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Scientific literature on AI technologies to enhance animal welfare, health and productivity

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This study investigates the transformative role of Artificial Intelligence (AI) technologies in the agricultural sector, specifically focusing on their applications in enhancing animal welfare, health monitoring, and productivity. Over the last decade, advancements in AI, including machine learning, Internet of Things (IoT) systems, computer vision, and sensor technologies, have significantly enhanced livestock management across various species, including poultry, pigs, dairy cows, sheep and rodents. The study synthesizes findings from literature published between 2010 and 2022, highlighting how AI solutions facilitate comprehensive environmental monitoring, enable early disease detection, and support behavioral analysis, thereby optimizing production metrics and promoting better animal welfare practices. By employing the Technology Readiness Levels (TRL) framework, the review categorizes these technologies according to their developmental stages, from prototype to operational use, underscoring their increasing integration into commercial farming.

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Furthermore, the paper discusses the broader implications of AI adoption, including economic benefits, compliance with welfare standards, and sustainability objectives. The insights presented emphasize the need for continued research and innovation to fully harness AI's potential in advancing animal management strategies and addressing the growing global demand for animal products. Overall, the findings confirm that AI technologies have demonstrated effectiveness in improving animal welfare, health monitoring, and productivity across diverse species and farming contexts.

KEY WORDS: artificial intelligence (AI) / animal welfare / livestock management / sustainable agriculture / health monitoring

The agricultural sector has experienced a significant transformation with the integration of Artificial Intelligence (AI) technologies into animal husbandry. Innovations such as Machine Learning, Internet of Things systems (IoT), Computer Vision, and AI-powered sensors are revolutionizing livestock management by addressing critical challenges like early disease detection, behavioral monitoring, and environmental management. These advancements are essential for balancing productivity with animal welfare standards [Marchewka *et al*. 2020, Bao and Xie 2022, Nowaczewski *et al.* 2023].

The global demand for animal products has been rising steadily. According to the FAO, the world's meat production is projected to increase by approximately 15% by 2030, with most growth occurring in low- and middle-income countries [FAO 2023]. Additionally, Eurostat data indicates that the EU alone produces over 13 million tonnes of poultry and around 23 million tonnes of pig meat annually, reflecting a high demand for efficient and sustainable production methods to meet consumer needs [Eurostat 2024]. However, this demand places considerable pressure on livestock systems, which must balance productivity with welfare to avoid compromising animal health [Sztandarski *et al*. 2021, Marchewka *et al*. 2023]. In response, the European Union has set high standards for animal welfare, urging member states to adopt advanced management practices that protect animals and ensure sustainable production [Serlikowska 2024].

AI-driven technologies offer essential tools to help farmers and producers meet these high standards. Machine Learning algorithms, for instance, have been applied to analyze large datasets of animal health parameters, enabling early disease detection and timely intervention before illness escalates [Berckmans 2014, Sadeghi *et al.* 2023]. This capability is crucial for preventing outbreaks in high-density livestock environments such as poultry farms, where diseases can spread rapidly and lead to substantial economic losses [Milosevic *et al.* 2019]. AI systems not only help identify health issues early but also provide accurate risk predictions, allowing for proactive management aligned with EU welfare policies.

AI is also increasingly used for environmental management in livestock systems, helping maintain optimal conditions for animal welfare. IoT-based solutions, comprising interconnected sensors and devices, enable real-time monitoring of environmental factors like temperature, humidity, and air quality. This continuous tracking ensures that animals remain in conditions conducive to their well-being, reducing stress and improving productivity [Lee *et al.* 2019]. Such technologies are particularly valuable in the EU, where strict environmental standards are enforced. For example, IoT systems have been successfully used in dairy farms to adjust ventilation and cooling, aligning with sustainability goals set forth by the European Green Deal to reduce emissions while enhancing agricultural productivity [Gehlot *et al.* 2022].

Behavioral monitoring, traditionally reliant on human observation, has also seen substantial advancements through AI. The development of Computer Vision systems allows for automated tracking of behaviors such as aggression, feeding, and movement patterns in real time [Lee *et al.* 2019, Dawkins 2021]. These systems can detect abnormal behaviors that may signal health or welfare issues, prompting quicker interventions and reducing risks of injury. Such technologies have significant implications for maintaining compliance with the EU's animal welfare policies, which emphasize the need for humane treatment and proactive welfare measures.

AI's benefits extend beyond individual animal monitoring to improving overall productivity. Models powered by Machine Learning have shown promise in optimizing feed conversion ratios, enhancing growth rates, and reducing resource consumption in species such as pigs, poultry, and dairy cows [Wang *et al.* 2022]. These productivity improvements are crucial as livestock systems face growing pressure to meet global demand efficiently, while minimizing environmental impact. Studies indicate that integrating AI in livestock management not only supports animal welfare but also contributes to more efficient and sustainable production systems, helping to align with FAO's recommendations for sustainable livestock production [Change 2016].

Despite these promising developments, AI technology applications in animal management are still at various stages of maturity. The Technology Readiness Level (TRL) framework is commonly used to assess the operational readiness of these technologies, which range from prototype stages to full commercial deployment [Kopler *et al.* 2023]. Some AI applications, such as IoT-based environmental monitoring, are already widely implemented in dairy and poultry farms, whereas more advanced models, like deep learning for complex behavioral analysis, are still in experimental phases [Cruz *et al.* 2024].

This study aimed to assess the effectiveness of AI technologies in enhancing animal welfare, health, and productivity across different species and contexts. By examining a wide range of AI applications, this research sought to understand how these technologies are integrated into livestock management and to what extent they improve outcomes for both animals and producers. The hypothesis was that AI technologies provide superior real-time monitoring and predictive capabilities, leading to better management of animal health, behavior, and environmental conditions, and ultimately, to significant improvements in animal welfare and productivity.

Material and methods

Study selection and data collection

This review was conducted following a structured approach to ensure comprehensive and unbiased selection of studies on AI applications in animal management. We searched multiple academic databases, including PubMed, Web of Science, and Scopus, using a predefined list of keyword strings to capture relevant studies. The search focused on literature published between January 2010 and December 2022 to cover recent advancements in AI technologies applied to animal welfare, health, and productivity.

Keyword strings used

The keywords related to AI technologies and animal welfare were used in various combinations and modified with additional terms like "livestock," "agriculture," "smart farming," and specific species names (e.g., "poultry," "dairy cows," "sheep") to refine the search further. To capture a broad range of studies, the following examples of keyword combinations were employed: AI in animal welfare, Machine Learning in livestock, IoT for animal health monitoring, Computer Vision for poultry welfare, Sensor-based monitoring in dairy farming, Deep Learning in pig health management, AI-based environmental monitoring in animal production, Animal behavior monitoring using AI, Automated health assessment in livestock, etc.

Inclusion and exclusion criteria

Studies were selected based on their relevance to the application of AI technologies in animal management. Included studies were those that directly applied AI methods - such as Machine Learning, Internet of Things, Computer Vision, and sensor-based systems - to monitor, assess, or enhance animal welfare, health, or productivity. Research involving agricultural species, including poultry, pigs, dairy cows, rodents, and sheep, was considered. In contrast, studies were excluded if they focused solely on theoretical AI models without practical application to animal welfare, were limited to human or non-agricultural subjects, lacked quantitative data, or fell outside the designated time frame of 2010 to 2022.

Data extraction and categorization

Following study selection, data were systematically extracted and organized, focusing on key parameters such as AI technology type: categorized into Machine Learning, IoT-Based, Computer Vision, Sensor-Based, and other emerging technologies. These categories were defined as follows:

The Internet of Things refers to a network of interconnected devices embedded with sensors and software, enabling autonomous data collection and exchange over the internet. IoT systems facilitate continuous environmental monitoring and real-time analytics in industries like agriculture, manufacturing, and urban planning. For example, in precision farming, IoT devices optimize irrigation and fertilization by tracking soil conditions, enhancing efficiency and sustainability [Ashton 2009, Gubbi *et al.* 2013, Dutton 2014].

Artificial Intelligence encompasses computational systems capable of tasks requiring human-like intelligence, including reasoning, learning, and decision-making. Techniques such as machine learning, robotics, and natural language processing allow AI to process vast datasets, uncover patterns, and automate processes. Applications span diverse fields, such as disease diagnosis in healthcare and fraud detection in finance, with modern advancements like deep learning further enabling complex tasks such as autonomous driving and image recognition [Mitchell 1997, Goodfellow *et al.* 2016, Russell and Norvig 2020].

Computer Vision, a subset of AI, focuses on interpreting and analyzing visual data to identify objects, track movement, and understand visual contexts. This technology supports a range of applications, including medical imaging, autonomous navigation, and surveillance, enhancing precision and efficiency. For instance, computer vision systems detect abnormalities in medical scans, aiding early diagnosis and treatment [Russakovsky *et al*. 2015, Gonzalez and Woods 2018, Szeliski 2022].

Machine Learning, a critical branch of AI, enables systems to learn from data without explicit programming, identifying patterns to make predictions or decisions. Its applications include recommendation systems, predictive analytics, and anomaly detection, with supervised, unsupervised, and reinforcement learning serving distinct purposes. ML has revolutionized industries like e-commerce and robotics by enabling adaptive and intelligent solutions [Mitchell 1997, Bishop 2006, Goodfellow *et al*. 2016].

Behavioral Analysis employs AI to study activity data, recognize patterns, and predict actions, blending data science with AI techniques. It is widely applied in security, healthcare, and marketing to assess risks, detect threats, or personalize services. For example, AI-powered behavioral analysis identifies anomalies in cybersecurity or provides targeted marketing recommendations based on customer interactions [Salganik 2019, Rohan *et al*. 2024].

AI-Based Sensors combine real-time data collection with intelligent analytics to detect anomalies, trigger alerts, or optimize operations. These sensors play crucial roles in predictive maintenance, environmental monitoring, and wearable technology, offering solutions in areas such as industrial automation and pollution control [Mclennan and Mahmoud 2019, Bainomugisha *et al.* 2024, Zhang *et al.* 2024].

Finally, Technology Readiness Level provides a systematic metric to evaluate technology maturity, from basic principles (TRL 1) to operational deployment (TRL 9). Originating from NASA, the TRL framework is widely used in agriculture to assess the deployment potential of innovative technologies in real-world environments [Mankins 1995].

Data analysis and descriptive statistics

Descriptive statistics were calculated for each parameter, including counts and percentages for AI technology types, welfare indicators, species, and TRL levels. Graphical representations such as bar charts and heat maps were created to illustrate distribution patterns, highlight research trends, and identify gaps in AI applications across various aspects of animal management.

Results and discussion

The collected literature (n=78) (Fig. 1) provides a comprehensive analysis of AI technologies and applications in animal management. Machine Learning and IoT-based systems dominate the studies, with significant contributions from Computer Vision, Deep Learning, and Sensor-Based technologies. These tools are applied across diverse species for monitoring animal health, behavior, and environmental conditions, targeting key areas such as behavioral and health monitoring, environmental management, and productivity enhancement (Tab. 1). The studies primarily focus on poultry and dairy cows, reflecting their prominence in agricultural production systems, while pigs, rodents, and sheep are also represented, highlighting the growing adoption of AI across varied contexts. AI applications are distributed across Technology Readiness Levels, ranging from 6 (Prototype Demonstration) to 9 (Operational Use). Most studies are concentrated at TRL 7 (System Prototype) and TRL 8 (System Complete), suggesting a transition from development to deployment, with operational systems predominantly observed in poultry and dairy cows.

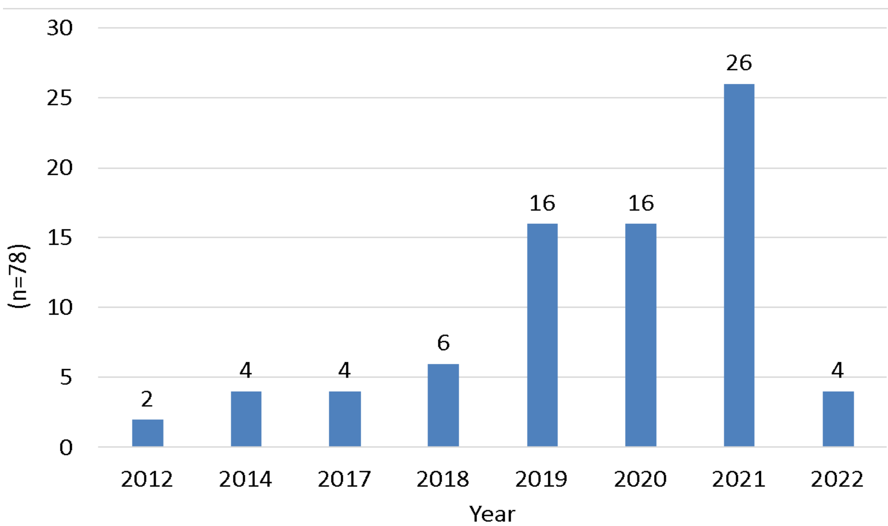

Fig. 1. Temporal trends in AI research studies on animal welfare and productivity.

Table 1. Overview of AI technologies and their applications across animal species in investigated studies

Aspect	Type	Articles (n=78)
AI technology	Computer Vision	13
	Deep Learning	4
	IoT-Based	12
	Machine Learning	27
	Other	8
	Sensor-Based	14
Animal species	Broilers	4
	Dairy Cows	16
	Pigs	12
	Poultry	23
	Rodents	15
	Sheep	8
TRL	6 (Prototype Demonstration)	12
	7 (System Prototype)	27
	8 (System Complete)	23
	9 (Operational Use)	16
Measurement category	Behavioral Monitoring	22
	Disease Detection & Management	22
	Environmental Monitoring	14
	Health Monitoring	12
	Other	2
	Productivity Monitoring	2
	Stress Detection & Management	4

Environmental monitoring and management

IoT and AI technologies have demonstrated significant potential in optimizing environmental conditions across various animal species, addressing critical factors that influence health, welfare, and productivity. These technologies utilize interconnected sensors and advanced algorithms to monitor and adjust environmental variables in real-time, ensuring optimal living conditions. For example, Gehlot *et al*. [2022], highlighted the application of IoT-based systems in dairy farming, where sensors continuously tracked temperature and humidity level. The collected data were analyzed using AI algorithms, enabling dynamic adjustments to cooling and ventilation systems to maintain stable and favorable conditions for dairy cows. This approach not only improved animal comfort but also reduced heat stress, contributing to enhanced milk production and welfare outcomes. Similarly, Cruz *et al*. [2024], demonstrated the integration of IoT and AI in poultry farming, focusing on temperature and air quality management. These systems employed real-time environmental monitoring to detect deviations from optimal conditions and automatically adjusted ventilation, heating, or cooling mechanisms. By maintaining stable temperature and air quality parameters, the systems significantly improved the welfare of poultry, reducing stress and promoting healthier growth environments.

Health monitoring and disease detection

The transformative impact of AI on early disease detection and health monitoring is evident across multiple studies, showcasing its ability to enhance animal welfare and productivity through timely interventions. Sadeghi *et al*. [2023] demonstrated the effectiveness of AI in poultry farming by enabling early detection of diseases, which minimized the spread of illness and reduced economic losses. The integration of AI-based monitoring systems allowed for rapid identification of abnormal behavioral or physiological patterns, facilitating earlier interventions that significantly improved animal health outcomes. In dairy cows, AI systems have been pivotal in predicting stress and disease, as highlighted by Guo *et al*. [2021]. These systems utilized advanced algorithms to analyze behavioral and physiological data, providing critical insights into the onset of health issues. Such predictive capabilities enabled farmers to implement targeted management practices, thereby enhancing both welfare and productivity. For sheep, AI has made strides in non-invasive pain detection. McLennan *et al*. [2019] used AI-driven facial expression analysis to identify signs of discomfort, marking a significant advancement in animal welfare monitoring by eliminating the need for physical interaction. Herlin *et al*. [2021] further expanded on this approach by employing wearable sensors to detect early indicators of illness in sheep, enabling prompt interventions and mitigating the escalation of symptoms. AI has also shown efficacy in addressing species-specific health challenges. Fang *et al*. [2024] applied AI tools to detect lameness and feather-pecking in broilers, issues that critically affect welfare and productivity. By analyzing movement patterns and behavioral cues, these systems provided precise and timely detection, improving management practices. Similarly, Wang *et al*. [2022] demonstrated the role of AI in optimizing feed conversion ratios for pigs, where models analyzed feeding behaviors and nutritional requirements to improve overall health and efficiency.

Behavioral monitoring and welfare assessments

Behavioral monitoring is a critical area where AI has made transformative contributions to animal welfare and productivity. The application of AI in detecting aggression in pigs, as demonstrated by Lee *et al*. [2019], allows for early interventions to prevent injuries and maintain group harmony. By analyzing real-time behavioral data, AI systems provide actionable insights that surpass traditional observation methods, enabling more precise and timely management decisions. Similarly, Berckmans [2014] employed AI to identify abnormal behaviors in pigs, particularly those indicative of early-stage diseases. This capability significantly enhances preventive health measures, reducing the spread of illness and improving the overall management of livestock health. AI's role in behavioral monitoring extends to neonatal livestock care. Baig *et al*. [2024] highlighted how a combined IoT and Li-Fi system allowed for continuous monitoring of calf behaviors, such as movement and sound detection, to assess health and identify distress signals. This innovative approach demonstrated the potential for real-time insights that reduce mortality rates and enhance welfare outcomes in newborn livestock.

One of the key advancements AI offers is the reduction of human bias in behavioral assessments. Liu *et al.* [2020] demonstrated how AI systems effectively evaluated rodent behaviors, providing consistent, objective data that eliminated the subjectivity inherent in human observations. This consistency is particularly valuable in research and laboratory settings, where accurate behavioral analysis is essential. Chiavacci *et al*. [2014] expanded on this by applying AI to detect signs of pain in laboratory animals, a crucial step in improving welfare standards in experimental environments. The ability to identify distress with precision and at an early stage enabled researchers to intervene promptly, ensuring better care and compliance with ethical standards. AI has also demonstrated its capacity to impact productivity while maintaining welfare standards. Wang *et al*. [2022] highlighted the role of AI in optimizing feed conversion ratio in pigs, where advanced models analyzed feeding behavior and nutritional needs to improve resource utilization and growth outcomes. In broilers, AI systems have further showcased their dual benefits of health monitoring and productivity optimization. Milosevic *et al*. [2019] applied deep learning models to monitor health conditions while simultaneously tracking and enhancing production metrics, demonstrating AI's potential to align welfare improvements with economic efficiency.

TRL levels of the AI technologies across animal species-specific studies

Figure 2 illustrates the distribution of Technology Readiness Levels across various species, highlighting the percentage of studies at each level, ranging from TRL 6 (Prototype Demonstration) to TRL 9 (Operational Use). The species studied include broilers, dairy cows, pigs, poultry, rodents, and sheep, reflecting the progressive development and application of AI technologies in livestock management.

At TRL 6 (Prototype Demonstration), the majority of studies focus on rodents, emphasizing early-stage development and testing in controlled environments. These studies assess the feasibility and initial performance of technologies without widespread application. For instance, Berckmans [2014] utilized computer vision and machine learning to monitor behaviors in pigs, marking a foundational step in early disease detection. Similarly, Lee *et al*. [2019] tested AI prototypes for detecting aggressive behaviors in pigs, showcasing the potential of AI systems to address specific welfare issues during this experimental phase.

At TRL 7 (System Prototype), research expands across multiple species, with pigs being most represented. This stage involves testing near-operational systems to evaluate performance in more realistic settings. Dawkins [2021] applied AI-based behavioral monitoring systems in poultry farms, enabling the tracking of behavioral patterns under production-like conditions. Guo *et al*. [2021] similarly developed AI-based stress and disease detection systems for dairy cows, combining sensor data with AI algorithms to improve health management in semi-operational environments. Broilers also feature prominently, as seen in Fodor *et al*. [2023], where prototype AI systems were designed to monitor productivity metrics, reflecting the growing diversity in applications at this readiness level.

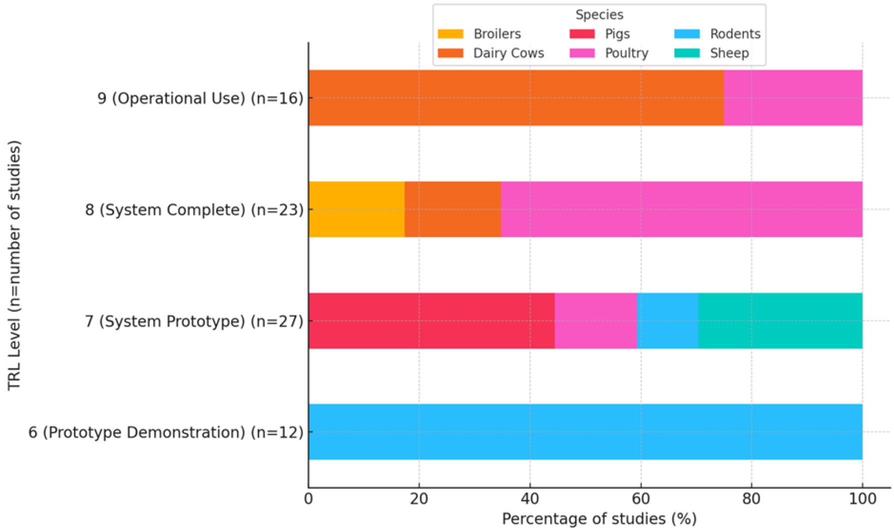

Fig. 2. Distribution of technology readiness levels (TRL) across animal species in investigated studies.

At TRL 8 (System Complete), a significant number of studies center on poultry, where AI technologies have achieved full functionality and readiness for deployment in commercial settings. Sadeghi *et al*. [2023] demonstrated early disease detection systems for poultry that operate effectively in production environments, ensuring practical application and reliable outcomes. Cruz *et al*. [2024] further exemplified this level by implementing AI-based monitoring systems for health and growth in poultry, achieving substantial improvements in welfare and productivity. Though fewer in number, broilers and dairy cows are also represented at this level, indicating ongoing advancements in their respective domains.

At TRL 9 (Operational Use), the integration of AI technologies into commercial farming operations is most evident in poultry and dairy cows. These studies showcase systems that are not only fully functional but also widely deployed to optimize productivity and welfare. For example, Gehlot *et al*. [2022] utilized IoT and AI technologies to adjust environmental parameters like temperature and humidity in dairy farms, ensuring optimal conditions for animal welfare. Guo *et al.* [2021] similarly employed AI-based sensors in operational dairy farms, enabling real-time management of stress and disease, which improved herd health outcomes. In poultry and pigs, Kopler *et al*. [2023] applied AI systems to monitor both welfare and productivity metrics in commercial farms, underscoring the widespread adoption and operational success of these technologies at this advanced readiness level.

AI technologies across animal species-specific studies

Figure 3 illustrates the distribution of AI technologies applied across different species, represented as a percentage of studies. These technologies include Computer Vision, Deep Learning, IoT-Based systems, Machine Learning, Sensor-Based systems,

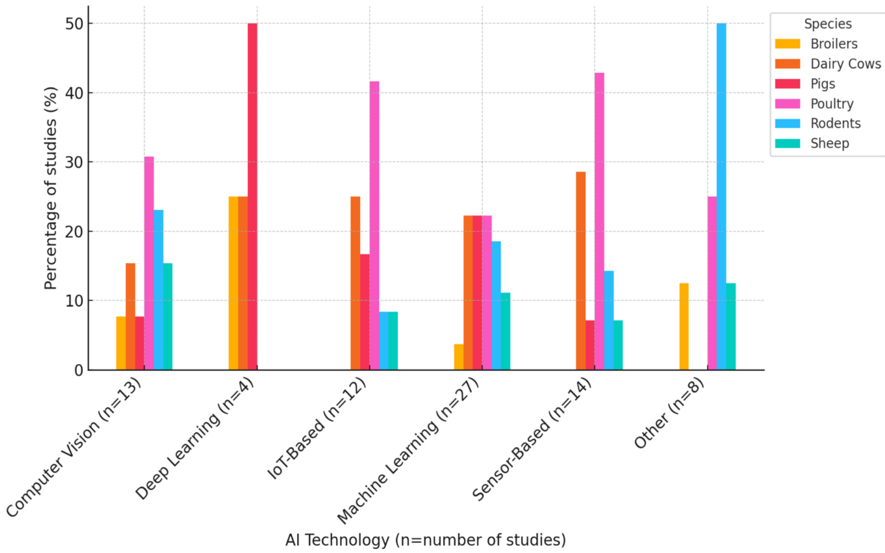

Fig. 3. Application of AI technologies across animal species in investigated studies.

and other emerging tools, with applications spanning dairy cows, pigs, poultry, rodents, and sheep. The prevalence of these technologies highlights the growing role of AI in addressing species-specific challenges in animal welfare and productivity. The distribution of these technologies reflects their tailored applications to species-specific welfare and productivity challenges, as further illustrated in Figure 4.

Machine Learning is the most widely represented technology, particularly in studies involving pigs and poultry. Sadeghi *et al.* [2023] utilized ML for early disease detection in poultry, enabling timely interventions to prevent the spread of infections in large flocks. Similarly, Guo *et al*. [2021] applied ML to monitor stress and disease in dairy cows, showcasing its adaptability to various species for comprehensive health management. In pigs, Berckmans [2014] combined ML with Computer Vision to identify abnormal behaviors, enhancing early interventions for welfare concerns. Sharma *et al.* [2022] extended ML's applications to rodents, exploring its potential for behavioral and health monitoring in laboratory settings, underscoring its versatility across species and environments.

IoT-Based technologies are highly represented across studies involving pigs, poultry, and dairy cows, reflecting their utility in real-time monitoring and management.

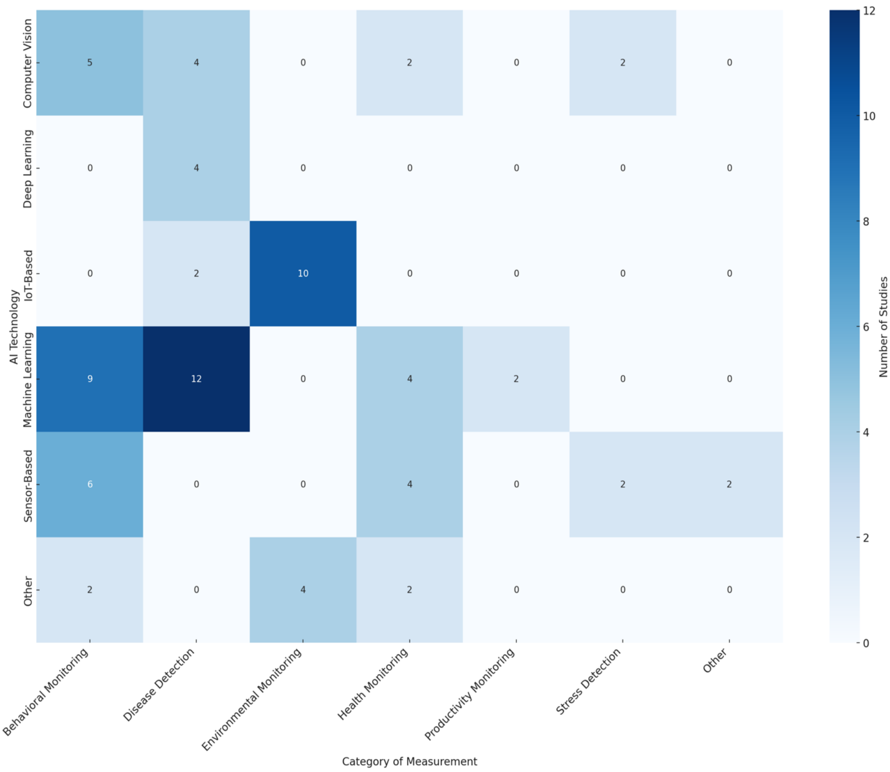

Fig. 4. AI technologies addressing species-specific welfare and productivity challenges.

Gehlot *et al.* [2022] implemented IoT systems to maintain optimal environmental conditions in dairy cow facilities, focusing on parameters like temperature and humidity to improve welfare. Similarly, Fodor *et al*. [2023] utilized IoT systems in poultry farms to regulate environmental factors such as air quality and lighting, demonstrating its impact on productivity and health. Lee *et al.* [2019] applied IoT-based monitoring in pigs to detect aggressive behaviors, enabling proactive welfare interventions. These examples highlight IoT's growing presence in commercial settings, providing continuous data to optimize both production and animal care.

Sensor-Based technologies play a prominent role, particularly in studies on rodents, poultry, and dairy cows. Guo *et al*. [2021] employed AI-enhanced sensors to track physiological stress in dairy cows, offering real-time data to support effective health management. Herlin *et al*. [2021] demonstrated the use of wearable sensors in sheep to monitor health and productivity, showcasing the potential of sensor networks in species that are less commonly studied. In rodents, Sanchez *et al*. [2016] employed sensor systems for laboratory monitoring, emphasizing the broad applicability of this technology in controlled environments to track behaviors and welfare metrics.

Computer Vision is widely applied across poultry, rodents, and dairy cows, with its highest concentration in poultry studies. Dawkins [2021] employed Computer Vision to monitor behavioral changes in poultry, providing insights into welfare conditions in large-scale production settings. Fang *et al*. [2024] used this technology to assess health and behavior in broilers, demonstrating its effectiveness in real-time welfare assessments. Guo *et al.* [2021] combined Computer Vision with ML to detect stress and disease in dairy cows, illustrating the adaptability of this technology for species-specific monitoring and health interventions.

Deep Learning appears less frequently but has notable applications in poultry and rodents. Milosevic *et al.* [2019] combined deep learning and Computer Vision to monitor welfare and productivity in poultry farms, showcasing the growing integration of advanced AI algorithms in commercial environments. While its adoption is limited compared to other AI technologies, deep learning demonstrates significant potential for complex data analysis and decision-making.

The studies analyzed in this dataset reveal a diverse and rapidly advancing field of AI applications in animal management, encompassing environmental monitoring, health management, behavioral tracking, and productivity optimization. The breadth of literature provides valuable insights into the current state of technology development and operational readiness, categorized effectively using the Technology Readiness Level framework. This approach highlights the varying stages of AI tools, from experimental prototypes to fully operational systems, enabling a clear understanding of their maturity and real-world applicability across species. Furthermore, AI tools have demonstrated their capacity to optimize productivity by improving feeding strategies, minimizing resource consumption, and promoting better growth outcomes. Their adaptability to high-density farming environments, particularly in poultry and dairy production, highlights their scalability and economic feasibility. The distribution of these technologies across various Technology Readiness Levels reflects their progressive maturation, with many applications, such as IoT-based environmental monitoring and Machine Learning for disease prediction, achieving high operational viability in commercial settings. This progression underscores the growing integration of AI into routine agricultural operations, positioning it as an indispensable component of modern livestock management.

The categorization of AI applications by TRL underscores their developmental trajectory. Lower TRL levels (e.g., TRL 6 and 7) indicate prototype systems tested in controlled environments, such as Computer Vision for detecting facial expressions in sheep [McLennan *et al*. 2019] and sensor-based systems monitoring stress in rodents [Herlin *et al.* 2021]. These studies demonstrate the potential for AI to address species-specific welfare challenges but also highlight the need for further refinement and validation. In contrast, higher TRL levels (TRL 8 and 9) reflect systems that have transitioned to widespread operational use. For example, Machine Learning has been extensively applied in poultry farming, where Sadeghi *et al*. [2023] demonstrated its efficacy in early disease detection, helping prevent outbreaks in densely populated environments. Similarly, IoT-based systems, as implemented by Gehlot *et al*. [2022], provide real-time environmental monitoring for dairy cows, enabling dynamic adjustments to temperature and humidity. These high-TRL applications illustrate the scalability and adaptability of AI in commercial settings, where welfare and productivity enhancements are critical.

The temporal trends in research output, from 2012 to 2022, reveal a growing interest in AI applications for animal management. The sharp increase in publications between 2018 and 2021, peaking at 26 articles in 2021, suggests heightened attention to emerging technologies and global challenges such as sustainability and food security [Bao and Xie 2022]. This surge may also reflect advancements in computational power, sensor technology, and collaborative efforts across disciplines. However, the decline to four articles in 2022 could indicate a cyclical consolidation phase or disruptions from external factors like the COVID-19 pandemic [Kim *et al*. 2020, Fang *et al.* 2024]. These trends underscore the evolving landscape of AI research, where periods of rapid growth are often followed by strategic reflection and technological maturation.

Machine Learning and IoT-based systems emerged as the most frequently utilized technologies, reflecting their versatility and scalability across species. Machine Learning has shown remarkable adaptability in health management, as evidenced by Guo *et al*. [2021], where it was used to predict stress and disease in dairy cows. Similarly, IoT-based systems have been extensively deployed for environmental monitoring, optimizing parameters like temperature and air quality to enhance welfare [Gehlot *et al*. 2022]. These technologies have largely achieved TRL 8 or 9, signifying their operational readiness and widespread adoption in commercial farming. In contrast, Computer Vision and Sensor-Based technologies have been applied in more niche areas, such as pain detection in sheep [McLennan *et al*. 2019] and behavioral monitoring in laboratory rodents [Herlin *et al*. 2021]. These tools often remain at lower TRL levels, requiring further refinement and validation to address challenges such as behavioral interpretation and environmental variability. Despite their experimental nature, these technologies offer promising solutions for species-specific welfare issues, paving the way for innovative approaches to animal care.

The focus of AI applications varies significantly by species, with poultry, pigs, and dairy cows receiving the most attention. This distribution reflects the economic importance of these species and the scalability of AI solutions in high-density farming environments. For instance, Dawkins 2021 employed Computer Vision to monitor poultry behavior, providing actionable insights into welfare conditions in production settings. In pigs, Berckmans [2014] combined Machine Learning and Computer Vision to detect early-stage diseases, showcasing AI's role in proactive health management. Meanwhile, dairy cows benefited from IoT systems and AI-powered sensors for stress and environmental management, demonstrating the potential for comprehensive welfare solutions in this sector [Guo *et al.* 2021, Gehlot *et al*. 2022]. Less commonly studied species, such as sheep and rodents, primarily utilized sensor networks and Computer Vision for welfare monitoring. Examples include wearable sensors for productivity metrics in sheep [Herlin *et al*. 2021] and AI-based tools for monitoring rodent behavior in laboratory settings [Sanchez *et al.* 2016]. While these applications are at earlier developmental stages, they highlight an emerging interest in addressing the welfare needs of diverse species.

Environmental monitoring emerged as a critical focus, particularly with IoT systems enabling real-time adjustments to temperature, humidity, and air quality in livestock facilities. These applications align with regulatory frameworks, such as the EU's animal welfare standards, and address the growing demand for sustainable farming practices [Alexoaei *et al*. 2022]. Health monitoring was another primary objective, with Machine Learning excelling in disease prediction and stress management across species. However, behavioral monitoring remains challenging due to the complexities of interpreting animal behavior, especially with Computer Vision systems still in the prototype stages [Lee *et al.* 2019, Dawkins 2021].

This study's strength knowledge in its systematic categorization of AI applications, providing a clear understanding of their operational readiness and potential impact on animal management. The use of TRL as a framework adds practical relevance, enabling stakeholders to assess the maturity of different technologies. However, the study is limited by its focus on peer-reviewed literature, excluding commercially available AI tools that may not have undergone rigorous validation. Additionally, the emphasis on key species like poultry and dairy cows may overlook the specific challenges faced by less commonly studied animals.

Future research should prioritize advancing lower-TRL applications, particularly in species-specific welfare and behavioral monitoring. Addressing challenges such as economic feasibility, farmer adoption rates, and data privacy will be essential for scaling these technologies. The integration of AI with other emerging technologies, such as blockchain and renewable energy, could further enhance its impact on animal management.

Conclusions

The findings underscore the transformative potential of AI technologies in advancing animal management practices, offering significant improvements in welfare, health monitoring, and productivity across a wide range of species, including poultry, pigs, dairy cows, sheep and rodents. AI-based systems, such as IoT, Machine Learning, and sensor technologies, have proven their ability to monitor environmental conditions, detect diseases early, and track animal behaviors with unprecedented accuracy and efficiency. These technologies enable proactive management strategies by reducing the time required to identify and address health and welfare issues, ultimately minimizing risks and enhancing overall animal care. The results support the hypothesis that AI technologies provide superior real-time monitoring and predictive capabilities, enabling earlier interventions and more precise management.

By reducing the incidence of disease and stress, these technologies not only enhance animal welfare but also align with global sustainability goals by improving resource efficiency and reducing environmental impacts. However, challenges remain, particularly for technologies in lower TRL stages, such as species-specific behavioral monitoring using Computer Vision, which require further research and validation to achieve widespread adoption.

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