralised at a single assessment site, facilitating welfare assessment compared to farm visits (Grandin, 2017). Additionally, evaluating welfare from the slaughterhouse perspective provides two distinct types of assessment: current and retrospective welfare. The on-site assessment of the current state allows monitoring of pig welfare throughout their stay at the slaughterhouse, from unloading after transport to the slaughter process. In contrast, the retrospective assessment provides information on welfare during the previous stages of the production cycle, such as transport and on-farm conditions.

A valid method for assessing animal welfare needs to be based on welfare indicators, including those based on the animal (i.e., animal-based) but also on resources and management practices (i.e., resource-based). Animal-based indicators can directly measure the physical and mental response of the animal, offering highly sensitive information about the welfare status and how the animal is coping with the environment. In contrast, resource-based indicators measure aspects of the animals' environment, and management-based indicators assess the relationship and practices between animals and caretakers. The scientific community suggests that animal-based indicators are preferable to measure animal welfare (EFSA Panel on Animal Health and Welfare, 2012). Indeed, current welfare assessment protocols (e.g., Welfare Quality®) focus on animal-based indicators as they are probably the most direct reflection of an animal's actual welfare (Velarde & Dalmau, 2012).

Using animal-based indicators allows for greater transparency in comparisons between different slaughterhouses (Velarde & Dalmau, 2012). Furthermore, animal-based indicators are appropriate for both antemortem and postmortem evaluations, as endorsed by the EFSA Panel on Animal Health and Welfare (2012). In slaughterhouses, antemortem evaluations (i.e., before killing) allow the detection of injuries, signs of illness, and behavioural changes that are only observable in live animals, such as the human-animal relationship (as assessed in the Welfare Quality® (2009) protocol), lameness, or fever. On the other hand, postmortem evaluations (i.e., after killing) enable examinations of injuries and marks on carcasses and viscera in the slaughter line. For instance, Vecerek et al. (2020) identified patho-anatomical findings in viscera, as indicators of compromised health in pigs.

Technology is rapidly evolving across all areas of life, including farm animal production. Precision livestock farming (PLF) is becoming a possible alternative for automatically assessing welfare at slaughterhouses (Voogt et al., 2023). Compared to traditional human observations, automated welfare evaluation permits continuous, objective and reliable assessment of a large number of animals, without human bias due to intrinsic personal components and fatigue caused by the high speed of production lines in slaughterhouses. Additionally, it allows for more direct measures of the single criteria to be included (Larsen et al., 2021). As direct manual observation by humans is currently standard for welfare assessment in slaughterhouses, there is scope for improvement through automation.

PLF encompasses a set of electronic tools and methods enabling automatic monitoring of phenotypical traits of farm animals. PLF technologies can be used to improve production and breeding, assess health and welfare, and control the environmental impact of production (Nielsen, 2022). Gómez et al. (2021) identified various types of PLF technologies that can be implemented for automatically monitoring pig welfare on-farm. Larsen et al. (2021) noted that most identified technologies focused on growing pigs, with significantly fewer technologies identified for monitoring during transport and in slaughterhouses.

Two reviews have been published on identifying and analysing technologies applied in slaughterhouses. Sandberg et al. (2023) focused their review on computer vision systems for ante- and post-mortem veterinary inspection and ensuring meat safety by detecting contamination and lesions. Voogt et al. (2023) focused on sensor technologies for monitoring welfare from the Regulatory Authority's perspective, and providing initiatives, opportunities and barriers for regulatory purposes. Both reviews covered three different meat-producing animals: cattle, poultry, and pigs. In contrast, this review focuses on pigs only and aims to gather animal-based indicators that can be automatically measured at slaughterhouses. Further, it aims to discuss commercially available PLF technologies for use in the slaughterhouse, as well as prototypes or transferable on-farm technologies that can feasibly assess welfare at slaughterhouses. A review of the literature together with a search of commercially available technologies and an expert consultation yielded the available technologies grouped according to the welfare indicator they measured, and their advantages and disadvantages to facilitate the selection of technologies for potential users.

2. Materials and methods

The technologies to assess welfare at the slaughterhouse were determined following three consecutive steps: (1) a systematic literature search, (2) an extensive Google web search, and (3) an expert consultation through a survey. This approach allowed to identify commercial solutions and prototypes, including those that were used in a research context.

2.1. Systematic literature search for welfare indicators

We conducted a literature search following the Preferred Reporting Items for Systematic and Meta-Analyses (PRISMA) guidelines (Page et al., 2021) to identify animal welfare indicators and methodologies for assessing welfare in pig production. The PRISMA flow chart can be found in Appendix A (see Fig. A.1).

The literature search was conducted using the search engines: Web of Science, PubMed, and Scopus, between November and December 2022. The terms of the search included were: (indicator* OR measure) AND (evaluat* OR validat* OR assess* OR audit OR test* OR measure*) AND ("animal welfare" OR "pig welfare" OR welfare) AND (slaughter* OR abattoir OR mortem OR farm* OR transport) AND (pig OR sow OR piglet OR weaner OR fatten* OR "sus scrofa domesticus" OR swine) AND NOT (guinea). These terms should appear in either the abstract, title or keywords. Only peer-reviewed articles written in English and published between January 2000 and December 2022 were considered. All experimental studies using animal-based and resource-based welfare indicators performed in all phases of pig production (growing pigs, sows, and piglets) assessed on farms, during transport, and at slaughterhouses were included.

Before screening the results, all articles that lacked an abstract or the author's name were excluded. After applying the first exclusion criterion, duplicates were removed. The remaining articles were screened to remove those with titles not aligned with the purpose of the review, e.g. articles not directly linked to animal welfare and focused on other scientific fields such as pathological, immunological, genetic, pharmaceutical, and nutritional trials. Articles based on species other than pigs and articles without information on the methodology of pig welfare assessment were removed.

2.2. Commercial search for available technologies

A commercial search based on the methodology described by Gómez et al. (2021) was conducted during April and May 2024 to identify technologies capable of assessing welfare using the animal-based indicators extracted from the literature review. The search was performed through the Google search engine, using the animal category *pig* and the technology using one of the following terms per each search: (automatic drinker OR automatic waterer), (activity sensor OR activity monitor), (RFID), (sensor), (thermal camera), (infrared thermal image), (infrared thermometer), (body-temperature sensor), (automatic weigh scale), (sorting scale), (weight camera), (body condition score sensor OR automatic body condition score), (body condition camera), (lameness sensor), (automatic lameness detection), (pressure mat OR force sensor), (automatic behaviour analyser), (image-based behaviour analyser), (automated welfare), (automated monitoring), (automatic sound analysis), (cough sensor OR cough monitor), (vocalisations analyser), (acoustic monitoring), (automatic lesion detector), (visual lesions), (automatic tail detection), (automatic lung assessment), (lung visual detection), (viscera automated assessment), (stunning effectiveness detection), (automated movement detection), (body posture detector).

For example, one search could be: *pig (automatic drinker OR automatic waterer)*. The first five pages with 10 hits each (50 hits) were reviewed per search. Commercially available technologies and prototypes that were still under development were also included for further review.

2.3. Expert consultation on technologies for welfare assessment

An expert consultation was conducted to identify potential technologies that had not been previously found through the literature and commercial searches. The consultation was performed through an online survey (see Appendix B), based on the indicators and technologies compiled from the previous searches. The form was designed using *EUSurvey*, an online survey management system for creating and publishing forms available to the public. Potential participants were identified within the framework of the aWISH project (Animal Welfare Indicators at the Slaughterhouse - aWISH, 2022), as it involves a large and diverse group of stakeholders, either as project partners collaborating in the project development or as members of the expert panel providing and sharing feedback from an external perspective. This approach ensured the gathering of a comprehensive overview of the state of the art since participants represent different fields of expertise, such as animal welfare and animal production researchers, technology developers and providers, competent authorities, and NGOs. In total, 123 people were contacted via email to participate anonymously in the survey. In total, 39 participated, achieving a response rate of 31.71 %.

3. Results

From the systematic review, commercial search, and expert consultation, 87 technologies assessing different animal welfare indicators in farms and slaughterhouses were identified. However, no technologies were identified for the transport stage. The technologies, covered a wide range of indicators, including feeding and drinking behaviour, activity level, body weight, body temperature, heat detection in sows, lameness, respiratory signs, noise, vocalisations, tail biting, tail position, animal handling, stunning and killing effectiveness, and lesions in viscera, ears, skin and tail.

The technologies were categorised into two groups based on their intended application: (1) those designed to be installed at the slaughterhouse, and (2) those intended for on-farm measurement, but with a potential for installation in the slaughterhouse as well.

3.1. Technologies developed for installation at slaughterhouses

The 16 technologies identified for animal welfare assessment via measurements in the slaughterhouse can be divided into three groups according to the area or stage of the slaughter process they are installed at: (1) lairage area, which encompasses all procedures when pigs are waiting to enter the slaughter line, (2) slaughter area, including the stunning and killing processes, and (3) carcass processing area, once animals are dead and carcasses are being processed for meat production.

In the lairage area, five different sensors were identified to assess noise (sounds), space availability in the pen, animal handling (to evaluate the behaviour related to the human-animal relationship), and automatic counting of pigs. In the slaughter area, five sensors were found to monitor stunning effectiveness and killing effectiveness. In the carcass processing area, six sensors were identified to evaluate lesions in viscera (lungs), and carcasses (skin, ears and tail). An overview of all the technologies can be found in Table 1.

3.2. Technologies developed for installation on farm, but with potential for installation in the slaughterhouse

Some sensors designed to measure indicators on-farm might also be adapted for use in various areas of the slaughterhouse, such as sensors that evaluate drinking behaviour or body weight could be deployed in the lairage area. Based on this approach, 52 out of 71 technologies identified for farm use, could be applicable in the slaughterhouse. Table 2 provides an overview of the technologies used to monitor cough, vocalisations, movements and activity, number of pigs, live weight, body temperature, water consumption, and tail-biting behaviour.

Since the purpose of this review is to focus and describe technologies used or feasible for in slaughterhouses, other technologies that measure indicators such as feeding behaviour and heat detection in sows were excluded, as these indicators are either not considered relevant or not aligned with slaughterhouse purposes. Technologies utilising accelerometers linked to ear tags were primarily excluded as wearable devices are considered unsuitable for slaughterhouse use, as they contain metallic components that could accidently enter the production chain, posing a hazard for food safety. A few technologies for assessing lameness were identified but excluded due to their immature development stage (e.g., lack of software for output interpretation) or because they were designed for other purposes, such as exclusive use in a research context, with no current intention of commercialisation. A detailed overview of the 19 excluded technologies, along with the reasons for exclusion, is provided in Appendix A (see Table A.1).

4. Discussion

This review aimed to explore PLF technologies that can contribute to the assessment of animal-based welfare indicators for pigs in slaughterhouses. Through this review, a comprehensive list of feasible PLF sensors for installation in slaughterhouse facilities to monitor pig welfare was identified. To further examine the relevance and significance of using technologies for welfare indicator assessments, these indicators were grouped according to the specific areas in which they are evaluated.

4.1. Lairage area

4.1.1. Drinking behaviour

Changes in drinking patterns and behaviours are influenced by stressors (Andersen et al., 2016) and diseases (Madsen & Kristensen, 2005). Deviations in drinking behaviour can serve as an early signal of illness outbreaks, e.g., diarrhoea in young pigs produces changes in drinking patterns one day before the visual signs appear (Madsen & Kristensen, 2005). Larsen and Pedersen (2022) observed higher water use in pens with tail damage events, probably as a consequence of higher activity in pigs. Water flow meter technologies quantify water consumption and allow the monitoring of drinking behaviours.

The vast majority of commercial products based on water flow meter

Table 1
Technologies developed to assess welfare of pigs at the slaughterhouse listed per area where they are applied, welfare indicator measured, type of technology, sensor, and provider. Sensors analysing the same indicator are presented in alphabetical order.

Area	Indicator(s)	Type of technology	Name of sensor	Provider
Lairage	Noise	Acoustic sensor	Noise Level Dashboard	Genba Solutions GmbH
	Space availability	Computer vision	Space availability	Genba Solutions GmbH
	Animal handling	Computer vision	AI4Animals	Deloitte
			Argus	Argus
			smaRt counting	Ro-Main
Slaughter area	Stunning effectiveness	Computer vision	CET' Automatique	Wel2be
			Monitoring of the CO_2 stunning	Genba Solutions GmbH
			Signs of life	Argus
	Killing effectiveness	Computer vision	VisStick	Danish Meat Research Institute
		Thermal camera	Bleeding Measurement in Pigs[a]	CLK GmbH
Carcass processing area	Lung lesions and pleurisy on carcass	Computer vision	ADAL	Farm4Trade
	Carcass and viscera lesions	Computer vision	ArtificialVet®	Company Mind
	Tail length, tail and ear lesions, injuries on the abdomen	Computer vision	CLASSIFAI® BOX	Software Logistik Artland GmbH
	Tail length, tail and ear lesions, injuries on the abdomen	Computer vision	CLASSIFAI® BOX	Software Logistik Artland GmbH
	Ear, skin, tail lesions and tail length	Computer vision	PigInspector	CLK GmbH
	Tail length and lesions	Computer vision	TailCam[a]	Danish Technological Institute - PigWatch
			TAILSCAN[a]	Farm4Trade

[a] Sensor technology currently under development.

technology are designed and installed for on-farm use, although they could be adapted to other purposes, such as quantifying water consumption in lairage pens at slaughterhouses. The three identified flow meters are commercially available at a global level through different providers associated with the developer companies and offer some relevant advantages. *Sonata Ultrasonic Residential Water Meter* (Arad Group, Tel-Aviv, Israel) uses ultrasonic technology to register highly accurate consumption, even capturing the lowest flow rates and features digital reading belonging to IoT (Internet of Things). However, since it is not specifically designed for farm purposes, it should be integrated into farm management software, e.g., Roter One Controller (Munters AB, Kista, Sweden). *Water Monitoring* (Fancom BV, Panningen, the Netherlands) is part of a suite of Fancom technologies that monitor various farm parameters. This flow meter is linked to climate controllers, providing alerts if water consumption (flow rate) increases or decreases, either within the same group of animals compared to previous days or between different groups. *WM1 Water Meter* (AgroLogic LTD, Netanya, Israel) calculates water consumption (litres) via a dry contact pulse and can be connected to AgroLogic climate controllers or operate as a standalone device. However, no data on the accuracy has been reported, and no scientific validation publications have been identified.

Assessing drinking behaviour at the slaughterhouse could serve as an indicator of welfare related to lairage, transport conditions or farm practices. However, water consumption during lairage remains largely unexplored. A few studies have demonstrated that poor transport conditions, including long journeys combined with high temperatures (Kobek-Kjeldager et al., 2023) in sows, and high stocking densities (Urrea et al., 2021) or prolonged fasting periods (Dalla Costa et al., 2016) in finishing pigs, are associated with fatigue. This fatigue leads animals to prioritise lying down in the lairage over other activities, such as drinking upon arrival at the slaughterhouse (Kobek-Kjeldager et al., 2023; Urrea et al., 2021). Contrarily, Brown et al. (1999a) observed that pigs exhibited immediate interest in drinking after transport. However, in another study, when Brown et al. (1999b) provided feed and water in the lairage to pigs transported for 16 and 24 h, the pigs prioritised eating before drinking, consuming water once their hunger was satisfied. These behavioural differences between drinking and lying down may be explained by the implementation of legislation (Council Regulation (EC) No 1/2005), which mandates access to water during transport. Currently, there is a lack of sufficient studies to evaluate the impact of water consumption on animal welfare during lairage at the slaughterhouse, underscoring the need for further investigation.

4.1.2. Animal handling

Handling pigs inappropriately during pre-slaughter stages, such as during unloading, driving to and from the lairage pens, and stunning, can cause significant stress and welfare issues (Brandt et al., 2017; EFSA AHAW Panel et al., 2020). Rough handling, excessive or incorrect use of electrical prods, paddles (Brandt et al., 2015; Stocchi et al., 2014), or failing to respect pigs' natural behaviours, such as not using the balancing point (area related to the blind spot where pigs cannot see the handler) for moving pigs in a certain direction (Grandin, 2016), are major concerns in animal handling. This incorrect handling induces fear-related behaviours (such as freezing or escape attempts) and pain from slipping and falling (Dalmau et al., 2009; O'Malley et al., 2018; Sardi et al., 2020). Moreover, improper handling can be associated with an increase in heart rate and stress-related factors found in the blood, and can potentially reduce carcass quality (Gerritzen et al., 2013; Rey-Salgueiro et al., 2018; Śmiecińska et al., 2011). Additionally, incorrect placement of stunning devices due to poor handling can lead to ineffective stunning, causing more pain and fear (Stocchi et al., 2014; von Wenzlawowicz et al., 2012).

Proper monitoring of the human-animal relationship is important from a regulatory, chain operator, and pig welfare standpoint (EFSA AHAW Panel et al., 2020; Voogt et al., 2023). Automated camera systems can assist in monitoring this and support decision-making. Within this review, four automated camera systems related to human-animal handling were found. Two systems monitor pig handling during pre-slaughter processes: *AI4Animals* (Deloitte, Amsterdam, the Netherlands) and *Argus* (Argus, Epe, the Netherlands), while the other two; *SmaRt Counting* (Ro-Main, Quebec, Canada) and *PigCounter* (PigBrother, Budapest, Hungary) are counting systems that could limit or facilitate pig handling.

AI4Animals and *Argus* use the existing CCTV (closed-circuit television) system at the location, with users subscribing to software that includes algorithms designed to detect incidents where animal welfare may be compromised in predefined categories. Both systems reduce traditional continuous CCTV footage to relevant moments, which can be

Table 2
Technologies developed to assess welfare of pigs at the farm with potential for installation in the slaughterhouse, listed according to welfare indicator, type of technology, name of sensor, and provider. Sensors analysing the same indicator are presented in alphabetical order according to their names.

Indicator	Type of technology	Name of sensor	Provider	Observations
Cough	Acoustic sensor	SoundTalks	SoundTalks NV	Multisensor Include environmental sensors
Vocalisations	Acoustic sensor	ALIS Grunty Sensor[a]	Greengage Global	
		STREMODO[a]	Research Institute of Farm Animal Biology (FBN)	
Movements and activity	Computer vision	Dilepix[a]	Dilepix	Count lying, eating, drinking, standing, aggressive behaviour
		Healthy Climate Monitor	Healthy Climate Solutions	Multisensor Include environmental sensors, sound analyser, and thermal camera
		PEEK Analytics	Copeeks SAS	Record the position of the animal within the pen Multisensor Include environmental sensors
		PigGuard	Serket B.V	Record drinking and eating behaviours
Animal handling	Computer vision	PigCounter	PigBrother	Counting pigs automatically
Body weight	Computer vision	Embedded vision prototype for livestock weight monitoring[a]	Lemberg Solutions	
		eYeGrow	Fancom BV	
		FarmSee	FarmSee Ltd	
		Growth sensor	GroStat	No longer commercialised as the company was dissolved
		iDOL 65 camera	Dol Sensors	
		OptiScan	Big Dutchman	
		PigBrother	PigBrother	
		PIGI	Corntec	
		PigVision	Asimetrix	Belong to SMARTFARM solution Combine different sensors
		Pigxcel™ ID	Smart Agritech Solution of Sweden	
		Qscan	Innovent Technology Ltd	
		WeightCheck	Big Dutchman	
		Weight-Detect™[a]	Innotech Vision	
		WUGGL One[a]	WUGGL GmbH	
	Load cells (scale)	ACCU-ARM Survey Scale	Osborne	
		Automatic Pig Weighing	Hotraco Agri	
		CIMA Automatic Marker	CIMA Animal Farming Equipment	
		CIMA Control Pig	CIMA Animal Farming Equipment	
		CIMA Identification	CIMA Animal Farming Equipment	
		CIMA Selection Gate	CIMA Animal Farming Equipment	
		PigScale	PigScale	Sorting scale
		SKIOLD Tristar	SKIOLD Group	Sorting scale
		TriSortPro	Big Dutchman	Sorting scale
Body temperature	Infrared thermometer	EVTSCAN thermometer	EVTSCAN	
		IRT207 The Heat Seeker 8:1	General Tools	
		TN418L1	Metris Instruments	
		YM-558D	Tebru	
	Infrared camera	Degree2act	Degree2act	Software FLIR One camera is required
	Thermal camera	FLIR One Pro LT	FLIR	Require a smartphone
		FLIR E8 Pro	FLIR	
		H4 Intelligent Thermal Camera	Guide Sensmart	
		IR Pad 640	Digatherm	
		IR Pad 320	Digatherm	
		T400	InfiRay	
		T630	InfiRay	
		TR256B	Mileseey Tools	
		TR256E	Mileseey Tools	
		X640D	Yoseen Infrared	
	Camera with temperature sensor	WUGGL One[a]	WUGGL GmbH	
Drinking behaviour	Flow water meter	Sonata Ultrasonic Residential Water Meter	Arad Group	
		Water Monitoring	Fancom BV	
		WM1 Water Meter	AgroLogic LTD	
Tail-biting	Computer vision	TAIL[a]	Dilepix	
Tail position		TailTech	Innovent Technology Ltd	Not clear if it is currently purchasable

[a] Sensor technology currently under development.

reviewed for accuracy and relevance, leading to concrete actions (e.g., operational changes, and personnel training). *Argus* is broader in scope than *AI4Animals*, as it uses sensors to detect equipment usage (e.g., stunning devices) to aid the algorithm's decision-making. *AI4Animals* focuses on unloading and driving to the lairage process steps, whereas *Argus* covers the entire pre-slaughter process from unloading to stunning. No information on validation and accuracy was found for either system, but both use a human reviewer step for each highlighted event to improve the system's accuracy at each facility.

PigCounter and *SmaRt Counting* are systems that include a camera to be installed in a hallway and software to count pigs. Hence, reducing the potential contact between humans and animals. Both systems count pigs, not handlers or other animals, and can do so while pigs are moving. *PigCounter* was designed for farm use but could, depending on the area specifics, also be used in a slaughterhouse. The *SmaRt Counting* system has both farm and slaughterhouse modules. Both products display data in real time on various devices via web applications. The *PigCounter* system also allows data to be sent via email or used in other software packages that the slaughterhouse might use. No validation information for these systems was found on their websites or in scientific literature. The *SmaRt Counting* website does claim that the system has an accuracy of at least 99.9 %. No accuracy numbers were found for the *PigCounter* system.

4.1.3. Tail biting behaviour

Tail biting is a multifactorial problem in pig husbandry that significantly impacts the pig's welfare from both the victim's and perpetrator's standpoint (Svoboda et al., 2023; Valros, 2018). The reasons why a perpetrator pig bites are complex, with several forms of tail biting existing (Henry et al., 2021; Taylor et al., 2010). Generally, stress influx is a primary cause, but there are many underlying risk factors (Henry et al., 2021; Taylor et al., 2010). A lack of manipulable materials for natural foraging behaviour is often cited as inducing tail biting, as pigs performing tail biting are often frustrated or unable to cope with their living conditions (Gomes et al., 2022; Telkänranta et al., 2014; Valros, 2018). Victim pigs are also strongly impacted by tail biting. Firstly, biting causes painful and stress-inducing lesions (Svoboda et al., 2023). Secondly, these lesions can become infected, leading to other health problems (vom Brocke et al., 2019). However, the relationship between tail biting, tail lesions, and health problems has not yet been shown as a cause-and-effect relationship, complicating their specific interactions (Valros, 2018).

Monitoring tail biting via tail lesions is seen as a good way to assess a pig's welfare as it relates to living conditions (Harley et al., 2014; van Staaveren et al., 2017). Monitoring tail-biting behaviour via PLF techniques is emerging for farm use, aiding management decisions and mitigating economic repercussions from tail-biting outbreaks (Hakansson & Jensen, 2022). Two technologies were found that can detect tail-biting behaviours, namely *TailTech* (Innovent Technology Ltd, Roslin, United Kingdom) and *TAIL* (Dilepix, Rennes, France). Both are prototypes developed for on-farm use but might be adapted for lairage pens at the slaughterhouse. The *Dilepix* website provides more information than the Innovent Technology Ltd website, but open-source publications using the *TailTech* system can be found (D'Eath et al., 2018, 2021). The *TailTech* system uses a 3D camera installed above the feeding area of a pen, with a vision-based algorithm detecting tail position: low-hanging *vs.* non-low-hanging tails. D'Eath et al. (2018) found that the system detected these tail positions with 73.9 % accuracy (sensitivity = 88.4 %, specificity = 66.8 %) and that low-hanging tails are more closely related to the frequency of tail lesions. Researchers continue analysing the relationship between tail position, tail biting, and other welfare behaviours using this system (D'Eath et al., 2021). On the other hand, the *TAIL* system works with any normal monitoring camera with an SD card. The *TAIL* system seems more geared towards veterinarians and technicians to help them advise farmers better. However, no information on accuracy and validation was found for *TAIL*. Both systems offer some flexibility with movable cameras but need a camera per pen.

These technologies could theoretically be adapted for use in slaughterhouse lairages but require further technological and scientific advancements. Technologically, one camera scanning multiple pens and a more continuous monitoring system would be more practical for lairages. Scientifically, more research is needed to understand the link between tail-biting and pre-slaughter processes. Pre-slaughter steps are known to induce stress (Vitali et al., 2021), and stress is often a key factor in tail-biting behaviour (Henry et al., 2021). However, limited evidence connects pre-slaughter phases to tail damage in post-mortem inspections. Van Staaveren et al. (2015) found a slight positive correlation ($r = 0.22$, $P > 0.05$) between lairage tail-directed behaviour and tail lesions on carcasses, while Vitali et al. (2021) linked post-mortem tail lesions to overnight stays in lairages.

Detecting tail-biting in lairages holds multifactorial value, provided technological and scientific challenges are addressed. It could identify batches prone to tail-biting, helping pinpoint farms with welfare issues. This is especially relevant when automated post-mortem inspection is unfeasible due to space restraints or when such monitoring is unfeasible at the farm (e.g., due to investment cost). Additionally, it could quantify stress levels caused by pre-slaughter processes, emphasising each chain operator's role in pig welfare. With these data, slaughterhouse welfare officers could make better-informed mitigation decisions, particularly for long-term improvements.

4.1.4. Pig coughing, stress vocalisations and environmental noise

Pig coughs and vocalisations reflect disease-specific behaviour and social behaviour, respectively (Gómez et al., 2021; Matthews et al., 2016). Coughing in pigs may indicate respiratory issues or suboptimal barn climate conditions (Ferrari et al., 2008; Van Hirtum & Berckmans, 2004), while other pig vocalisations are increasingly considered as a non-invasive way to assess pig welfare (Briefer et al., 2022; Manteuffel et al., 2004). Additionally, sounds from the environment may also affect pig welfare at unloading, lairage and driving to the stunner in the slaughterhouse (EFSA AHAW Panel et al., 2020).

Four acoustic sensor systems were identified in the current review with the purpose of monitoring coughs on farm (SoundTalks, SoundTalks NV, Leuven, Belgium), stress vocalisations at different stages of production including transport and slaughter (ALIS Grunty Sensor, Greengage Agritech Ltd, Edinburgh, UK; STREMODO, Research Institute of Farm Animal Biology (FBN), Dummerstorf, Germany), and noise levels at the slaughterhouse (Noise Level Dashboard, Genba Solutions GmbH, Zwentendorf, Austria).

SoundTalks, the technology for cough monitoring, is commercially available as a plug-and-play system consisting of a gateway and portable monitors that can be installed above the pens in a pig room. An algorithm monitors the pigs respiratory distress using historical data and variation in a specific room (Pessoa et al., 2021). Pessoa et al. (2021) found that the respiratory distress index determined by the sensor in a room of finisher pigs correlated ($r = 0.5$) with manually recorded coughing frequencies during 5-min observations at pen level. Cough monitors are mainly developed and studied for on-farm use for early detection of respiratory issues (e.g., Berckmans et al., 2015). While cough monitors likely could be adapted to the slaughterhouse environment, it could be argued that this is of lesser value at this stage of production in terms of diagnostic value or treatment. However, it may assist in identifying batches of sick pigs who may require more attention during inspection of viscera, if this information could be provided real-time to veterinary inspectors on the slaughter line. The respiratory distress index towards the end of the finisher period (week 21–24 of age) was strongly correlated with the prevalence of scar lesions and pneumonia in lungs measured at slaughter ($r > 0.7$) (Pessoa et al., 2021). It is currently unclear whether a similar relationship would be observed when monitoring coughing in the lairage, as other factors, such as air quality or poor conditions during transport, could affect the respiratory system impacting animal welfare.

The presence of stress vocalisations reflects pain or fear in pigs, which may be an important animal-based measure at slaughter (EFSA AHAW Panel et al., 2020). The technology to measure stress vocalisations is in development at different providers or research groups, with the intent to measure distress calls. The *STREMODO* system consists of a network gateway and sensor nodes and has been tested in different contexts (Schön et al., 2004). The percentage of misclassification was low (<5 %) and the classification of distress calls by the *STREMODO* was strongly correlated (r = 0.78–0.87) with the assessment of six human experts of the same audio recording (Schön et al., 2004). On the other hand, *ALIS Grunty Sensor* is being developed to become part of a platform of integrated sensors, web App, and data analytics. Information on this prototype is limited, but it is designed to provide real-time alerts based on distress calls.

It should be noted that the technologies can only measure pig sounds on a group level within a certain space, and not on an individual level. However, with both coughing and stress vocalisations it seems possible to pinpoint locations where sounds originated from or to focus on specific locations of interest on farms (Schön et al., 2004; Silva et al., 2008). This may assist in identifying problem areas in lairage or driving to the stunner, but this would need to be tested in the slaughterhouse environment.

Finally, sounds from the environment can impact pigs' welfare, with noise levels between 70 and 120 dB recorded in slaughterhouses (reviewed by EFSA AHAW Panel et al., 2020; Faucitano, 2010; Weeks, 2008). Sound recording devices or apps have been used in the past to measure sound levels in pig slaughterhouses (e.g., Iulietto et al., 2018; Vermeulen et al., 2016), but few are specifically designed for this purpose with real-time, continuous monitoring. The commercial sensor found in the current review, *Noise Level Dashboard*, consists of a mobile sensor unit (50–100 dB measuring range) that can be installed in the lairage or raceway. This would allow corrective measures to limit noise levels at slaughter, but further research is needed to confirm this threshold. To the best of current knowledge, no scientific studies have been published using this particular sensor. However, Voogt et al. (2023) highlighted the existence of systems that detect resource- and management-based measures, such as noise level, for regulatory purposes.

4.1.5. *Activity level*

Activity levels in pigs are studied in terms of general behaviours (in frequency or duration), such as feeding, lying, standing, and locomotion, as well as the diurnal behavioural patterns. Behavioural activity can be an indicator of animal welfare, whereby activity is likely to decrease when animals are ill, reflecting their sickness behaviour (Dantzer, 2004; Weary et al., 2009). In contrast, activity may increase in the days directly prior to a tail biting outbreak (Statham et al., 2009) and can therefore also signal potential welfare issues. Marked changes in specific behaviours or patterns can also be an indicator of poor animal welfare (Matthews et al., 2016). For example, pigs may change their feed intake pattern in response to heat stress, illness, tail biting wounds or feed competition (Bus et al., 2021). As the decrease, increase or change of activity may signal a welfare issue, it is important to establish the normal activity level and the deviations thereof, especially on farms.

From video images, activity can be inferred from pixel differences between consecutive images, which thereby describe the motion (e.g., Motion History Image). This has for example been used to automatically detect general activity (Ott et al., 2014), and aggression between pigs (Viazzi et al., 2014), with a threshold for the intensity of pixel motion (Chen et al., 2019). Pig activity has also been studied through infrared motion sensors (Ni et al., 2017). Automatic video analysis of activity levels in pigs has been shown to strongly correlate with the observations done by a human (r = 0.92: Ott et al., 2014) and therefore has potential for usage in the slaughterhouse.

In the present review, four on-farm sensors (Dilepix, Dilepix, Rennes, France; PigGuard, Serket B.V, Amsterdam, the Netherlands; PEEK Analytics, Copeeks SAS, Saint-Évarzec, France; and Healthy Climate Monitor, Healthy Climate Solutions, Driebergen-Rijsenburg, the Netherlands), and one developed for slaughterhouses (Space Availability, Genba Solutions GmbH, Zwentendorf, Austria), were identified, all of which assessed activity by measuring movement from video or still images.

The company *Dilepix* uses neural networks to track the activity of pigs at different stages of production, and can automatically distinguishing sow postures, such as lying and standing, from video (Durand et al., 2023). *PigGuard* offers a pig recognition system that uses visual data and deep-learning algorithms to recognise pigs individually within a group. *Serket* has an online platform for pig farmers to monitor the pigs, with the aim to automatically detect health problems at an early stage and provide a warning to the farmer. *Serket's* website claims that individual pigs can be tracked over short durations with an 80–85 % accuracy for movement, a 90–95 % accuracy for eating and drinking behaviour and an 80–90 % accuracy for heat stress. Copeeks SAS offers monitoring solutions for several species, including pigs. Their commercial multi-sensor product *PEEK Analytics* measures activity level of the animals, in addition to the atmosphere in the building and water consumption (as separate modules). The applicability of the product has been tested under commercial conditions. The results of *PEEK Analytics* correlated well with human observations on pig posture (r = 0.77) and pigs' location within in pen (r = 0.77), but less with activity level (r = 0.35) (Allueva Molina et al., 2023). The low correlation may be due to the methodology of assessment not being comparable between human and sensor-based assessment (Allueva Molina et al., 2023). A better agreement was reached in a related study, both for activity level (r = 0.90) and number of moving pigs (r = 0.94) (Ko et al., 2023). The multi-sensor *Healthy Climate Monitor* records environmental parameters and takes images of animal behaviour. The pictures are automatically analysed to infer the movement from pixel differences between images. Sound is recorded continuously, which can indicate screaming, coughing and sneezing. The infrared thermography option can provide information on heat stress. The *Healthy Climate Monitor* was used to assess differences in, amongst others, movement of *M. hyopneumoniae*-infected pigs (Sonalio et al., 2024), where the infected pigs moved significantly less than the control pigs. Specifically for slaughterhouses, a commercially available technology called *Space availability* was developed. The camera system is mounted above the waiting pen in the slaughterhouse and uses object detection to recognise and count the pigs. Based on this, the space availability is calculated at 5-s intervals.

PigGuard, PEEK Analytics, Healthy Climate Monitor and *Space availability* are currently available on the market and can be purchased, while *Dilepix* is still in the prototype phase. Technologies to measure activity levels, either by measuring movement from video or still image, can be used in slaughterhouses to detect deviating activity levels in the lairage area, including aggression between pigs. It can also be used to assess space usage, which can give an indication of crowding and heat stress according to the level of distribution within the pen. Detecting sick animals based on activity may be less suitable to the lairage conditions, as it may be a challenge to determine a baseline level of activity due to the frequent movement of animals entering and leaving the lairage area. However, efforts to detect injured animals (e.g., lame animals) based on prolonged inactivity may be worthwhile.

4.1.6. *Body weight*

Body weight reflects the growth of an animal, acting as a vital indicator of health, such as detecting disease outbreaks (Brandl & Jørgensen, 1996), and efficient productivity (Schofield et al., 1999; Wang et al., 2008). Although the conventional method of directly weighing pigs is the most accurate, making pigs pass through a scale induces stress and fear in the animals (Brandl & Jørgensen, 1996; Liu et al., 2023; Wang et al., 2008), and is labour-intensive and time-consuming for the operating personnel. Thus, various indirect methods for obtaining weight with non-contact methods have been studied over the years to improve both human and animal welfare.

Examples are self-access and automatic scales (Wang et al., 2008), photogrammetry and digital images (Franchi et al., 2023), and computer vision-based systems (Jiang et al., 2024). However, each technologies presents advantages and limitations that need to be considered.

Some self-access automatic scales are required to be placed within the pen, occupying valuable space (Kongsro, 2014). However, they do provide accurate and continuous measurements (Fernandes et al., 2019; Schofield et al., 1999) allowing for monitoring weight variations between pen mates. Nevertheless, the continuous accumulation of dirt and faeces on and under the platform causes inaccurate weight readings that are barely detectable (Schofield et al., 1999). In addition, the scales require a period of adaptation and training for the animals, and the operators must ensure cleanliness of the mechanical parts to ensure proper functioning.

Six automatic-scale systems were identified in the current review with the purpose of monitoring body weight for farm use (CIMA Control Pig, CIMA Identification, CIMA Automatic Marker and CIMA Selection Gate and CIMA Animal Farming Equipment, Pavía, Italy; Automatic Pig Weighing, Hotraco Agri, Hegelsom, the Netherlands; ACCU-ARM Survey Scale, Osborne, Kansas, USA; TriSortPro, Big Dutchman, Vechta, Germany; PigScale, PigScale, Lelystad, the Netherlands; and SKIOLD Tristar, SKIOLD Group, Sæby, Denmark).

CIMA Control Pig and *PigScale* are mobile scales that can be easily installed without requiring modification of facilities. *CIMA Control Pig* is a platform which provides the advantage of weighing pigs in motion, and guiding pigs to specific pens using a gate system, which can be installed in the corridors of the lairage pens. In contrast, *Automatic Pig Weighing* requires a fixed installation. *TriSortpro, ACCU-ARM Survey Scale, CIMA Control Pig,* and *PigScale*, enable the classification of pigs into different groups using colour marking with spray markers. The *ACCU-ARM Survey Scale* was previously used as a reference weigh scale in the development of an image-based weighing system by Kollis et al. (2007). *SKIOLD* achieves highly accurate pig sorting, with nearly 98 % precision; however, this percentage has not been verified in the literature. Similarly, *PigScale* claims to achieve average weight measurements with a deviation of 2 %, but this has not been verified by scientific studies.

Technologies capable of continuous and real-time live weight measurement, primarily based on image analysis techniques (as used by Schofield, 1990; Brandl & Jørgensen, 1996; Wang, Yang, Winter, & Walker, 2006; Kollis et al., 2007; Banhazi et al., 2011) typically rely on either 2D or 3D cameras to capture a substantial number of images of pigs within their pens. Subsequently, image analysis algorithms are applied to extract specific dimensional features of the pigs, leading to a weight estimation (Tscharke & Banhazi, 2013). However, strategic camera placement is crucial for achieving accurate weight predictions (Banhazi et al., 2022b) and to ensure that the visual sampling is both representative and evenly distributed. Additional factors, such as animal behaviour and farm management practices, significantly impact the accuracy of weight monitoring systems.

Fourteen products based on image analysis were identified in the current review with the purpose of monitoring body weight for farm use. These include FarmSee (FarmSee Ltd, Hod HaSharon, Israel), Embedded vision prototype for livestock weight monitoring (Lemberg Solutions, Lviv, Ukrain), Pigxcel™ ID (Solution of Sweden, Sjövik, Sweden), WUGGL One (WUGGL GmbH, Lang, Austria), Growth sensor (GroStat, Shropshire, United Kingdom), Weight-Detect™ (Innotech Vision, Tjele, Denmark), iDOL 65 camera (Dol Sensors, Aarhus, Denmark), OptiScan and WeightCheck (Big Dutchman, Vechta, Germany), eYeGrow (Fancom BV, Panningen, the Netherlands), PigBrother (PigBrother, Budapest, Hungary), PigVision (Asimetrix, Durham, USA), PIGI (Corntec, Kyoto, Japan), and Qscan (Innovent Technology Ltd, Roslin, United Kingdom).

Embedded vision prototype for livestock weight monitoring, WUGGL One, PIGI, and *OptiScan* are handheld and portable devices. The *Embedded vision prototype* uses a 3D camera with computer vision and a convolutional neural network (CNN) to estimate weight from photos taken of pigs' backs, displaying the results on a small screen. *OptiScan* employs a 3D and infrared camera connected to a tablet, estimating weight by analysing the pig's shape and height from the photos taken. *WUGGL One* is a smartphone-like device and determines weight by allowing the user to select the pig through the device's camera display. However, the product is still under development. *PIGI*, a software designed for Apple smartphones under a subscription, uses AI to estimate weight and calculate meat distribution from photos taken from above. The software works for pigs weighing 30–130 kg and automatically identifies different breeds. While none of these products provide information on accuracy, and no scientific validation studies were found, the *PIGI* website claims 98 % accuracy based on internal experimental tests. These technologies offer innovative approaches to weight estimation, but further validation and scientific evaluation are needed to confirm their reliability under practical conditions.

Several ceiling-mounted, camera-based technologies have been developed to estimate the weight of finisher pigs using advanced imaging and artificial intelligence. *eYeGrow* employs a 3D camera and claims up to 98 % accuracy for pigs weighing 25–130 kg, though no scientific publications validate this. Similarly, *Growth Sensor* and *PigBrother* report weight estimation accuracies of over 97 % and 97.91 %, respectively, but these claims are based solely on internal data without peer-reviewed evidence. However, the *Growth Sensor* seems to be no longer commercialised due to the company's closure. *FarmSee* uses a camera equipped with computer vision and AI for continuous monitoring and individual recognition across breeds, but no accuracy data has been provided. *Pigxcel™ ID* estimates weight with a ±2 kg margin using camera and AI, yet no scientific validation supports these claims. *Qscan* integrates AI modelling and 3D sensor imaging to monitor weight above drinking areas, but no accuracy data is reported. *WeightCheck* combines camera technology and AI, claiming 98.5 % accuracy in finisher pigs and the capability to assess 15–25 pigs per sensor.

In contrast to these systems, which largely lack peer-reviewed validation, some technologies have demonstrated promising results in published studies. *Weight-Detect™* is a non-contact weighing system based on image analysis, achieving average predictive errors of less than 3 % in average group weights (Banhazi et al., 2022b). Similarly, the *iDOL 65 camera* uses a 3D camera that captures an image every 10 s to calculate the average weight of pigs over the last 24 h. This system is effective for pigs weighing 7–110 kg, showing a concordance correlation coefficient of >0.96 with scale-based body weight measurements and an estimated error of ≤3.6 % for the median weight (Franchi et al., 2023). *PigVision*, part of the *SMARTFARM* solution, integrates a small camera and AI with multiple sensors, achieving over 95 % similarity with direct scale measurements ($r = 0.989$, $p < 0.001$; Gómez Martínez et al., 2024). While these technologies show potential for non-invasive weight estimation, their widespread adoption and performance under commercial farm conditions still requires further independent validation.

Body weight has been extensively studied over the years, primarily to achieve better production optimisation. Consequently, nowadays most technologies have been researched and developed for farm use, as supported by the results of this review. However, they could be installed in slaughterhouse facilities to monitor animal body weight in the lairage area. At the slaughterhouse, in addition to controlling weight, live body weight could be used for distributing pigs in the pens, since pigs should be able to rest comfortably after transport by controlling stocking densities. Pig comfort is related to enough space allowance, which is based on body weight (EFSA AHAW Panel et al., 2020).

4.1.7. Body temperature

The body temperature of pigs is related to their health and welfare. Measurements of body temperature can indicate hyper- and hypothermia, potentially caused by infectious diseases, stress or inadequate environment, such as too high or low ambient temperatures (Gómez et al., 2021; Soerensen & Pedersen, 2015). Body temperature is usually determined by inserting a thermometer into the pig's rectum, an invasive method that may be stressful for the animal. Skin measurements may cause less stress, particularly on the ears (ear canal and outer ear), as well as on the eyes and udder. The skin temperature of pigs seems to be highly correlated with body temperature (Stukelj et al., 2022; Soerensen & Pedersen, 2015). However, the skin measurements can be affected by different factors, such as the pigs' age, due to the insulating effect of subcutaneous fat in older pigs (Racewicz et al., 2021), heat stress (Abuajamieh et al., 2018), the pig's biological status, like oestrus in sows (Zhang et al., 2019), by dirt and moisture on dry skin on the pig's body (Schmid et al., 2021), the individual physiological variability or skin emissivity (Redaelli et al., 2024). Non-contact thermometers and thermal imaging cameras are used for skin temperature measurements, which are not only quick but also reduce disease transmission. In particular, thermovision can be used to detect injuries and inflammations on different body regions, as well as stress levels (Racewicz et al., 2021).

Infrared thermometers are normally hand-held devices that measure the surface temperature at specific body points by measuring the body's own radiation infrared energy. These thermometers can be used quickly in different locations (farm, transport, slaughterhouse). However, there may be differences in the measured temperatures between different thermometers and different parts of the body (Koch et al., 2023). Well-perfused areas of the body, such as the base of the ear, have been confirmed in various studies as suitable measuring sites for infrared measurements in pigs (Koch et al., 2023; Zhang et al., 2019). Various hand-held infrared measuring devices are available. Some are offered as veterinary products specifically for measuring the body temperature of pigs and other animals (EVTSCAN, Veterinary Thermometer, Shenzhen, China or Thermometer YM 558D, Tebru, Shenzhen, China), while others have been developed for industry and food production and, due to their technical specifications, can also be used to measure the body temperature of pigs (Metris Instruments TN418L1, New York, USA, or IRT207 Heat Seeker 8:1, General Tools, New York, USA). The *IRT207 Heat Seaker 8:1* has been used in several scientific studies aimed to evaluate heat stress in pigs, and differences between measured skin temperature and rectal temperature in the heat-stressed pigs were shown (Abuajamieh et al., 2018; Kvidera et al., 2024; Mayorga et al., 2024; Seibert et al., 2018). The *Degree2act* (Degree2act, Barcelona, Spain) system gives farmers or other caretakers the opportunity to monitor herd health by measuring the pigs' skin temperature. The *Degree2act* App is installed on a smartphone (specific models only) and the temperature is measured using the attached *FLIR One* or *FLIR One Pro camera* (Teledyne FLIR, Wilsonville, USA). The system allows deviations from the normal temperature to be detected and reacted to, by using a traffic light system (green = pigs are detected within camera reach, yellow = slight deviation, red = alarm). The system was evaluated in a study involving sows, comparing rectal temperature with measurements from other regions, with the vulva region ($r = 0.95$, $p < 0.001$) being the most recommended as a measuring site (Ramis et al., 2017).

While the measurement of an infrared thermometer is limited to a specific point, thermal cameras detect the temperature of a larger area (Foster et al., 2021). Numerous thermal cameras are available, eight out of ten identified in this review were initially developed for industrial use, including the T400 and T630 (InfiRay, Anhui, China), FLIR E8 Pro and FLIR One Pro LT (Teledyne FLIR, Wilsonville, USA), TR256B and TR256E (Mileseey Tools, City of Industry, USA), X640D (Yoseen Infrared, Wuhan, Hubei, China) and H4 Intelligent Thermal Camera (Guide Sensmart, Wuhan, China). Two tablets, the IR Pad 640 and IR Pad 320 (Digatherm, ICI infrared cameras Inc., Beaumont, USA), were specifically designed for use in the veterinary field. *IR Pad 640* and *IR Pad 320* include software for analysis of the thermal images and allow the images to be send via e-mail. The manufacturer's website claims a thermal accuracy of ±1 °C, providing more precise measurements than the thermal cameras designed for industrial applications, which typically have a thermal accuracy of around 2–5 °C.

Hand-held devices by FLIR have been used in several studies for body temperature measurements of pigs (Stukelj et al., 2022; Petry et al., 2017; Chem et al., 2022). This review focuses on the *FLIR E8 Pro*, a hand-held thermal imager, as well as the *FLIR One Pro LT*, a camera that needs to be attached to a smartphone. Whilst both cameras feature multi-spectral dynamic imaging, combining both visual and thermal spectrums, they do not offer a high thermal accuracy at ± 2 °C (FLIR E8 Pro) or ± 5 °C (FLIR One Pro). Another possibility to measure body temperature in pigs is presented through a smartphone-like device called *WUGGL One* (WUGGL GmbH, Lang, Austria), which is designed to measure body weight using a camera. A sensor for temperature measurements is included. The website does not offer more specifics on the temperature sensor and the product is currently under development.

All the presented infrared thermometers and thermal cameras are portable and can in theory be used on farm, on transport, and at the slaughterhouse. In the slaughterhouse, they may be used by veterinarians to quickly detect deviations in body temperature and thus symptoms of illness in the pigs. This can be done upon arrival of the animals and immediately before slaughter. Heat stress on the transport vehicle or in the slaughterhouse could also be detected, although the informative value may be limited since the body surface temperature during heat stress is not necessarily correlated with the core body temperature (Abuajamieh et al., 2018; Seibert et al., 2018). In addition, the skin surface of pigs in lairage can be very moist due to the occasional use of sprinkler systems (Vitali et al., 2014). This can limit the reliability of temperature measurement on the skin surface. Measuring temperature based on radiation is strongly influenced by environmental conditions, such as ambient temperature, humidity, and interference in radiation by reflection from water and metal surfaces. Additionally, other external factors, such as physical efforts, time of feeding, time window of the measurements, heating sources nearby or wind, can influence the accuracy of the results. Technical factors during the measurements, such as distance, view angle and the type of device or thermic and special resolution, must also be considered (Redaelli et al., 2024). Therefore, the results of infrared measurements of the temperature on the skin surface must be interpreted with caution. Furthermore, the development of automated interpretation technologies capable of generating alerts for temperature fluctuations in animals remains unexplored.

In addition, infrared thermometers can also be used for quality assurance of meat after slaughter. However, this application requires devices with a different measurement range to monitor lower temperatures for cooling.

4.2. Slaughter area

4.2.1. Stunning and killing effectiveness

Pigs can experience pain and distress if not rendered unconscious promptly and adequately before slaughter. Maintaining unconsciousness during stunning and killing is a key factor to prevent unnecessary pain and distress. Monitoring consciousness involves assessing brain function and neurological responses. In slaughterhouse operational conditions, indicators of consciousness include brainstem reflexes, such as corneal reflex, rhythmic breathing, vocalisations, and coordinated physical movements, as these are all indicators of brain responsiveness (Llonch et al., 2013). The absence of these indicators confirms that the pig is unconscious and unable to perceive pain or any other negative emotion. The European Food Safety Authority (EFSA AHAW Panel et al., 2020) suggests a strict monitoring of these indicators during slaughter to assess the risk of consciousness recovery and the associated thread for animal welfare.

Automated sensors offer precision and objectivity (Gómez et al., 2021) for detecting physiological signs, such as corneal reflexes and brain activity, in real-time. This reduces human error and allows immediate intervention if inadequate stunning occurs. Sensors also enhance efficiency in high-throughput slaughterhouses and generate data for improving welfare practises over time. By automating these assessments, slaughterhouses can ensure humane treatment while maintaining compliance with regulatory standards (Voogt et al., 2023).

Among these automatic measurements, two different types of technologies can be differentiated. First, the sensors that monitor stunning effectiveness, mostly focused on the assessment of a variety of brain stem reflexes. Second, there are sensors that can monitor the killing process, where the focus is on the signs of death, ensuring that pigs will not regain consciousness, and the carcass can be effectively processed.

For monitoring the stunning effectiveness, three sensors were identified that are normally installed in the slaughter line and that are able to monitor the consciousness of every slaughtered pig and provide data at an individual level: *CET' Automatique* (Wel2be, Le Rheu, France), *Monitoring of the carbon dioxide (CO_2) stunning* (Genba Solutions GmbH, Zwentendorf, Austria) and *Signs of life* (Argus, Epe, the Netherlands). None of them have been externally validated. The *CET' Automatique* is based on computer vision that is capable of monitoring whether pigs show corneal reflex after an automatic air blow is directed towards the eye. Thus, the effectiveness of stunning is based on the outcome of the corneal reflex. Although this is the most widely used reflex to monitor stunning effectiveness, for a reliable assessment of consciousness, it is preferable to combine it with other reflexes (Verhoeven et al., 2015). The *Monitoring of CO_2 stunning* bases its assessment on a combination of movements of the carcass, including mouth opening (which can be associated to respiration) and body movements. These two indicators may provide a reliable assessment, as according to Verhoeven et al. (2015) the combination of various brain stem reflexes may reduce the likeliness of false positives. There is no evidence about the validity of the previous sensors, suggesting that independent research is needed to make these results publicly available for transparency.

The killing process can be automatically monitored using two sensors: *VisStick* (Danish Meat Research Institute, Taastrup, Denmark) and *Bleeding Measurement in Pigs* (CLK GmbH, Altenberge, Germany). These are based on different technologies but both focus on the bleeding effectiveness, as inadequate sticking might cause insufficient blood flow and the risk that pigs are not dead before carcass processing (EFSA AHAW Panel et al., 2020; Velarde & Dalmau, 2024). *VisStick* is a commercially available computer vision system designed to monitor the bleeding process of slaughtered pigs. Following the sticking of the neck, a camera checks whether blood is flowing from each pig. If no blood flow is detected, it notifies the operator to ensure the sticking is done correctly. This sensor, which needs to be installed at the slaughter line, has been internally validated, and according to the provider, it reached a detection range between 98 and 100 %. Alternatively, *Bleeding Measurement in Pigs* uses a thermal camera that is capable to detect that the bleeding is correct. This sensor is not commercially available yet and no data on its effectiveness is available.

The stunning and slaughter process is one of the critical moments for the welfare of pigs. There are technologies available to monitor signs of stunning and killing effectiveness, but their effectiveness needs to be scrutinised. If their monitoring capacity is validated, they will offer an important opportunity to control this highly sensitive moment for pigs.

4.3. Carcass processing area

4.3.1. Skin and viscera lesions

The assessment of skin and tail lesions at the slaughterhouse is a useful tool for the evaluation of the lifetime welfare status as lesions acquired at least 10 weeks before slaughter remain visible on the pig carcass (Carroll et al., 2018). Post-mixing aggression at the farm, before or after loading, during transport or lairage can result in the accumulation of skin lesions mainly occurring in the front third of the body caused by bites targeted at the ears, face and neck and the flanks (Turner et al., 2006). Tail lesions and tail length are important animal welfare indicators, not only because an intact tail without major lesions is a proof for the absence of serious husbandry and health deficiencies that result in tail biting (Smulders et al., 2006; Wallgren et al., 2019), but also because routine tail length measurement can serve as valuable tool to monitor tail lesions and docking at herd-level (Heinonen et al., 2021; Valros et al., 2020). The slaughterhouse plays a key role in assessing tail biting behaviour on farms, as an effective method for monitoring this aberrant behaviour should incorporate both tail length and tail lesions observations. Tail lesions can also provide an entry site for pathogens, potentially leading to secondary infections that manifest as pleurisy, pneumonia and pleuropneumonia (Teixeira et al., 2016), and which have been identified as the number one causes for whole carcass rejections (Martínez et al., 2007). These viscera lesions, among others, represent serious health conditions and should be considered as indicative of poor welfare.

Two systems for the detection of viscera lesions were identified in the present review: *ADAL* (Farm4Trade, Atessa, Italy) and *ArtificialVet*® (Company Mind, Oldenburg, Germany). Both companies also offer solutions to detect different kinds of lesions on the carcass, and Farm4-Trade additionally provides the option for tail measurement by using the *TAILSCAN* system. The three other systems identified that are used in the carcass processing area are mainly focus on the detection of external lesions, including tail lesions, and tail length (CLASSIFAI® BOX, Software Logistik Artland GmbH, Quakenbrück, Germany; PigInspector, CLK GmbH, Altenberge, Germany; and TailCam, Danish Technological Institute, Taastrup, Denmark). Technical implementation of the currently available solutions always involves a stationary camera system located at the slaughter line. The integrated software analyses the photographic images and scores them based on the absence or the presence, as well as the extent (or length), of a specific trait. Most of the offered systems represent prototypes of which some are commercially available, while others are not yet on the market. Notwithstanding the above and though not explicitly stated on the websites, the majority of these technologies still seem to be under continuous development in order to include additional features and improve algorithm and AI performance. For one of the technologies, *TailCam*, it is not clear if the technology provider is striving for further development as the official website is currently unavailable.

In the current review, a high backlog demand regarding validation of sensor outputs was identified. For only three out of the six systems are validation results for selected sensor outputs publicly available. The *ADAL* system can detect pleurisy with an accuracy of 85.5 % (specificity = 96 %, sensitivity = 92 %). The DL-based model that is used to distinguish healthy from diseased lungs reached a sensitivity and specificity close to 100 % when compared with veterinarians' annotations (Bonicelli et al., 2021) and the correlation rate between scores recorded by the veterinarians and those calculated by the DLBM was very high ($r = 0.96$).

Blömke et al. (2020) tested the *PigInspector* system and found an overall sensitivity of 77 % and an overall specificity of 96.5 % for ear lesions. With an overall positive predictive value of 59 % and an overall negative predictive value of 98.5 %, the accuracy amounted to 95.4 %. For tail lesions, the overall sensitivity was 77.8 % and overall specificity 99.7 %. The overall positive predictive value was 72.4 %, while the overall negative predictive value was 99.8 %, resulting in an accuracy of 99.5 %.

The third and last technology for automatic detection of skin and/or viscera lesions with publicly accessible validation results is *TailCam*. In the final PigWatch test report, a very good correlation was found between manually measured tail length and values calculated by the *TailCam* system (RMSE = 1.95; $r = 0.90$). Serious tail lesions were detected with a sensitivity of 61 %, while 39 % were misclassified as "Small lesion". The sensitivity for "Small lesion" was 75 %. In 3 % of all cases, a "Small lesion" was misclassified as "Lesion" and 22 % were incorrectly assigned to the category "No lesion". The overall specificity for the applied algorithm was 96 % with 4 % of tails without any signs of tail bites being misclassified as "Small lesions".

4.4. General discussion

This review highlights the promising advancements in the technological development of animal welfare assessment at slaughterhouses. In addition to identifying 16 technologies designed for continuous and systematic welfare monitoring in pigs at slaughterhouses, this study underscores the applicability of 52 technologies developed for on-farm use, which could potentially be applied at various stages of the slaughter process. This demonstrates the technological potential, particularly in the antemortem phase, which has been scarcely addressed until now. Automated welfare monitoring from the slaughterhouse perspective represents a paradigm shift and offers significant potential in the study of animal welfare. Nevertheless, several challenges and limitations must be overcome to ensure the effective utilisation of these technologies in a real environment.

Before addressing the challenges and limitations presented by the technologies, it is important to highlight the lack of harmonisation in the scoring of animal-based indicators at slaughterhouses. For instance, tail length lacks a validated scoring system for welfare monitoring, which is particularly problematic when evaluating docked versus undocked pigs, as the interpretation differs. Establishing a standardised scoring system for each gold standard could contribute to more harmonised assessments. This step may serve as a crucial starting point before validating technologies.

The limited number of technologies designed for slaughterhouse use may be attributed to several factors, such as the challenge to reliably measure indicators in the slaughterhouse environment (e.g., noise interfering with sound measurements) but also place and time restrictions (e.g., live animals are there only briefly, and the slaughter lines operate at very high processing speeds). At the same time, the technology must be robust enough to be used in slaughterhouse conditions, which are characterised by high humidity, contrasting temperatures (cooling area versus scalding area), and the need for frequent cleaning.

Another reason could be the difficulty in creating a universal sensor that can be installed in various types of slaughterhouses, as both the hardware and software need to be adapted to each environment. This is because the infrastructure and construction of each slaughterhouse, as well as the working methods, differs between facilities, requiring significant development work and expertise in the field. For example, an algorithm developed for monitoring visceral lesions must be adapted depending on whether the viscera are hanging from a hook or lying on a tray, as this changes the required camera angle. Additionally, other factors must be considered, such as ensuring a stable internet connection and proper cabling, traceability, and data storage and data protection.

Another possible reason may be a reluctance from slaughterhouses to implement such technologies. For some indicators, it is difficult to determine when the indicator changed, and this could potentially lead to false claims. For example, if a broken leg is detected at the slaughterhouse, then it is unclear for what duration it has been in this condition and who is responsible for it, as it could have happened at the farm, on the truck, or in the lairage area. Slaughterhouses increasingly face threats by activists (Davis, 2018) and, understandably, they may not want to be associated with negative welfare indicators for which it might not be straight-forward to trace the origin.

Therefore, a first step may be to focus on the indicators for which it is easier to determine when they have occurred. For example, if a pig presents a lower body weight compared to the average of the batch, it might be an indicator that the health and welfare of this pig was compromised under farm conditions. Indicators, such as stunning effectiveness, relate exclusively to the welfare at the slaughterhouse and can give a clear indication of the welfare at that instance. Other indicators, such as tail or skin injuries, may have occurred within a relatively short period. Given the conditions during transport and lairage, where aggression among unfamiliar pigs often prevails, it could be hypothesised that fresh lesions arise from the transport or lairage and older lesions will have started at the farm. A second step may be to increase the level of detail that the technologies can distinguish, which in the future may potentially provide information on the duration of suffering (e.g., discoloration of tissue associated with injury). Objectively assessing these lesions from the slaughterhouses' perspective would help improve best practices regarding the fitness of pigs for transportation.

Other points important to remark are related to the lack of validity of the technologies linked to the cost of investments. Frequently, the precision and potential of such systems are overstated, leading to unrealistic expectations (Hartung et al., 2017). Clear communication regarding the inherent sources of imprecision is essential. Although sensors can deliver technically accurate measurements, several factors affect predictive precision in commercial environments. Therefore, it is crucial to manage end-users' expectations regarding the achievable accuracy and benefits of image-based sensors, for example, in weight monitoring systems (Kopler et al., 2023; Banhazi et al., 2022a; Banhazi et al., 2024). Furthermore, it is worth noting that the results of this review indicated that the transportation phase remains largely unexplored in terms of automated assessment of animal welfare using technologies. Future research should focus on expanding technological capabilities to assess welfare during the transportation phase, ensuring a comprehensive understanding and monitoring of animal welfare throughout the production chain.

5. Conclusions

The findings of this review underscore the considerable advancements in technologies to assess pig welfare. Many technologies seem to have potential applicability in slaughterhouses, particularly in antemortem welfare assessment. The technologies currently employed and scientifically studied in greater depth in slaughterhouses, primarily focus on assessing welfare through post-mortem lesion evaluations on carcasses. This highlights a significant gap in the integration of welfare assessment technologies for other critical indicators and stages, such as monitoring the welfare status of pigs at lairage area.

While there is a high potential for automated welfare assessment, the technologies discussed in this review still require substantial development, and especially validation to function effectively in slaughterhouse environments. Many existing systems are not yet sufficiently robust, validated, or adaptable to meet the diverse requirements of different facilities. Addressing these challenges is essential for achieving reliable and client-specific solutions.

Although the potential of automated systems to monitor pig welfare is undeniable, the road to practical implementation and widespread adoption is still considerable. Collaborative efforts among researchers, industry stakeholders, and technology developers will be crucial in overcoming these challenges and unlocking the full potential of automated welfare monitoring systems.

CRediT authorship contribution statement

Angela Ramon-Perez: Writing – review & editing, Visualization, Investigation, Conceptualization, Writing – original draft, Methodology, Formal analysis. **Irene Camerlink:** Writing – original draft, Writing – review & editing, Funding acquisition. **Nienke van Staaveren:** Writing – original draft, Writing – review & editing. **Kristina Maschat:** Writing – review & editing, Funding acquisition, Writing – original draft. **Kenny van Langeveld:** Writing – review & editing, Writing – original draft. **Thomas Banhazi:** Writing – original draft, Writing – review & editing, Funding acquisition. **Michaela Fels:** Writing – review & editing, Funding acquisition, Writing – original draft. **Maite Jachens:** Writing – review & editing, Writing – original draft. **Jarissa Maselyne:** Writing – original draft, Writing – review & editing, Funding acquisition. **Björn Forkman:** Methodology, Conceptualization, Writing – review & editing, Funding acquisition. **Pol Llonch:** Writing – original draft, Supervision,

Methodology, Conceptualization, Writing – review & editing, Visualization, Project administration, Funding acquisition.

Declaration of generative AI and AI assisted technologies in the writing process

No generative AI or AI-assisted technologies were used during the preparation of this work.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: ARP, IC, NVS, KVL, KM, MF, MJ, JM, BF and PL declare no conflict of interest. TB is employed by Innotech Vision. However, this relationship has not hindered conducting an objective review of all the technologies on the market and an analysis of their potential.

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Appendix A

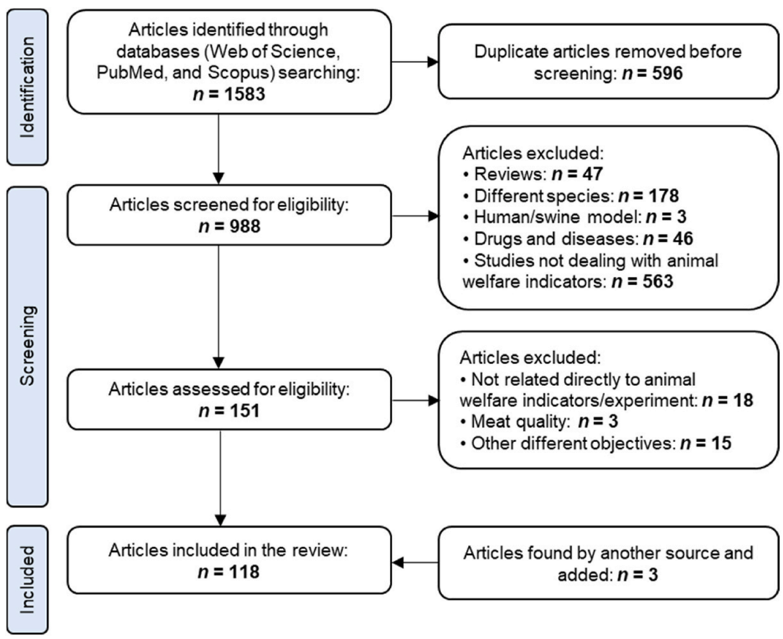

Fig. A.1. Modified Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram (Page et al., 2021) with the review search strategy and study selection.

Table A.1
Technologies excluded for being unfeasible for slaughterhouse use.

Indicator	Type of technology	Sensor name	Provider	Specifications				Observation	Reason (s)
				Rearing	Fattening	Sow	Level		
Feeding behaviour	Load cells (feeder)	EasySlider	Big Dutchman			x	F		Not fit in the slaughterhouse context
		Call-In Pro			x	x	G		
		CallMatic Pro			x	x	G	Drinking assessment included	
		CallBack Pro			x	x	G		
		IntelliTek sow feeding station	Fancom BV			x	G		
		FaroTek				x	F		
		Accu-TEAM™	Osborne			x	G	Include weight assessment	
		FIRE® Pig Performance Testing System			x	x	G	Include weight assessment	
		SaFIRE™ Feeder		x			G	Include weight assessment	
		Fidos Gestation	Roxell			x	G		

(continued on next page)

Table A.1 (*continued*)

Indicator	Type of technology	Sensor name	Provider	Specifications				Observation	Reason (s)
				Rearing	Fattening	Sow	Level		
		SKIOLD ESF	SKIOLD			x	G		
		SKIOLD Smart-Feeder				x	F		
		SKIOLD Genstar Testing Station				x	G	Include weight assessment	
Heat sow detection	Thermal camera	GWIZ	Dilepix					Assess body temperature	Not fit in the slaughterhouse context
	Computer vision	smaRt Breeding	Ro-Main					Assess postures behaviours	
Movements and activity	Accelerometer	SMARTBOW	Zoetis					No longer commercialised	Designed for cattle. Used in pig research.
		FITPIG	HOP Ubiquitous S.L					Not clear if is still under study	Research project result (prototype)
Lameness	Load cells (force plate)	SowSIS	ILVO and U. Ghent						Developed for academic research in sows. No research in finisher pigs even in farm context. Not commercially available
	Modular pressure measurement platform	Strideway ™ Animal Gait Analysis system version 7.8	Tekscan						Designed for other species, no feasible for animals with hooves. Lack of software to obtain processed lameness data

F: individual assessment at the farrowing pen.
G: individual assessment at the group level.

Appendix B. Online survey for Expert Consultation

The survey used for the Expert Consultation can be found online at https://ec.europa.eu/eusurvey/runner/aWISH-TechonolgySurvey.

Data availability

Data will be made available on request.

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