

Technological systems for assessing pig welfare: trends, applications, and future perspectives

Sistemas tecnológicos para la evaluación del bienestar animal en porcinos: revisión de tendencias y aplicaciones

Celso López-Soto^a, Laura Afanador-Barajas^b, Irma Morales-Rodríguez^a, Jairo R. Hernández-Niño^c, Juliana M. Castañeda-Medina^{a*}

Abstract:

Animal welfare in pig production systems is a key component for sustainability, productive efficiency, and the quality of animal-derived products. In this context, the development and implementation of technological systems have enabled significant advances in the objective assessment and continuous monitoring of animals' physiological, environmental, and behavioral conditions. The aim of this study was to analyze trends and applications of technological systems used for assessing animal welfare in pigs through a structured review of scientific literature published between 2012 and 2024. The literature search was conducted in international scientific databases such as ScienceDirect, SpringerLink, and Scielo, using keywords in both English and Spanish related to animal welfare, pigs, and monitoring technologies. Primary and secondary studies were selected based on predefined inclusion criteria. The results show a steady increase in scientific output over the period analyzed, with a predominance of English-language publications. The main issues addressed include thermal stress, abnormal behavior, animal health, and physical condition. The most widely used technologies include imaging systems (2D and 3D), wireless sensor networks, adiabatic cooling systems, and accelerometers, which enable real-time monitoring of welfare indicators. In conclusion, the integration of technological systems in pig production represents a fundamental tool for improving animal welfare, optimizing production systems, and supporting data-driven decision-making

Keywords:

Animal welfare, pig production, precision livestock farming, monitoring technologies, sensor systems, behavioral analysis

Resumen:

El bienestar animal en los sistemas de producción porcina constituye un elemento clave para la sostenibilidad, la eficiencia productiva y la calidad de los productos de origen animal. En este contexto, el desarrollo e implementación de sistemas tecnológicos han permitido avances significativos en la evaluación objetiva y el monitoreo continuo de las condiciones fisiológicas, ambientales y comportamentales de los animales. El objetivo de este estudio fue analizar las tendencias y aplicaciones de los sistemas tecnológicos empleados en la evaluación del bienestar animal de los porcinos, mediante una revisión estructurada de la literatura científica publicada entre 2012 y 2024. La búsqueda se realizó en bases de datos científicas internacionales como ScienceDirect, SpringerLink y Scielo, utilizando palabras clave en inglés y español relacionadas con el bienestar animal, los porcinos y las tecnologías de monitoreo. Se seleccionaron estudios primarios y secundarios según criterios de inclusión definidos. Los resultados muestran un incremento sostenido en la producción científica durante el periodo analizado, con predominio de publicaciones en inglés. Las principales problemáticas abordadas incluyen el estrés térmico, el comportamiento anormal, la salud animal y la condición física. Entre las tecnologías más utilizadas destacan los sistemas de imagen (2D y 3D), las redes de sensores inalámbricos, el enfriamiento adiabático y los acelerómetros, que permiten el monitoreo en tiempo real de indicadores de bienestar. Se concluye que la integración de tecnologías en la producción porcina constituye una herramienta fundamental para mejorar el bienestar animal, optimizar los sistemas productivos y fortalecer la toma de decisiones basada en datos.

Palabras Clave: Bienestar animal, producción porcina, ganadería de precisión, tecnologías de monitoreo, sistemas de sensores, análisis del comportamiento

^a Universidad Autónoma del Estado de Hidalgo; <https://orcid.org/0009-0004-2528-9573>, lo354774@uaeh.edu.mx; <https://orcid.org/0009-0005-3611-4485>, irma_morales@uaeh.edu.mx; <https://orcid.org/0009-0005-7743-7352>, ca397283@uaeh.edu.mx

^b Investigadora Posdoc DGAPA, Departamento de Microbiología Molecular, Instituto de Biotecnología, Universidad Nacional Autónoma de México (UNAM), <https://orcid.org/0000-0002-8133-7048>, laura.afanador@gmail.com

^c Universidad Internacional del Trópico Americano, Colombia; <https://orcid.org/0000-0003-1269-4305>, jairohernandez@unitropico.edu.co.

*autor de correspondencia

Fecha de recepción: 20/03/2026, Fecha de aceptación: 18/04/2026, Fecha de publicación: 05/07/2026

1. Introduction

Animal welfare in pig production systems has gained increasing global attention due to its direct impact on productivity, product quality, and the sustainability of agro-food systems. Pig production is one of the main sources of animal protein worldwide, driving the adoption of strategies to optimize both production performance and animal welfare.

The concept of animal welfare has evolved into a comprehensive approach that encompasses not only physical health but also animals' mental state and their ability to express natural behaviors [1]. In this regard, international organizations such as the World Organization for Animal Health have established guidelines defining animal welfare in terms of the absence of pain, stress, and suffering, as well as the provision of appropriate environmental conditions that ensure comfort, safety, and access to essential resources [2].

In intensive pig production systems, several factors—including thermal stress, high stocking density, disease incidence, and abnormal behaviors—pose significant challenges to maintaining adequate welfare conditions [3]. Traditionally, the assessment of these factors has relied on direct observation and periodic measurements, which limits the early detection of welfare issues and timely decision-making.

In this context, the development of precision livestock farming technologies has enabled the implementation of automated systems for continuous monitoring of physiological, behavioral, and environmental variables. Technologies such as imaging systems, wireless sensor networks, and wearable devices have demonstrated strong potential to improve the objective and real-time assessment of animal welfare [4, 5].

Despite these advances, challenges remain in integrating, accessing, and applying these technologies across different production contexts. Therefore, the aim of this study was to analyze trends and applications of technological systems for assessing pig welfare through a structured review of recent scientific literature.

2. Methodology

2.1 Study design

This study was conducted as a structured literature review in accordance with the principles of systematic reviews. The methodological approach was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) [6] to ensure transparency, reproducibility, and rigor in the selection and analysis of scientific literature.

2.2 Search strategy

A comprehensive literature search was carried out in international scientific databases, including ScienceDirect, SpringerLink, Scielo, and Web of Science. The search covered publications from January 2012 to December 2024.

The search strategy was based on combinations of keywords in English and Spanish using Boolean operators:

- (“animal welfare” AND pigs AND technology)
- (“pig welfare” AND sensors AND monitoring)
- (“bienestar animal” AND porcinos AND tecnologías)
- (“ganadería de precisión” AND cerdos)

Only peer-reviewed articles were considered to ensure scientific quality.

2.3 Inclusion and exclusion criteria

The selection of studies was conducted according to predefined inclusion and exclusion criteria:

Inclusion criteria:

- Primary and secondary research articles
- Studies focused on pig production systems
- Publications addressing technologies applied to animal welfare
- Articles published between 2012 and 2024
- Publications in English or Spanish

Exclusion criteria:

- Duplicate records
- Conference abstracts without full text
- Non-scientific sources (web pages, blogs, or non-peer-reviewed content)
- Studies not directly related to pig welfare or technological applications

2.4 Study selection process

The study selection process was carried out in three stages:

1. Identification: Articles were retrieved from the selected databases using the search strategy.
2. Screening: Titles and abstracts were reviewed to assess relevance.
3. Eligibility: Full-text articles were evaluated according to inclusion and exclusion criteria.

A flow diagram was constructed to illustrate the selection process (Figure 1), including the number of records identified, screened, included, and excluded at each stage.

2.5 Data extraction and analysis

Relevant data from the selected studies were extracted and organized into a structured database using spreadsheet software. The following variables were recorded:

- Year of publication
- Authors and journal
- Type of study
- Technologies applied
- Welfare indicators evaluated
- Main findings and applications

A qualitative synthesis of the information was conducted to identify trends, technological categories, and major application areas related to pig welfare.

2.6 Quality assessment of studies

To ensure the reliability of the included studies, a qualitative assessment of methodological quality was performed based on the following criteria:

- Clarity of objectives
- Appropriateness of study design
- Description of technological tools
- Validity of welfare indicators
- Reproducibility of methods

Each study was classified as:

- High quality
- Moderate quality
- Low quality

Only studies classified as high or moderate quality were included in the final analysis.

2.7 Data synthesis

The selected studies were analyzed using a descriptive and comparative approach. Technologies were grouped into categories such as:

- Imaging systems
- Sensor-based systems
- Environmental control technologies
- Behavioral monitoring tools

The analysis focused on identifying patterns, research trends, and the most relevant technological applications for improving animal welfare in pig production systems.

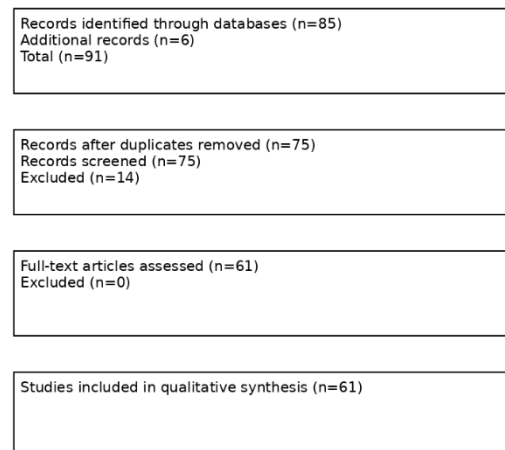


Figure 1. PRISMA flow diagram. This figure illustrates the systematic selection of scientific articles included in the review of technological systems applied to pig welfare. The process follows PRISMA 2020 guidelines and includes four stages: identification (records retrieved from databases), screening (removal of duplicates and evaluation of titles and abstracts), eligibility (full-text assessment), and inclusion (final studies analyzed). The diagram reports the number of records at each stage, as well as the reasons for exclusion.

2.8 Limitations of the study

This review presents some limitations:

- Potential publication bias due to the inclusion of peer-reviewed articles only
- Predominance of English-language studies
- Variability in methodologies and welfare indicators among studies

- Limited availability of data from developing regions

3. Results and Discussion

3.1 Trends in scientific production

The analysis of the selected studies (n = 61) revealed a steady increase in scientific production on technologies applied to pig welfare between 2012 and 2024. A noticeable rise in publications was observed from 2018 onwards, indicating growing research interest in precision livestock farming and welfare-monitoring technologies. This trend reflects the increasing global concern regarding animal welfare and the need for more efficient and sustainable pig production systems.

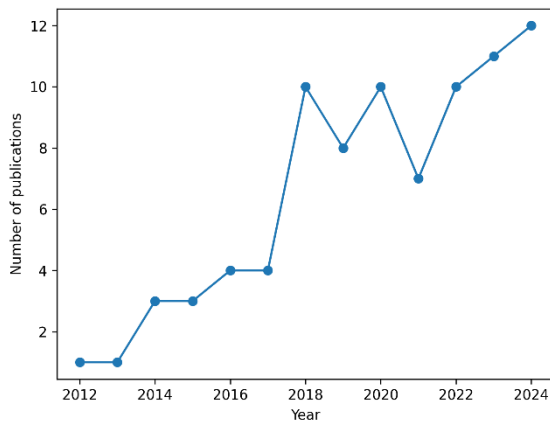


Figure 2. Trends in scientific publications on technologies applied to pig welfare (2012–2024). This figure shows the annual distribution of scientific publications included in the review. The data reflect a progressive increase in research output over time, with a marked growth after 2018, highlighting the rising interest in precision livestock farming and technological approaches to animal welfare. The x-axis represents the publication year, and the y-axis indicates the number of studies per year.

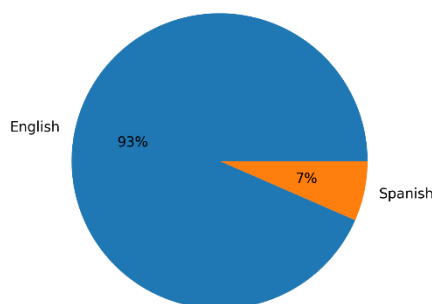


Figure 3. Distribution of selected studies by language, showing the predominance of publications in English over Spanish. This figure presents the proportion of publications by language, showing the predominance of English-language articles over Spanish-language studies. The distribution reflects global research trends and highlights the limited scientific production available in Spanish in the field of pig welfare and monitoring technologies.

3.2 Distribution by language and sources

Most of the selected studies were published in English (n = 57), while only a small proportion were available in Spanish (n = 4). This highlights a significant gap in scientific production in Spanish-speaking regions and suggests the need for increased regional research efforts. Regarding data sources, most studies were retrieved from major scientific databases, including ScienceDirect and SpringerLink, underscoring their relevance as primary sources of peer-reviewed research.

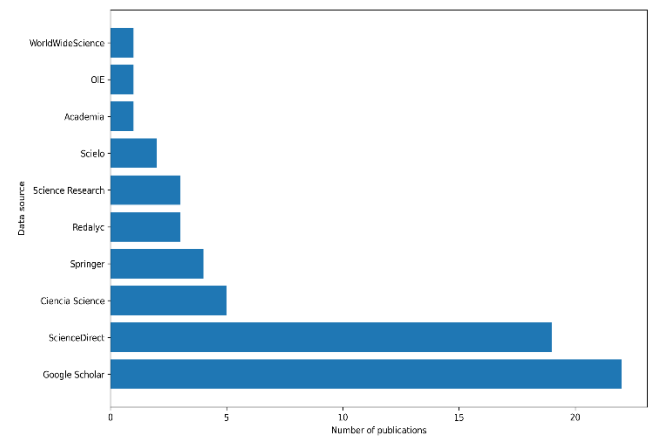


Figure 4. This figure illustrates the number of selected studies by database, including ScienceDirect, SpringerLink, Web of Science, Scielo, and Google Scholar (for complementary searches). The results emphasize the dominance of major international scientific databases as primary sources of peer-reviewed literature in this field.

3.3 Main welfare challenges addressed

The reviewed literature identified several key challenges affecting pig welfare: thermal stress, abnormal and aggressive behavior, animal health and lameness, and physical condition and growth performance. Among these, thermal stress and behavioral disorders were the most frequently

addressed, reflecting their critical impact on productivity and animal well-being.

3.4 Technological systems applied to pig welfare

The analysis allowed the classification of technologies into four main categories:

a) Imaging systems

Imaging technologies, including 2D and 3D cameras and thermal imaging, are widely used to monitor behavior, body condition, and temperature. These systems enable non-invasive and continuous observation of animals.

b) Sensor-based systems

Wireless sensor networks and wearable devices, such as accelerometers, provide real-time data on animal activity, movement patterns, and physiological responses.

c) Environmental control technologies

Technologies such as adiabatic cooling systems are essential for mitigating thermal stress and improving housing conditions.

d) Behavioral monitoring tools

Advanced systems using artificial intelligence and machine learning allow the detection of abnormal behaviors, such as aggression or tail biting, facilitating early intervention.

3.5 Implications for pig production systems

The integration of technological systems into pig production represents a significant advancement toward precision livestock farming. These technologies enable:

- Early detection of health and welfare issues
- Improved decision-making

- Increased productivity and efficiency
- Enhanced sustainability

However, challenges remain regarding cost, accessibility, and adaptation to different production contexts, particularly in developing regions.

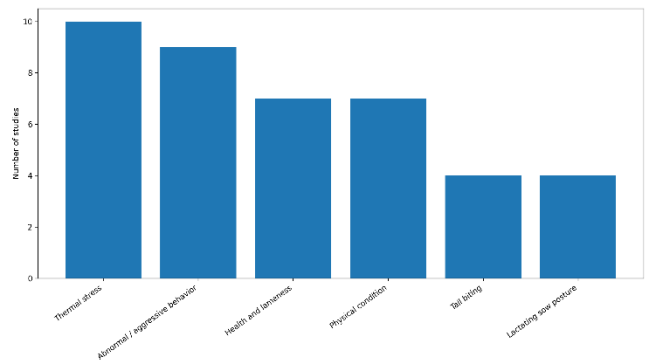


Figure 5. This figure summarizes the principal welfare issues reported in the selected studies, including thermal stress, abnormal or aggressive behavior (e.g., tail biting), health disorders (such as lameness), and physical condition. The frequency of each category reflects its relative importance in the scientific literature, with thermal stress and behavioral problems being the most reported factors affecting pig welfare.

3.6 Critical discussion of technological applications in pig welfare.

The reviewed studies highlight that technological innovation in pig production is not limited to monitoring systems but also includes interventions that directly modify animal behavior, environmental conditions, and management practices [7-9]. This broader technological spectrum reflects a transition from passive observation to active welfare management. One of the most significant advances is the use of sensor-based systems, particularly accelerometers and wireless sensor networks, which enable continuous and real-time monitoring of animal activity, physiological responses, and behavioral patterns [10-12]. These systems provide valuable data for early detection of health issues, such as lameness or disease, reducing reliance on subjective human observation.

However, their effectiveness depends on data integration and interpretation, which remain challenges in commercial production systems.

Similarly, imaging technologies, including 2D and 3D vision systems and thermal cameras, have demonstrated high potential for non-invasive welfare assessment [9, 13, 14]. These tools enable detection of changes in body condition, temperature, and behavior without direct animal handling, thereby minimizing stress. The integration of artificial intelligence and machine learning further enhances their capacity for automated behavior recognition [15-18]. Nevertheless, limitations related to cost, computational requirements, and environmental variability still restrict their widespread adoption. Environmental control technologies, such as adiabatic cooling systems, play a crucial role in mitigating thermal stress, one of the most critical welfare challenges identified [19-21]. These systems have shown positive effects on animal comfort and productivity, emphasizing the importance of environmental management as a key component of welfare strategies.

In contrast, emerging technologies such as pheromone-based systems and behavioral conditioning tools (e.g., pig toilets) represent innovative approaches that aim to directly influence animal behavior [22]. These technologies demonstrate promising results in reducing aggression, improving hygiene, and enhancing welfare conditions. However, their implementation remains limited and requires further validation under commercial conditions. Additionally, technologies related to slaughter and euthanasia, including CO₂ stunning and nitrogen foam systems, raise important ethical and welfare considerations [23-25]. While these methods aim to minimize suffering, their effectiveness and acceptability remain debated, underscoring the need for ongoing research and refinement. Overall, the integration of these technologies supports the development of precision livestock farming systems, enabling data-driven decision-making and improved welfare outcomes.

However, key challenges remain, including high implementation costs, lack of standardization, and limited accessibility for small-scale producers. Future research should focus on developing cost-effective, scalable, and user-friendly technologies adaptable to diverse production contexts.

3.7 Future challenges and research trends in pig welfare assessment

The rapid development of technological systems for assessing pig welfare has created new opportunities to improve health, behavior, and productivity in pig production systems. However, several challenges remain that must be addressed to ensure these technologies effectively improve pig welfare under real production conditions. A major challenge is integrating welfare-relevant data, particularly those related to pig behavior, thermal comfort, and health status. While current systems can monitor variables such as movement, temperature, and activity patterns, there remains a need to link these measurements to validated welfare indicators, including stress responses, social interactions, and behavioral expressions in pigs. This highlights the importance of developing species-specific welfare assessment models.

Another key limitation is the adaptation of technologies to pig production environments. Pig housing systems vary widely in density, flooring type, ventilation, and management practices. Technologies must therefore be robust enough to function accurately under these conditions, especially in detecting welfare problems such as tail biting, lameness, and heat stress. The use of artificial intelligence in pig welfare monitoring is an emerging trend with high potential. Machine learning algorithms can improve the detection of abnormal behaviors, such as aggression or reduced activity, which are often early indicators of compromised welfare. However, the development of reliable models requires large datasets specifically generated from pig populations, which are still limited.

In addition, future research should focus on developing integrated welfare indicators for pigs that combine behavioral, physiological, and environmental data. Current approaches often evaluate these parameters separately, potentially underestimating the complexity of pig welfare.

Economic and practical constraints also remain significant. The implementation of advanced technologies must be feasible for producers, ensuring that improvements in pig welfare are compatible with production efficiency and profitability. Finally, emerging trends such as low-cost sensor systems, Internet of Things (IoT) technologies, and real-time monitoring platforms have the potential to enhance pig welfare by enabling continuous and precise assessment of environmental conditions and animal responses. These innovations may facilitate more proactive management strategies, ultimately improving both animal welfare and production sustainability.

4. Conclusions

This study provides a comprehensive overview of technological systems used to assess animal welfare in pig production, highlighting the growing importance of precision livestock farming in modern animal agriculture. The results demonstrate a clear increase in scientific interest over the analyzed period, reflecting the global need to improve pig welfare while maintaining productivity and sustainability. The findings indicate that the most relevant welfare challenges in pigs—such as thermal stress, abnormal behavior, lameness, and health disorders—are increasingly being addressed through advanced technological solutions. Among these, imaging systems, wireless sensor networks, accelerometers, and environmental control technologies have shown significant potential to enable continuous, non-invasive, real-time monitoring of welfare indicators.

Beyond monitoring, the reviewed technologies contribute to a shift toward proactive welfare management by enabling early detection of behavioral and physiological changes in pigs.

This represents a substantial improvement over traditional assessment methods, which are often limited by subjectivity and low temporal resolution.

However, the study also identifies important limitations. The adoption of these technologies is still constrained by high implementation costs, lack of standardization, and limited accessibility in diverse production contexts. Additionally, there remains a gap between technological measurements and the interpretation of these data in terms of validated pig welfare indicators. Future developments should focus on integrating multiple data sources, improving the accuracy of pig-specific welfare assessment models, and promoting scalable, cost-effective solutions. In this context, the incorporation of artificial intelligence and real-time monitoring platforms offers promising opportunities to enhance both animal welfare and production efficiency.

In conclusion, technological systems are a key tool for advancing pig welfare, but their successful implementation will depend on their practicality, accessibility, and alignment with pigs' biological and behavioral needs.

Acknowledgments

This work was supported by UNAM Posdoctoral Program (POSDOC)

Conflict of Interest

There are no conflicts of interest.

References

1. Reimert, I., et al., *Towards an integrated concept of animal welfare*. *Animal*, 2023. **17**: p. 100838.
2. Petrini, A. and D. Wilson, *Philosophy, policy and procedures of the World Organisation for Animal Health for the development of standards in animal welfare*. *Revue Scientifique Et Technique-Office International Des Epizooties*, 2005. **24**(2): p. 665.
3. Maes, D.G., et al., *A critical reflection on intensive pork production with an emphasis on animal health and welfare*. *Journal of animal science*, 2020. **98**(Supplement 1): p. S15-S26.
4. Gómez, Y., et al., *A systematic review on validated precision livestock farming technologies for pig production and its potential to assess animal welfare*. *Frontiers in veterinary science*, 2021. **8**: p. 660565.
5. Benjamin, M. and S. Yik, *Precision livestock farming in swine welfare: a review for swine practitioners*. *Animals*, 2019. **9**(4): p. 133.

6. Mantsiou, C., et al., *A simple guide to systematic reviews and meta-analyses*. The international journal of lower extremity wounds, 2025. **24**(4): p. 894-899.
7. Marić, K., et al., *Smart pig farms: Integration and application of digital technologies in pig production*. Agriculture, 2025. **15**(9): p. 937.
8. Trabachini, A., et al., *Precision Livestock Farming Applied to Swine Farms—A Systematic Literature Review*. Animals, 2025. **15**(14): p. 2138.
9. Ferreira, M.F., M. Nunes, and M. Vieira-Pinto, *Non-Invasive Human-Free Diagnosis Methods for Assessing Pig Welfare at Abattoirs: A Systematic Review*. Animals, 2025. **15**(17): p. 2500.
10. Huang, Y., et al., *Behavior Classification and Rhythm Analysis of Pigs Based on Wearable Sensors*. Smart Agricultural Technology, 2025: p. 101457.
11. Reza, M.N., et al., *A review of sound-based pig monitoring for enhanced precision production*. Journal of Animal Science and Technology, 2025. **67**(2): p. 277.
12. Ding, L., et al., *Wearable sensors-based intelligent sensing and application of animal behaviors: A comprehensive review*. Sensors, 2025. **25**(14): p. 4515.
13. Vargas González, P., *Pobreza, migración y desempleo: mujeres en la región Otomi-Tepehua de Hidalgo*. Nueva antropología, 2011. **24**(75): p. 93-109.
14. Ndams, V., *Thermal Imaging Technology for Rapid In-vivo Evaluation of Carcass Composition in Growing-finishing Pigs*. 2025, University of Manitoba.
15. Lei, K., et al., *Research on video behavior detection and analysis model for sow estrus cycle based on deep learning*. Agriculture, 2025. **15**(9): p. 975.
16. Sukkuea, A. and P. Akkajit, *Improved Detection and Classification of Precise Behaviors in Group-Housed Pigs using Deep Learning Models*. Engineered Science, 2025. **37**: p. 1808.
17. Alameer, A., et al., *Automatic recognition of feeding and foraging behaviour in pigs using deep learning*. Biosystems engineering, 2020. **197**: p. 91-104.
18. Bharadwaj, S.M., *AI-ML Powered Pig Behavior Classification and Body Weight Prediction*. 2024, Virginia Tech.
19. Godyń, D., et al., *Use of different cooling methods in pig facilities to alleviate the effects of heat stress—a review*. Animals, 2020. **10**(9): p. 1459.
20. Mun, J.Y., A. Hosseindoust, and J. Kim, *Strategies and Advances in Mitigating Heat Stress for Lactating Sows Productivity*. Animal Industry and Technology, 2026.
21. Katiyar, R., et al., *Effect of heat stress on pig production and its mitigation strategies: a review*. Tropical animal health and production, 2025. **57**(3): p. 139.
22. Sankarganesh, D., et al., *Pig pheromones and behaviors: a review*. Theriogenology, 2021. **175**: p. 1-6.
23. Mace, J.L. and A. Knight, *Pig welfare and ethical considerations during abattoir stunning: CO₂ vs. alternative methods such as argon gas*. Frontiers in veterinary science, 2025. **12**: p. 1542798.
24. Health, E.P.o.A., et al., *The use of high expansion foam for stunning and killing pigs and poultry*. EFSA journal, 2024. **22**(7): p. e8855.
25. Sindhøj, E., C. Lindahl, and L. Bark, *Potential alternatives to high-concentration carbon dioxide stunning of pigs at slaughter*. Animal, 2021. **15**(3): p. 100164.