Review

Not peer-reviewed version

Agency in Livestock Farming - A Perspective on Human–Animal–Computer Interactions

Suresh Neethirajan *

Posted Date: 10 June 2025

doi: 10.20944/preprints202506.0694.v1

Keywords: precision livestock farming; animal agency; farm animal welfare; human–animal– computer interactions; AI in agriculture; animal-centered design; human-centric intelligent systems

Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a Creative Commons CC BY 4.0 license, which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Review

Agency in Livestock Farming—A Perspective on Human–Animal–Computer Interactions

Suresh Neethirajan [1,2]

[1] Faculty of Computer Science, 6050 University Avenue, Dalhousie University, Halifax, Canada

[2] Faculty of Agriculture, Agricultural Campus, PO Box 550, Dalhousie University, Truro, NS,Canada B2N 5E3

* Correspondence: sneethir@gmail.com

Abstract: The adoption of precision livestock farming (PLF) and advanced artificial intelligence enabled computing technologies is radically altering intensive animal agriculture, yet it also raises urgent questions about animals' autonomy. In this critical review, I examine animal agency—the capacity for animals to make informed choices and exert control over their surroundings—while scrutinizing how human–animal–computer interactions (HACI) in human-centric intelligent systems may either support or undermine this agency. By drawing on research from animal cognition and welfare science, alongside case studies involving automated milking, wearable sensors, and AI-driven monitoring, I highlight promising avenues for personalized care and the encouragement of natural behaviors. At the same time, I reveal the profound risks of over-surveillance, algorithmic control, and the erosion of empathetic stockmanship that can accompany increased automation. I argue that meaningful ethical design must take an animal-centered approach, ensuring technologies expand rather than confine behavioral repertoires. Interdisciplinary methods—integrating engineering, ethology, and ethics—are essential for fostering real empowerment. Equally critical is engaging stakeholders who represent diverse agricultural perspectives, including small-scale, organic, and regenerative operations, to guard against exclusionary "one-size-fits-all" solutions. I also underscore the need to address data privacy concerns, farmer skill transitions, and potential biases embedded within AI. Ultimately, I call for transparent dialogues, thorough impact assessments, and adaptive design principles that put animal agency at the core of digital livestock transformation. By balancing higher productivity with deeper respect for animal autonomy, I propose that human-centric intelligent systems can reconcile moral responsibilities toward humane treatment with the practical realities of global food demand. Through this balanced approach, future innovations in livestock management can uphold both ethical imperatives and operational viability, shaping a new paradigm in which animals are recognized as active participants rather than passive inputs.

Keywords: precision livestock farming; animal agency; farm animal welfare; human–animal–computer interactions; AI in agriculture; animal-centered design; human-centric intelligent systems

1. Introduction

Modern livestock farming is at a critical juncture shaped by the confluence of multiple global forces, including surging population growth, escalating consumer demand for protein, environmental sustainability pressures, and shifting cultural attitudes toward the moral standing of animals (Schillings et al., 2023; Neethirajan, 2023a; de boer and Aiking, 2022; Ammann et al., 2024). Over the past two decades, the industry has embraced technological breakthroughs in feed optimization, disease detection, and reproduction management. Yet, these developments are increasingly overshadowed by deeper concerns regarding both the ecological impact of animal agriculture and the quality of life that farm animals experience. In particular, precision livestock farming (PLF) exemplifies the drive toward automation and data-centric practices, offering new tools to boost efficiency and productivity. Sophisticated sensor networks, wireless data transmission, and

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

machine learning algorithms facilitate remote monitoring, enabling managers to identify subclinical illnesses and optimize husbandry tasks in real-time (Neethirajan & Kemp, 2021; Neethirajan et al., 2024a).

Simultaneously, the rise of human-centric intelligent systems pivots attention toward the broader social and behavioral dimensions of how humans interact with computer-driven devices (Shneiderman, 2022; Lou et al., 2024). Extending this framework beyond human contexts opens the door for a more radical rethinking of multi-species interactions—in particular, the ways in which technology mediates the relationship between farmers and animals. Viewed through this lens, the farm becomes a stage where humans, animals, and computational systems converge, each influencing the others' behaviors and well-being. This triad of human–animal–computer interactions (HACI) pushes beyond merely automating tasks; it implicates questions of moral responsibility, empathy, and the potential for digital tools to either enhance or erode animals' capacity for self-expression.

While many proponents of advanced automation emphasize its capacity to deliver individualized care—reducing forced handling and improving disease surveillance—sceptics caution that the inherent datafication and surveillance in PLF may trivialize the autonomy of farm animals by treating them as interchangeable data nodes (Zhang et al., 2024a; Neethirajan, 2024b; Chang et al., 2023; Gehlot et al., 2022). This concern is not purely philosophical: over-reliance on algorithmic assessments risks standardizing farm operations at the expense of deeper, more intuitive stockmanship and genuine empathetic contact. Accordingly, a critical exploration of agency—animals' capacity to exert meaningful control over their environment and daily experiences—stands at the heart of current debates surrounding digital livestock transformation (Wolfert et al., 2021; Lupton, 2023).

Central to this discussion is the notion of animal agency, which extends welfare beyond the mere avoidance of negative states. It argues for actively promoting positive experiences, choice, and self-directed behavior (Nelson et al., 2023; Wemelsfelder, 2024). Such a paradigm invites us to reimagine the role of technology: rather than imposing mechanistic oversight, can digital tools be harnessed to uphold or even expand the behavioral repertoire of farm animals? Equally pertinent are human-centric intelligent systems. Originating in the realm of human–computer interaction design, these systems aspire to cultivate meaningful, context-sensitive user experiences. Translating their principles into multi-species contexts requires bridging human-centered logic with animal cognition and welfare science (Mancini et al., 2022; McGraw et al., 2023).

Precision livestock farming serves as a key driver of these debates. Wearable sensors, robotic feeders, automated climate controls, and AI-based health alerts hold undeniable promise for real-time, targeted interventions (Monteiro et al., 2021; Neethirajan, 2020; Neethirajan, 2021a; Neethirajan, 2022c). Yet each novel technology provokes questions about who truly benefits, and under what conditions. For instance, at what point does round-the-clock surveillance migrate from benevolent oversight to oppressive monitoring? And how might algorithms tasked with predicting "optimal" behaviors inadvertently marginalize animals whose personalities or social needs deviate from expected norms? To evaluate these issues, it is necessary to analyze not just the hardware or software but the relational dynamics that emerge among farmers, their livestock, and digital infrastructures (Neethirajan, 2020c; Hannan, 2020).

Together, these concerns reflect a growing recognition in the literature that the digitization of livestock farming should not be viewed as an unequivocal advancement but rather as an opportunity to recalibrate the human–animal relationship. Evidence from multiple studies highlights both the opportunities and risks associated with this transformation. For instance, digitization has been shown to improve animal welfare by enabling real-time monitoring and individualized care, as demonstrated in studies on wearable sensors and automated health alerts (Zhang et al., 2024; Neethirajan & Kemp, 2021). However, other research cautions that over-reliance on data-driven technologies can lead to increased surveillance and a reduction in empathetic stockmanship, potentially diminishing animals' autonomy (Lupton, 2023). These findings underscore the

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

importance of ensuring that ethical frameworks evolve alongside technological innovations to address the moral and practical implications of increasingly automated systems (Dawkins, 2025). The subsequent sections of this perspective clarify how PLF can simultaneously enable and constrain animal agency, examine the shifting nature of farm labor, and propose design strategies for integrating human-centric principles that also acknowledge the autonomy of non-human participants.

1.1. Defining Animal Agency and Human-Centric Intelligent Systems

Animal agency in farm contexts conveys the capacity of animals to make meaningful choices, engage in self-directed actions, and influence aspects of their surroundings (Nelson et al., 2023; Wemelsfelder, 2024). This view moves beyond preventing suffering to encompass opportunities for exploratory, affiliative, or play behaviors that animals actively seek. Meanwhile, human-centric intelligent systems emphasize the creation of technologies respectful of user contexts and experiences (Shneiderman, 2022; Lou et al., 2024). Although initially aimed at enhancing human–computer interaction, these design principles can be extended to multi-species settings through Animal-Computer Interaction (ACI), challenging researchers to develop interfaces, sensors, and algorithms that account for animals' cognitive and emotional needs (Mancini et al., 2022; McGraw et al., 2023).

Precision livestock farming employs an array of digital tools—ranging from wearable devices that record physiological data to automated climate systems that fine-tune ventilation and temperature, alongside AI-powered health-monitoring platforms (Neethirajan, 2020; Neethirajan, 2021a; Neethirajan, 2022c). Understanding how these technologies intersect with agency requires an exploration of human–animal–computer relationships on the farm. Farmers interpret sensor outputs to inform decisions; animals react to altered routines or gating systems; and the technology itself reshapes daily interactions, often in ways that neither farmers nor animals fully anticipate (Neethirajan, 2020c; Hannan, 2020).

1.2. Objectives and Structure of the Review

Objectives

- Examine the evolving concept of animal agency in livestock contexts, using insights from welfare science and cognitive ethology to assess how technology might encourage or inhibit animals' capacity for self-directed behavior.
- Map the contemporary landscape of PLF technologies, highlighting both their emancipatory potential and the ethical quandaries they present.
- Analyze shifting human–animal relationships as increasing automation reconfigures practical husbandry tasks and redefines ethical responsibilities.
- Investigate design frameworks rooted in human-centric systems and ACI, focusing on strategies to uphold animal autonomy while integrating the pragmatic needs of producers.
- Propose forward-looking directions for implementing responsible and inclusive digital livestock solutions that respect diverse farming contexts, including small-scale, organic, and regenerative systems

Structure

Section 2 outlines how animal welfare thinking has evolved from basic labor-intensive care to large-scale industrial systems that historically overlooked animal agency. Section 3 reviews key PLF technologies—such as wearable sensors, AI-powered monitoring, and automated feeding or milking - demonstrating how they can personalize husbandry but also risk oversurveillance and reduced stockmanship. A table compares each technology's potential to either promote or limit animal agency. Section 4 explores how automation reshapes the human–animal dynamic. It discusses the

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

shift from hands-on husbandry to data-driven decision-making, highlighting ethical concerns around objectification, privacy, and consent. Section 5 delves into autonomy by examining how AI tools and robotics can expand or undercut animals' control over daily life. Section 6 introduces animal-centric design principles, drawing from user-centered practices in human–computer interaction. Section 7 emphasizes inclusivity in digital livestock development, pointing out that farms vary in size, resources, and philosophy. Section 8 broadens the horizon, arguing that ongoing technological and biological co-evolution shapes both animal welfare and farm operations. Section 9 concludes by underscoring that PLF and human-centric systems can either enhance or erode animal agency. It urges mindful integration of digital tools with ethical imperatives, promoting guidelines that reconcile technological innovation, practical viability, and respect for animals' autonomous capacities.

2. The Evolving Concept of Animal Agency in Livestock Farming

2.1. Historical Perspectives on Farm Animal Welfare and Behavior

For centuries, livestock rearing relied on direct, labor-intensive practices. Farmers learned to interpret subtle cues—body posture, vocalizations, feeding patterns—through consistent, hands-on observation, fostering nuanced empathy and responsive care (Ekesbo and Gunnarsson, 2018; Torgerson-White, 2022; Webster, 2022; Hausberger et al., 2021). However, traditional methods were not without welfare limitations: preventable suffering arose from inadequate disease management, overwork in draught animals, and insufficient understanding of behavioral needs (Ekesbo and Gunnarsson, 2018; Webster, 2022). Interventions often occurred reactively, addressing only overt signs of distress rather than proactively ensuring holistic welfare. By the mid-20th century, intensification shifted practices toward large-scale confinement systems designed to maximize yields (Blaxter et al., 2024; van der Laan et al., 2024).

While these industrial models overshadowed animal agency—reducing livestock to passive production units (Browning and Veit, 2021; Spinka, 2019)—they also catalyzed welfare science frameworks like the "five freedoms," which systematically addressed hunger, discomfort, pain, fear, and restricted behavior (Littlewood et al., 2023; Neethirajan, 2024D). Nevertheless, implementation gaps persisted, particularly in poultry and swine systems, where standardization often conflicted with individual needs (Molnar, 2022; Drummond, 2022). Modern technological solutions now face a dual challenge: mitigating the shortcomings of industrialized methods while avoiding romanticizing older practices that, despite fostering empathy, frequently fell short of contemporary welfare standards. Recent advances in animal cognition research underscore this tension, revealing livestock as capable of complex behaviors and emotional experiences (Abdai and Miklosi, 2024; Liu and Yin, 2024), thereby demanding technologies that expand—rather than constrain—agency.

2.2. Cognitive and Emotional Capacities of Livestock Species

In the past few decades, cognitive ethology research has forcefully countered assumptions of farm animals as cognitively simplistic or emotionally neutral. Multiple examples illustrate this more profound intelligence:

Pigs demonstrate considerable problem-solving abilities, advanced spatial cognition, and social acumen akin to Machiavellian intelligence (Nawroth et al., 2019; Rault et al., 2021). They can use mirrors to locate hidden food—an indicator of self-awareness once considered exclusive to primates (Lage et al., 2022). These animals also engage in tactical deception, modifying their behavior around dominant conspecifics to gain access to resources (Maffezzini et al., 2023; Collarini et al., 2024). Cows form intricate social ties and can recognize both herd-mates and individual humans over long periods (Rørvang and Nawroth 2021; Cornips and van Koppen, 2024). They exhibit emotional contagion, mirroring stress or excitement in companions, suggesting rudimentary empathic capacity (Stenfelt et al., 2022; Nogues, 2023). Their ability to remember social partners underscores why stable social groupings are often critical for bovine welfare.

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

Sheep have shown impressive face-recognition skills and maintain memory of specific individuals—human or ovine—even after extended intervals (Langbein et al., 2023; Bushby et al., 2018). They also discern emotional expressions in peers, reflecting a level of socio-emotional sophistication rarely attributed to ruminants (Raoult et al., 2021b; Muhammad et al., 2022). Chickens, often dismissed as primitive, perform numerical discrimination tasks and display marked preferences for certain environmental enrichments (Tahamtani et al., 2018; Loconsole et al., 2021). They navigate relatively complex learning paradigms and demonstrate multifaceted social hierarchies (Marino, 2017). These insights affirm that farmed birds, too, possess capacities for curiosity, adaptability, and social engagement (Webster, 2022; Campbell and Lee, 2021). Collectively, such research broadens our understanding of livestock beyond mere "production units." Instead, it positions them as sentient creatures capable of goal-directed behavior, emotional complexity, and adaptability to changing environments. Confronting this reality prompts us to scrutinize how modern agriculture can either nurture or stifle an animal's autonomy.

2.3. From Instrumental Views to Agency-Centered Approaches

Historically, many livestock operations were assessed by metrics like growth rates, feed conversion ratios, and overall yield, reducing welfare to a peripheral concern (Clarke and Knights, 2021). Over the last few decades, however, welfare science and ethical theory have increasingly advocated providing opportunities for exploration, social interaction, and choice—pillars of genuinely humane farming (Webster and Margerison, 2022). Within this shift, the notion of *agency* has emerged as pivotal. Agency entails the individual's capacity to initiate actions shaped by internal motivations, as opposed to merely reacting to external stimuli (Jensen et al., 2023; Hernandez et al., 2022). Even limited chances for self-regulation—such as letting a pig decide between rooting substrate or puzzle feeders—can significantly enhance psychological well-being (Hennessy and Marsh, 2021; Dawkins, 2025). By extension, an agency-centered model challenges the tendency to evaluate farm management purely through production-driven indices. Instead, it forces us to ask whether each housing arrangement, feeding regimen, or technological innovation expands or restricts animals' ability to make self-directed choices (Browning and Veit, 2025). This perspective has deep implications for how we adopt emerging digital tools in livestock farming: Are these tools deployed to bolster animals' control over their lives, or merely to refine top-down efficiency?

2.4. Ethical and Philosophical Underpinnings of Animal Agency

Debates surrounding animal ethics vary widely. Utilitarians often weigh costs and benefits, aiming to minimize suffering while maximizing human utility (Garner, 2024). Rights-based theorists, by contrast, argue that animals hold inherent moral rights—potentially including rights to autonomy (Rutledge-Prior, 2024). Meanwhile, capabilities-based approaches adapted from human ethics emphasize species-specific abilities—such as free movement, social bonding, and exploratory behaviors—as fundamental. Without genuine choice, many of these key behaviors remain unrealized (Wemelsfelder, 2024). In practice, these theoretical stances have real consequences for policy and technological design. A pig's innate desire to root, for example, may be deemed a core capability that modern farming methods must accommodate (Neethirajan, 2024a). Failing to do so might undermine not just welfare but the moral underpinnings of the system itself. Some critics question the feasibility of fully respecting animal autonomy while still meeting commercial demands. Yet the rise of concepts like "positive welfare" and "a life worth living" (Stucki, 2023; Webster, 2016) reflects a societal pivot: animals' subjective experiences are increasingly valued, prompting the agriculture sector to re-evaluate everything from breeding programs to barn architecture.

2.5. Key Challenges to Agency in Modern Farming

Despite growing recognition of livestock cognition, numerous structural and practical constraints impede agency in commercial contexts. High-density housing systems for poultry and

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

swine severely restrict mobility, preventing exploration, social grouping, and solitary retreat, which are essential for behavioral expression (EFSA AHAW Panel, 2023). Genetic selection for productivity, such as breeding broilers for rapid growth, often results in animals with skeletal deficiencies that compromise their ability to move normally (Misztal and Lourenco, 2024). Rigid protocols for milking or feeding schedules prioritize uniformity over individual variation, suppressing animals' natural rhythms and preferences (Bhoj et al., 2022; Marumo et al., 2022). Additionally, intensive workflows in large-scale operations limit farmers' capacity to provide personalized care or interpret subtle behavioral cues, further marginalizing the emotional and cognitive needs of individual animals (Papakonstantinou et al., 2024). Neglecting emotional states such as stress, frustration, or boredom undermines animals' potential for pleasurable experiences and reduces opportunities for agency (Neethirajan et al., 2021F; Vigors et al., 2021).

While these challenges reflect a low baseline for welfare in many modern systems, precision livestock farming (PLF) offers potential solutions. Continuous monitoring technologies can detect early health issues or environmental discomfort, enabling timely interventions tailored to individual needs (Neethirajan & Kemp, 2021). However, the same technologies risk amplifying surveillance and intensifying productivity demands if not guided by ethical frameworks. For example, invasive monitoring systems may prioritize efficiency over autonomy, reducing animals to data points rather than sentient beings with distinct preferences. Ultimately, whether PLF enhances or diminishes agency depends on the philosophies driving its implementation - whether the focus is on empowering animals or merely optimizing production processes.

2.6. Agency as a Core Component of Welfare

Growing interest in "positive welfare" underscores that animals should not merely be safeguarded from harm but offered avenues for self-expression and fulfillment (Webber et al., 2022). Under such a paradigm, technology can become an invaluable means of expanding agency. Systems that allow for voluntary milking, flexible feeding schedules, or engaging enrichment devices have the potential to honor animals' behavioral repertoires more faithfully. Simultaneously, consumer preferences are shifting toward ethically produced animal products, which amplifies market pressure for more humane systems (Moran and Blair, 2021; Alonso et al., 2020). This alignment of consumer demand with advanced computing solutions might catalyze broader adoption of agency-oriented design. Yet formidable barriers remain: meeting profitability targets within large-scale operations, accounting for climate impacts, and managing distribution networks are ongoing hurdles (Neethirajan, 2024P). By highlighting animals' cognitive sophistication and emotional richness, the rationale for re-envisioning welfare as a cornerstone of livestock production grows harder to ignore.

The transformation from a minimal "avoid harm" paradigm to one grounded in positive experiences and autonomy clearly intersects with the accelerating field of precision livestock farming. However, absent robust ethical oversight and genuine stakeholder collaboration, the risk remains that advanced automation could retreat into a cold, purely mechanistic approach, overshadowing the intangible but essential elements of animal autonomy. The sections that follow will scrutinize these emerging human–animal–computer relationships more closely, focusing on how digital innovations can be calibrated to truly prioritize agency in contemporary livestock systems.

3. Precision Livestock Farming: Technologies and Implications

3.1. Overview of Precision Livestock Farming (PLF)

Precision Livestock Farming (PLF) represents a rapidly evolving branch of smart agriculture, combining sensor networks, AI analytics, and real-time data flows to refine animal management (Jiang et al., 2023). In principle, PLF aims to optimize resource use, boost productivity, and promote animal welfare through timely responses to physiological or environmental indicators. Advocates often characterize PLF as a multifaceted solution capable of reducing production costs, enhancing yields, and meeting a growing market for ethically derived livestock products. Yet, its ultimate

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

effectiveness hinges on both technical design and the ethical frameworks under which it is deployed. In some cases, PLF can personalize husbandry and enrich an animal's behavioral repertoire; in others, it can reinforce rigid, production-focused approaches that accentuate surveillance while neglecting animals' emotional or social complexities. Table 1 synthesizes insights from interdisciplinary literature and expert perspectives to evaluate how key PLF technologies influence animal agency. The analysis reflects a conceptual framework rather than results derived from a systematic review.

Table 1. Technologies in Precision Livestock Farming (PLF) and Their Potential Impacts on Animal Agency.

Technology	Description	Potential Benefits for Animal Agency	Potential Risks to Animal Agency
Wearable Sensors	Track physiological metrics (e.g., heart rate, movement)	Early detection of health issues, tailored interventions	Over-surveillance, device discomfort, misinterpretation of data
Automated Feeding Systems	Deliver precise rations based on individual needs	Reduced competition, stress among group-housed livestock	Algorithmic regulation limiting natural foraging patterns
Robotic Milking Systems	Allow cows to self-select milking times	Alignment with natural rhythms, reduced stress	Potential for over-reliance on technology, reduced human-animal interaction
Environmental Monitoring Systems	Auto-adjust ventilation, temperature, and lighting	Improved comfort, reduced stress from environmental factors	Potential for rigid system architecture limiting animal choice
AI-Driven Analytics	Aggregate sensor data for early disease detection and decision support	Timely interventions, enhanced welfare	Over-reliance on algorithmic decision-making, potential for bias
GPS Collars	Track movement patterns, grazing preferences, or social networks	Enhanced understanding of animal behavior, better pasture management	Potential for over-surveillance, privacy concerns
Smart Enclosures	Dynamically change pen partitions or open gates based on animal distribution and microclimate preferences	Flexibility for animals to choose cooler or warmer zones, more social or solitary areas	Risk of trapping or stressing animals if not well-designed
Automated Climate Systems	Adjust temperature and humidity levels based on sensor data	Improved air quality, reduced stress from environmental factors	Potential for over-reliance on automation, neglecting animal preferences

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Technology	Description	Potential Benefits for Animal Agency	Potential Risks to Animal Agency
Interactive Enrichment Devices	Provide cognitive challenges and rewards based on animal interactions	Enhanced exploration, cognitive stimulation, and autonomy	Potential for over-stimulation or frustration if not well-designed
Virtual Fencing	Use GPS and sensors to create dynamic boundaries	Allows animals to select different forage zones or microhabitats within the boundary	Risk of confusion or stress if boundaries are overly restrictive
Multi-Zone Climate Control	Partition barns into zones with varying temperature and ventilation levels	Animals can move to zones that suit their comfort, reducing forced crowding	Potential for complex system management, high infrastructure costs
Behavioural Monitoring Systems	Use computer vision or sensors to detect abnormal behaviors	Early detection of health issues, improved welfare	Potential for misinterpretation of data, over-surveillance
Automated Health Monitoring	Use AI to predict disease outbreaks or detect health risks	Timely interventions, reduced antibiotic usage	Potential for over-reliance on technology, neglecting human observation skills
Data-driven Decision Support	Use aggregated sensor data to guide feeding, milking, and health interventions	Enhanced data insights, facilitating empathic or informed care	Potential for algorithmic overreach, reducing human empathy and skill
Robot-Assisted Handling	Use robotic arms for tasks like milking, feeding, or cleaning	Reduced labor, potential for more gentle handling	Risk of reduced human-animal interaction, deskilling
Open-Source Sensor Platforms	Provide adaptable, low-cost sensor solutions for diverse farm types	Increased accessibility for small-scale or organic farms, potential for more inclusive technology adoption	Challenges in standardization, potential for data privacy issues
Integrated Farm	Combine data from various sensors and systems for comprehensive farm management	Enhanced efficiency, potential for more holistic welfare assessments	Risk of complex system management, high infrastructure costs

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

3.2. Wearable Sensors and Biometric Devices

Wearable sensors constitute a central component of PLF, as they allow uninterrupted 24/7 monitoring of livestock. Devices such as accelerometers can identify subtle signs of lameness or estrus (Dhaliwal et al., 2024), while heart rate monitors detect fluctuations in stress or rest states (Neethirajan, 2020X). Rumen sensors help predict acidosis by measuring pH (Neethirajan & Kemp, 2021), and GPS collars map out movement patterns, grazing habits, or social networks in extensive farming systems (Rivero et al., 2021). These tools collectively enable early and tailored interventions, offering the potential for more individualized welfare. However, caution is essential. Over-surveillance can arise if algorithms trigger frequent or disruptive responses that limit animals' autonomy, and comfort issues associated with wearable devices may undermine welfare (Herlin et al., 2021). Further, data misinterpretation remains a persistent risk if algorithms are not validated or if managers rely too heavily on automated alerts (Neethirajan, 2024D). Consequently, wearable sensors hold promise for mitigating stress and disease only when embedded in systems that account for animal well-being rather than strictly maximizing productivity.

3.3. Environmental Monitoring Systems and Smart Enclosures

PLF extends beyond individual animals to the broader environment in which they live, incorporating an array of sensors that measure and control factors such as temperature, humidity, and air quality. Temperature and humidity detectors can automatically modulate ventilation or cooling systems (Andrade et al., 2022; George and George, 2023), while ammonia sensors in poultry housing help maintain healthier air (Hofstetter et al., 2021). Automated light cycles attuned to species-specific circadian rhythms further reduce stress (Neethirajan, 2024N). Systems known as "smart enclosures" integrate these data streams, adjusting pen partitions and doorways based on where animals congregate, local climate conditions, or social preferences (Xiong, 2019). By tailoring microenvironments in real time, these technologies can theoretically grant animals greater spatial choice—seeking warmth, privacy, or congregation as desired. Yet the success of such innovations depends on robust engineering that prevents inadvertent entrapment or conflict. Without careful design, smart enclosures may unintentionally increase stress by limiting retreat routes or misaligning with the species' behavioral needs.

3.4. Automated Feeding, Milking, and Robotics

Automation in feeding, milking, and various robotic tasks epitomizes the move toward more precise, less labor-intensive livestock management. Automated feeding systems, for instance, can deliver ration sizes that match each animal's developmental stage or lactation cycle, potentially reducing competition and aggression in group-housed settings (Kopler et al., 2023). Robotic milking stations, meanwhile, allow cows to determine when to be milked, which can align with their natural circadian rhythms and diminish stress (Aerts et al., 2022). Robot-assisted arms or cleaning units can free human caretakers from repetitive chores, supposedly granting them more time to address nuanced welfare concerns. Still, the degree to which these measures expand animal choice depends greatly on how the technology is implemented. A poorly structured automated feeding schedule, for example, may simply regulate intake more rigidly, while neglecting an animal's preferred feeding times. Similarly, although self-selected milking can reduce some stressors, it may alienate farmers from direct observation of animals' behavioral shifts. In short, automation has clear potential to enrich welfare and reduce labor strain, but its ethical impact hinges on whether it is employed to broaden animals' autonomy or further mechanize their daily routines.

3.5. AI-Driven Analytics and Decision Support Tools

Artificial intelligence has rapidly emerged as a key driver in PLF, aggregating and interpreting sensor data to detect early warning signs of disease, predict breeding windows, or suggest real-time adjustments to feed composition. Such analytics can identify subtle behavioral deviations—like

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

decreased rumination or altered locomotion—that might elude human observers (Neethirajan, 2020X; Rivero et al., 2021). Early identification of potential health issues can lead to targeted interventions, such as isolating contagious individuals or adjusting environmental conditions to reduce stress. However, reliance on AI can also exacerbate ethical and practical dilemmas. Farmers may gradually defer their own judgment to "black box" algorithms, risking a loss of hands-on intuition and empathy (Baur and Iles, 2023). Algorithms trained on biased data might misinterpret species-specific behaviors or overlook significant variables specific to a certain farm environment. Furthermore, automated triggers—such as isolating an animal identified as "at risk"—can inadvertently restrict normal social or exploratory behaviors, undercutting the agency these technologies might otherwise promote. Balancing the efficiency of AI-based decision-making with the farmer's experiential knowledge thus remains a critical challenge.

3.6. Opportunities and Challenges in PLF Adoption

The widespread adoption of PLF presents a complex spectrum of opportunities and challenges. Among the clear benefits is more judicious resource utilization, which can mitigate environmental footprints and potentially drive positive consumer perceptions. Early detection of diseases through continuous monitoring offers the promise of prompt interventions and reduced antibiotic usage, aligning with broader public health goals. PLF may, moreover, enhance animal autonomy by accommodating individual preferences, such as free-choice milking or personalized feeding schedules, and can generate data-driven insights that inform more humane, empathic care.

Yet, several significant barriers persist. The prohibitive costs of implementing sophisticated sensor systems can deter smaller-scale farms from harnessing these innovations, thereby reinforcing existing inequalities. The rise of automation also brings the potential for caretaker deskilling if human observation and empathy are overshadowed by dashboards and alerts. More alarmingly, PLF risks commodifying animals when data optimization supersedes less tangible welfare aspects, such as social bonding or emotional well-being. Regulatory oversight and accountability remain key unresolved issues, as data privacy, algorithmic transparency, and responsible handling of biometric information are frequently overlooked. These gaps underscore that while PLF can invigorate farming with unprecedented precision and responsiveness, its success ultimately depends on whether farmers, policymakers, and technologists commit to centering animal agency and welfare in both system design and day-to-day management.

4. Human–Animal–Computer Interactions (HACI) in Farming

The advent of technologically mediated farm environments has altered traditional caretaker responsibilities in profound ways. Rather than spending most of the day feeding, cleaning, or milking, many farmers now oversee data-centric operations and monitor automated processes. This transformation can be liberating, as it frees time for more specialized tasks that demand nuanced judgment. Yet it also risks eroding direct contact with animals, potentially undermining the deep empathy and intuitive acumen that characterize skilled stockmanship. As "digital stockmanship" gains ground, researchers and practitioners alike worry that overreliance on dashboards may displace essential observational skills, weakening the bonds that historically allowed farmers to sense subtle shifts in animals' well-being (Robertson and Riley, 2024). Modern farming thus stands at a crossroads: can computer-mediated systems reinforce empathy and honed perception, or will they prioritize algorithmic efficiency over the relational richness that fosters genuine welfare?

Sensor-driven technologies have further complicated the interaction between humans and animals by reframing how farmers perceive their herds or flocks. Automated alerts and daily "health scores" can indeed reveal patterns previously invisible to casual observation, illuminating hidden discomfort, irregular feeding, or nascent diseases. However, these data-driven insights may also reduce an animal's individuality to a set of parameters, creating the risk that caretakers see only a digital abstraction rather than a sentient creature with context-specific behaviors. If algorithms fail to accurately reflect an animal's genuine state—or misinterpret species-specific behaviors—misguided

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

interventions or delayed responses can result. The interplay among sensor feedback, human judgment, and the animals' own adaptive signals thus remains central to maintaining robust welfare standards in high-tech settings.

Automated decision-making offers tantalizing possibilities for timely healthcare interventions but raises questions about control and autonomy. For example, when AI systems detect reduced rumination or abnormal gait and decide that an animal should be isolated or forcibly examined, the animal's own preferences become secondary to the algorithm's directive. There is legitimate debate over whether such automated surveillance fosters animal welfare or imposes an environment of perpetual oversight that can stifle agency. Even though data privacy controversies in human contexts might not map seamlessly onto farm animals, the principle of respecting animals as active subjects rather than passive data points remains crucial. Overreliance on AI can relegate animals to mere objects of optimization, unless developers build systems that respond to animals' self-initiated cues—such as voluntarily approaching a treatment station—in ways that uphold choice and minimize undue coercion. Background monitoring (e.g., environmental sensors) lacks direct intervention, whereas active systems (e.g., automated gates) directly limit autonomy. The former poses minimal ethical risk if data informs non-coercive adjustments.

Striking a balance between technological efficacy and compassionate husbandry calls for an intelligent synthesis of computerized tools with human expertise. Farmers who routinely cross-check sensor data against real-world interactions can interpret anomalies more accurately, ensuring that automated alerts do not replace on-the-ground empathy. This hybrid model respects the farmworker's ability to discern subtle lameness, social tensions, or even distinct personalities within a herd, while also harnessing real-time analytics for early disease detection. However, the risk of "deskilling" remains acute if younger caretakers receive insufficient training in reading behavioral cues and instead rely heavily on digital prompts (Baur and Iles, 2023; Prause, 2021). Targeted programs that integrate data literacy with traditional stockmanship may help cultivate "data-savvy empathic stockpeople" (McCaig et al., 2023), preserving intuitive understanding while equipping farmers with modern analytical prowess.

Ethical dilemmas abound in these evolving human–animal–computer relationships. Some critics argue that objectifying animals as data streams minimizes recognition of their emotional complexity. Others highlight algorithmic overreach, where opaque AI models complicate accountability in the event of welfare failures. Surveillance imposes moral considerations regarding an animal's dignity, even if the animal cannot articulate privacy demands in human terms. Moreover, the notion of consent remains fraught: wearable sensors or camera installations typically occur without an animal's meaningful choice, prompting debates about paternalism and moral considerability. Smaller operations or alternative farms may be disproportionately excluded from such digital ecosystems, unable to afford high-end technologies or unwilling to align with highly standardized approaches. Effective governance requires stakeholder dialogue and robust frameworks that integrate human-centric and animal-centric priorities. By foregrounding empathy, accountability, and genuine respect for animals as sentient subjects, the adoption of technology in livestock farming has the potential to enhance—rather than erode—animal agency.

The ethical considerations in human–animal–computer interactions in livestock farming are multifaceted and critical to the design of responsible PLF systems. Table 2 critically examines these ethical considerations and their implications for animal agency, emphasizing the need for an animal-centered approach to technology design and implementation.

Table 2. Ethical Considerations in Human–Animal–Computer Interactions (HACI) in Livestock Farming.

Ethical Consideration	Description	Implications for Animal Agency	Stakeholder Responsibilities

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

Objectification	Reducing animals to data flows	Ignoring emotional complexity, intangible welfare aspects	Ethicists, policymakers to ensure holistic welfare assessments
Algorithmic Overreach	Lack of transparency in AI-based decisions	Complicating accountability for welfare issues	Technologists, policymakers to implement transparent, explainable AI
Privacy	Continuous surveillance without consent	Impact on animal dignity, moral respect	Ethicists, policymakers to establish data protection guidelines
Consent	Animals cannot meaningfully consent to wearable sensors or camera observation	Moral questions about paternalistic approaches	Ethicists, policymakers to develop frameworks respecting animal autonomy
Social Justice	Exclusion of smaller or alternative farms from advanced solutions	Inequitable access to technology	Policymakers, technologists to ensure inclusive, accessible solutions
Deskilling	Over-reliance on technology, reducing human observation skills	Impact on empathetic bonds, stockmanship	Farmers, trainers to emphasize hands-on skills, data interpretation
Surveillance-Induced Stress	Continuous monitoring causing environment	Disrupting normal behaviors	Farmers, technologists to design systems minimizing stress

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

	modifications or interventions		
Rigid System Architecture	Virtual fences or gating confining animals in dynamic but human-defined zones	Limiting genuine free movement	Farmers, technologists to design flexible, adaptive systems
One-Size-Fits-All	Standardized robotic interfaces not accounting for individual differences	Frustration or learned helplessness	Technologists, farmers to implement personalized solutions
Lack of Recognition of Emotional Complexity	Ignoring animals' emotional states—stress, frustration, boredom	Reducing scope for pleasurable experiences or choice	Ethicists, policymakers to emphasize emotional welfare
Cultural Acceptance	Resistance to technology adoption due to cultural or traditional practices	Impact on technology uptake, animal welfare	Farmers, policymakers to engage in cultural dialogue, training
Economic Feasibility	High infrastructure costs limiting technology adoption	Impact on small-scale or organic farms	Policymakers, technologists to develop cost-effective solutions

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Technical Reliability	Wearables or robotic systems requiring user-friendly interfaces and minimal downtime	Reliable systems enhance animal welfare by providing consistent monitoring, reduce downtime for farmers, and increase trust and adoption of PLF technologies across diverse farming contexts.	Technology developers, farmers, and policymakers must collaborate to design robust, user-friendly systems that withstand farm conditions, ensure regular maintenance, and establish standards for reliability and accessibility.

Anthropomorphism in Ethical Design - Navigating Risks and Realities

As precision livestock farming (PLF) systems evolve, ethical frameworks must carefully balance scientific evidence with intuitive interpretations of animal experience. A central tension arises around anthropomorphism—the attribution of human-like emotions or intentions to animals. While livestock lack abstract notions such as "privacy" or "surveillance," Emerging observations and anecdotal reports indicate that certain monitoring technologies may be associated with stress-related behaviors in livestock, such as withdrawal, avoidance of devices, or signs consistent with physiological arousal. These physiological and ethological indicators warrant serious attention, yet they must not be conflated with human cognitive analogs.

For instance, cattle avoiding robotic milking stations may be reacting to noise frequencies or floor vibrations rather than any abstract discomfort with being observed. Misreading such behavior through an anthropocentric lens can distort design priorities, leading to superficial "non-invasive" solutions that neglect functionality or animal needs. Conversely, overlooking the animal's capacity for stress, frustration, or discomfort risks normalizing welfare compromises in the name of efficiency.

The challenge, then, is to validate welfare impacts through species-specific, behaviorally grounded evidence (e.g., consistent use of enrichment items or avoidance behaviors during interventions). Technologies should be assessed using observable indicators—such as variability in movement patterns, heart rate variability, or preference-based testing—rather than assumed psychological states. For example, dairy cows frequently and voluntarily using automated grooming brushes signal positive engagement without requiring anthropomorphic justification. Similarly, pigs' frustration in the absence of rooting substrates reflects an unmet behavioral drive, not a philosophical longing for "freedom."

Ethical PLF design must incorporate ergonomic wearables, low-stress interfaces, and minimally disruptive automation—grounded not in imagined animal narratives, but in robust, reproducible welfare science. Public concerns about animal dignity, while often shaped by anthropomorphic framing, can still be addressed through transparent data practices and empathetic system design. Crucially, farmers and developers alike should be equipped to interpret behavioral cues not as metaphors for protest but as signals of welfare states, grounded in species-appropriate biology. By walking this careful line, PLF can avoid ethical overreach while still advancing animal-centered innovation.

5. Impact of Autonomous Technologies on Animal Agency

Autonomous technologies have introduced notable shifts in how farm animals experience choice and control in their daily environments. When thoughtfully designed and carefully implemented, these systems can extend a meaningful range of options to animals, thereby fostering autonomy and reducing stress. For instance, voluntary milking stations offer cows the ability to align milking with their own internal rhythms, reducing discomfort from over-distended udders and alleviating the pressures of a regimented milking schedule. Automated feeding mechanisms can grant animals the

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

freedom to approach feeders at times they choose, which often reduces aggressive competition and promotes a more harmonious group dynamic (Bhoj et al., 2022; Marumo et al., 2022). Likewise, interactive enrichment devices, capable of responding to an animal's engagement patterns, can stimulate exploration and self-directed activities. Each of these innovations exemplifies a form of "everyday autonomy," underscoring that enhanced agency is not purely an abstract ideal but has tangible effects on diminishing frustration, aggression, and stress.

Despite these promising developments, technology can also delimit agency when applied without an animal-centered perspective. Algorithmic regulation that rigidly sets feeding times based solely on productivity metrics can, for example, undermine an animal's natural foraging rhythms. Similarly, continuous monitoring can become intrusive if it frequently triggers environmental modifications or corrective interventions, potentially unsettling normal behaviors and causing what might be termed "surveillance-induced stress." Systems like virtual fencing, which use GPS and software-based boundaries, may offer flexible grazing areas but can inadvertently confine animals to human-defined zones that disregard individual preferences for social grouping or solitary exploration. Standardized robotic interfaces sometimes neglect the wide variability in temperament, social rank, or even morphological differences. Such "one-size-fits-all" technologies risk inducing frustration or learned helplessness in animals that do not adapt well to uniform protocols. Hence, advanced automation, while a significant catalyst for reform, does not automatically guarantee meaningful choice. The central determinant is whether underlying design decisions explicitly prioritize agency by accommodating the individual preferences and behavioral repertoires of each species.

The question of privacy and the notion of the "*quantified animal*" adds another ethical and practical layer to these debates. Precision livestock farming (PLF) often involves collecting continuous physiological or behavioral data, echoing the "quantified self" phenomenon observed in human wearables. Unlike humans, however, animals cannot consent to data gathering, nor can they articulate concerns over the intrusiveness of unremitting surveillance. Although animals may not have a concept of privacy paralleling human experience, imposing ubiquitous data collection risks steering managerial decisions toward purely instrumental ends—such as optimization of feed conversion or growth rates—rather than promoting animals' spontaneous, self-directed behaviors (Neethirajan & Kemp, 2021; Herlin et al., 2021). Caretakers might become overly reliant on graphs or dashboard alerts, reducing nuanced empathic observation and potentially weakening the human–animal bond. On the other hand, when data analytics reveal subtle changes in gait or appetite that would otherwise escape human notice, early and more targeted support becomes feasible. The ethical balance hinges on whether collected metrics feed into gentle, welfare-enhancing interventions or whether they amplify restrictive control mechanisms designed solely for productivity gains.

Several research efforts have proposed integrating animal feedback more directly into farm management, sometimes referred to as preference testing or behavior-led design. By documenting how animals use optional resources—ranging from supplementary bedding types to varied feeding stations—systems can refine conditions according to the animals' exhibited preferences. Over time, such "voting with their hooves" can guide iterative improvements, bridging the gap between purely top-down management and a model that responds to tangible animal choices (Dawkins, 2025). This iterative cycle of observation, experimental variation, automated monitoring, and adaptive environment mirrors principles of user-centered design, but applied to a multi-species context. Although these methods still rely on interpreting behavioral cues rather than verbal feedback, they offer a plausible route to genuine empowerment, as animals effectively co-create the conditions in which they live. By refining thresholds, modifying feeding schedules, and periodically re-assessing outcomes, such approaches align well with the broader goal of making technology a conduit for autonomy rather than an instrument of control.

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

6. Animal-Centric Design in Human-Centric Intelligent Systems

Efforts to expand agency through precision livestock farming converge with the concept of animal-centric design in human-centric intelligent systems. This paradigm shift draws on insights from user-centered engineering, refocusing attention on the cognitive, emotional, and social requirements of nonhuman stakeholders. It challenges technologists and engineers to think beyond cost savings or data accuracy and to incorporate robust ethological knowledge about each species' behavioral needs. Importantly, it stresses providing genuine choice and adapting to individual variation, rather than forcing uniform routines that might be convenient for managers yet frustrating for animals (Browning and Veit, 2025).

Several guiding principles undergird animal-centric design. Species-specific ethology remains essential, since design solutions that ignore natural behaviors—such as rooting in pigs, dustbathing in chickens, or grooming interactions in cattle—risk creating environments discordant with innate drives (Spinka, 2019). Equally crucial is choice provision, ensuring animals can select from multiple feeding zones, temperature gradients, or enriched spaces that respect the complexity of their social and cognitive worlds (Hennessy and Marsh, 2021). Cognitive and emotional fit demands that devices and interactive systems be neither understimulating nor overwhelming; the right balance may encourage exploration without inducing stress. By prioritizing minimal intrusiveness, developers avoid wearable sensors or enclosure modifications that irritate or constrain natural postures. Finally, adaptive learning recognizes that animals are not homogenous: adjustable thresholds and personalized settings can respond to variations in temperament or health, preventing a "one-size-fits-all" approach from curtailing individual agency (Jensen et al., 2023; Hernandez et al., 2022).

Implementing such designs requires close collaboration among ethologists, technologists, farmers, and policymakers. Ethologists validate prototypes to ensure alignment with natural behaviors while detecting signs of stress or preference during pilot trials. Engineers ensure hardware durability under farm conditions and code algorithms that accurately interpret sensor data to adjust environmental parameters as needed. Farmers contribute practical insights regarding budget constraints, workflow patterns, and local climate or infrastructural realities (McCaig et al., 2023). However, the quest for animal-centric design may place additional burdens on farmers by demanding technical expertise and time beyond their current capacities. For example, wearable sensors often require farmers to interpret complex dashboards while managing individualized interventions—a task that risks overwhelming smaller-scale producers with limited resources (Prause, 2021; Baur & Iles, 2023). Policymakers can mitigate such challenges by incentivizing training programs that integrate data literacy with traditional stockmanship skills or by subsidizing user-friendly technologies tailored to diverse farming contexts.

Case studies illustrate how an animal-centered ethos can manifest in tangible welfare-enhancing systems. For example, interactive puzzle feeders for pigs demand manipulation of levers or panels to access feed or enrichments, engaging their curiosity and exploratory instincts (Nawroth et al., 2019; Maffezzini et al., 2023). By calibrating challenge levels, such devices accommodate varying skill sets while preventing dominant individuals from monopolizing resources. Automated milking systems augmented with preference testing for corridor widths or brushing stations similarly allow cows to shape aspects of their own milking experiences (Aerts et al., 2022; Kopler et al., 2023). A cow choosing milking intervals that suit its udder pressure or daily rhythms exercises agency that would be untenable under fixed schedules. Virtual fencing uses GPS collars to signal mild vibrations or auditory cues as animals approach a digitally defined boundary (Xiong, 2019). While critics warn of potential stress from abrupt boundary changes, supporters highlight increased freedom for animals to roam across varied terrains once fine-tuned to respect individual learning curves. Similarly, multi-zone climate control systems segment barns into distinct temperature and ventilation areas, offering animals an active role in deciding where they find optimal comfort (Andrade et al., 2022; George & George, 2023). Yet each system must be evaluated not simply for mechanical efficacy but for how effectively it honors animals' capacity for exploration, control, and self-expression.

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

Although promising, animal-centric PLF remains constrained by economic feasibility, customization demands, cultural acceptance, and technical reliability. Infrastructure outlays for wearable sensors or advanced climate systems are often steep barriers for smaller-scale producers (Moran & Blair, 2021; Alonso et al., 2020). Disparities in farm architecture complicate standard product deployment while necessitating context-specific solutions that may not scale easily. Some farmers remain skeptical of highly mechanized approaches due to concerns about eroding personal connections with livestock or the complexity of managing individualized systems alongside existing workflows. Rugged interfaces must withstand dusty and humid conditions while minimizing downtime (Neethirajan, 2024D). Policy measures—including targeted subsidies for small-scale producers—can encourage broader adoption while ensuring technologies align with practical realities.

7. Toward Inclusive and Responsible Digital Livestock Technologies

Recent developments illustrate that digital technologies can serve as either instruments of empowerment or tools of increased oversight in livestock systems. To ensure these innovations genuinely enhance welfare, a shift toward inclusive and responsible design is paramount. Anticipatory governance provides a framework for diverse stakeholders—farmers, veterinarians, technologists, ethicists, consumer groups, and environmental advocates—to collaboratively define the purpose and consequences of digital solutions (Baur and Iles, 2023; Prause, 2021). However, the commercialization of PLF introduces inherent tensions: profit-driven priorities often sideline ethical co-design, favoring standardized, scalable technologies over context-specific, agency-centered systems. For instance, developers may prioritize marketable features like productivity analytics while neglecting stakeholder-driven needs such as behavioral enrichment interfaces (McCaig et al., 2023). Overcoming this requires intentional mechanisms to align commercial incentives with ethical imperatives, such as subsidies for collaborative R&D or certification programs that reward transparency in data usage and animal-centric outcomes.

Diverse farming perspectives challenge developers to contemplate alternative modes of production that prioritize ecological harmony and animal agency. Organic and regenerative practitioners emphasize holistic approaches, where animals' behavioral needs intersect with soil health and biodiversity (Papakonstantinou et al., 2024). Yet, commercial PLF systems often clash with these philosophies due to high costs or rigid architectures. For example, wearable trackers designed for confined dairy systems may disrupt free-ranging practices if not adapted to pasture-based contexts (Moran and Blair, 2021; Alonso et al., 2020). Bridging this gap demands participatory design frameworks where farmers co-lead technology prototyping, ensuring tools align with local ethics and operational realities. Open-source platforms and modular hardware could further democratize access, enabling smaller farms to customize solutions without relying on proprietary, profit-driven models.

Policy and regulatory bodies play a critical role in fostering collaboration amid commercialization. Current welfare standards rarely account for agency metrics, but incorporating choice-related indicators into audits (e.g., voluntary milking participation rates) could incentivize ethical innovation (EFSA AHAW Panel, 2023). Data governance must also address corporate control of livestock biometrics, ensuring farmers retain ownership and algorithms prioritize welfare over productivity (Hofstetter et al., 2021). Multi-stakeholder committees - including representatives from small-scale farms and animal advocacy groups - could evaluate PLF technologies pre-deployment, assessing impacts on autonomy and equity. For instance, AI-driven feed systems optimized for growth rates might be redesigned to allow individualized meal timing, balancing efficiency with self-directed behavior.

The socio-technical success of PLF hinges on integrating tools into daily routines without eroding empathetic stockmanship. Participatory methods like scenario workshops can reveal hidden biases, such as industrial assumptions that high stocking densities are unavoidable (Robertson and Riley, 2024). By contrast, regenerative farmers might advocate for sensor networks that monitor

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

rotational grazing impacts on soil and herd health, aligning technology with ecological stewardship. Ethicists and engineers must collaborate to embed welfare safeguards into AI, such as algorithms that flag prolonged inactivity in broilers but avoid penalizing natural rest periods (Dawkins, 2025).

Ultimately, reconciling commercialization with ethical collaboration requires reimagining value chains. Hybrid business models that pair technology sales with farmer training programs could balance profit and welfare, while blockchain traceability might link premium markets to verifiable agency-enhancing practices (Neethirajan, 2024P). By centering stakeholder dialogue and adaptive governance, PLF can evolve beyond a profit-driven narrative to foster systems where animals, farmers, and ecosystems thrive in tandem.

8. Long-Term Implications and Future Directions

8.1. Animal Agency and Technological Co-Evolution

Technological innovation in livestock farming proceeds neither in isolation nor at a fixed pace but through an ongoing dialogue among industry stakeholders, researchers, policy-makers, and farm animals themselves. Although animals do not articulate preferences in human language, their behavioral changes can guide system refinements. In this co-evolutionary process, adaptive AI may emerge that not only flags anomalies but also tailors management to individual animals' distinct social cues, temperaments, or coping styles. Similar advances might include the "bio-design" of enclosures that incorporate embedded sensors, enabling animals to manipulate temperature levels, lighting patterns, or microenvironments according to preference. Over time, interactive robotics could facilitate social bonding and gentle grooming behaviors, taking signals from posture or vocalizations to intervene in group dynamics only when beneficial.

Such innovations raise foundational questions about the long-term ramifications of technology on farmed species. If selective breeding begins to favor individuals that adapt more readily to sensor-based tracking or AI-optimized feeding cycles, the genetic and behavioral trajectories of domesticated animals may shift. Whether these alterations ultimately broaden or constrain animal agency remains an open question, requiring longitudinal analysis of welfare impacts and social interactions across generations. Understanding how domesticated species adapt cognitively or emotionally to persistent technological interventions can help clarify whether the digital era amplifies the innate potential for autonomy or funnels animals into narrower behavioral repertoires. Carefully designed studies that integrate ethological assessments, gene expression data, and on-farm behavioral observations stand to offer a richer view of how technology's iterative modifications affect the essence of animal agency.

8.2. Longitudinal Studies on Welfare Outcomes and Human–Animal Bonds

Despite the fervent adoption of precision livestock farming (PLF) in many regions, robust longitudinal research on its welfare effects remains notably sparse. Short-term experiments frequently highlight immediate benefits such as early disease detection, improved feed efficiency, or minor stress reductions, yet evidence about the sustainability of these gains over multiple production cycles is limited. It is unclear whether welfare benefits plateau, improve further, or even deteriorate as animals adapt or become desensitized to automated routines. For instance, a system that initially mitigates stress by allowing flexible feeding might later induce complacency, leading to diminished exploratory behaviors if the environment remains predictably controlled.

The human–animal bond also warrants deeper exploration in longer studies. Farmers who rely on extensive dashboards might find their empathy either eroded—through reduced direct interaction—or heightened, if data-driven insights deepen their understanding of individual animals' needs. Over successive generations, stockmanship practices could either become more refined, incorporating "data empathy" that merges algorithmic signals with hands-on care, or devolve into a reliance on remote supervision that overlooks subtle nuances observable only through close contact. Moreover, as data-based personalization grows, relationships between caretakers and animals might become more individualized or paradoxically more detached. Interdisciplinary projects that blend

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

veterinary science, anthropology, and human–animal studies could illuminate these socio-emotional dynamics across entire lifespans of herds and flocks. Such insights may prove crucial for guiding how PLF is scaled and integrated to maintain welfare-positive outcomes rather than succumbing to mechanistic oversight.

8.3. Expansion Beyond Mainstream Industrial Systems

Although PLF research and implementation have been most intensive in large-scale poultry, pig, and dairy operations, there is considerable scope for broadening its reach to less industrialized contexts. Small ruminants such as sheep and goats, as well as aquaculture species, remain understudied but could benefit from sensor technologies and automation tailored to their unique spatial and social needs. Similarly, water buffalo, camels, and other regionally significant livestock receive sparse attention in academic discourse, yet targeted applications of wearable monitoring devices or automated feeding systems might address welfare and efficiency concerns in these domains.

Alternative farming models also offer fertile ground for innovation. Organic, regenerative, and pasture-based systems often prioritize ecological integration and free-range behaviors, which may require PLF tools to accommodate less uniform environments and more variable management practices. In areas where power supplies or internet connectivity are inconsistent, low-cost, robust solutions that work offline or rely on minimal infrastructure could greatly expand global equity in livestock innovation. Open-source sensor platforms, for instance, may empower communities with limited resources to partake in digital agriculture while aligning with local cultural norms around animal husbandry. Such expansions may not only advance equity but also spur novel insights into how animals express agency under widely different environmental, cultural, and logistical conditions.

8.4. Bridging Theory and Practice: Human-Centric Intelligent Systems

Human-centric paradigms highlight user experience, trust, transparency, and accountability. Adapting these principles to farm animals is complex, given that livestock cannot verbally indicate frustration or satisfaction. Nevertheless, behavioral and physiological cues can act as proxies for "feedback," forming the basis for a multi-species interpretation of user-centered design. Research in Animal-Computer Interaction (ACI) demonstrates strategies to incorporate animals' intentions into system functionalities. For instance, reward-based interfaces allow animals to "opt in" to data collection or environmental adjustments, mimicking the core ethos of human consent in technology use. While these designs pose challenges in calibration and reliability, they can enhance agency by transforming the relationship between farm animals and devices from passive monitoring to an interactive, choice-driven dynamic.

Explainable AI, generally aimed at human users who need clarity on algorithmic decision-making, could also improve on-farm accountability. By providing transparent rationales for interventions—such as isolating an animal flagged as ill—managers can verify accuracy and ethical justification. This approach has the potential to reduce blind trust in automated solutions, encouraging farmers to retain critical insight and empathy. Policy interventions may also require that any PLF system collecting biometric data prove a net welfare benefit and a measurable expansion of autonomy. By bridging the gap between ethically guided human-centric ideals and animal realities, such measures help ensure that digital transformation in agriculture does not devolve into a mere exercise in optimization but instead elevates welfare and respects the inherent value of the animals involved.

8.5. Rethinking Livestock for the Twenty-First Century

Considerations of animal agency within a technologically advanced agricultural framework invite a deeper reevaluation of how societies conceptualize livestock. Historically, domestication

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

entrenched a hierarchy in which humans regulated every dimension of an animal's life. The digitization of farming could exacerbate such control if sensors and algorithms merely refine confinement methods, or it could partially reverse these dynamics by allowing animals to exercise real-time choices. Offering animals meaningful autonomy does not necessarily upend farm economics; rather, it can align with evolving consumer sensitivities and premium markets that privilege humane treatment.

Nevertheless, philosophical critiques persist, including arguments that true welfare cannot be achieved in an exploitative system oriented toward production, regardless of technological sophistication. Although such critiques challenge the basic premise of animal agriculture, pragmatic realities suggest that animals will continue to be farmed for the foreseeable future. In that context, integrating an agency-based ethic represents a more constructive and ethically forward path than ignoring sentience altogether. Granting animals greater latitude to exhibit core behaviors—roaming, socializing, or selecting dietary times—may not establish utopian conditions. Yet it does signal a move toward reconciling economic imperatives with moral obligations, a stance bolstered by rising consumer demand for ethically produced goods.

Through this lens, it becomes apparent that precision livestock farming need not be a monolithic force. When guided by the careful study of animal behavior, interdisciplinary stakeholder collaboration, and the clear articulation of welfare-oriented goals, PLF can offer not just incremental improvements but a paradigm shift in how humans and farm animals relate. Under such a vision, smart systems become conduits for respecting animal autonomy, mitigating suffering, and forging new ethical frameworks that redefine the boundaries of domestication in a rapidly changing century.

9. Conclusions

By exploring how precision livestock farming (PLF) and human-centric intelligent systems transform the relationships between humans, animals, and technology, I have underscored the critical importance of recognizing—and deliberately enhancing—animal agency in modern agriculture. This perspective goes well beyond simply reducing stress or preventing disease; rather, it places animals' capacity for self-determination, natural behavior, and social connectivity at the center of design and management strategies. Although PLF has been heralded as a means of improving productivity and better monitoring individual animals, my analysis reveals that uncritical reliance on automation and data can inadvertently reduce animals to passive objects of surveillance. In contrast, a truly animal-centered approach that integrates sensor data with empathic stockmanship can foster a more balanced interplay of technology and welfare, granting animals a voice (albeit indirect) in shaping their own living conditions.

An essential outcome of this review is the demonstration that technology need not always undermine autonomy if it is conceived and implemented ethically. By assessing automated milking systems, AI-driven monitoring tools, and wearable sensors, I have shown that these innovations can tailor care to individual animals and provide insights that would otherwise be imperceptible through conventional means. They can also reveal previously hidden dimensions of animal behavior and preference, such as shifts in movement patterns or social interactions, that farmers and engineers can adapt into more humane and flexible housing designs. Consequently, the core message that emerges is the possibility of integrating advanced computing with established ethological principles, thus creating a synergy that respects both productivity demands and the moral imperative to treat animals as sentient beings with intrinsic worth.

Nevertheless, the introduction of sophisticated technology alone does not guarantee an elevation in the quality of life for farm animals. Technology remains only as enlightened as the guiding values behind it. If industry goals prioritize efficiency and cost-effectiveness without accounting for animals' emotional and cognitive capacities, the very sensors and automated systems intended to detect welfare issues might simply reinforce confinement, regimentation, and a disconnection between farmers and their herds. My findings emphasize that in order to prevent these pitfalls, those who design and operate PLF systems must explicitly account for animal agency—

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

ensuring opportunities for self-expression, genuine choice, and the ability for animals to control key features of their immediate environments. By understanding animals' behavioral repertoires in detail, technology can become a channel through which positive welfare outcomes are achieved rather than a tool of further commodification.

The notion of human-centric intelligent systems expands our appreciation of how animals, farmers, and technologies interact. This perspective highlights that while farmers gain potential new insights and efficiencies from data-driven dashboards, they also risk losing the intimate, empathic connections that foster nuanced understanding of individual animals. To avoid such unintended consequences, training and system design must retain a place for hands-on, empathetic stockmanship. Another recurring theme in this review is that the perspectives of smaller-scale, organic, or regenerative operations are often marginalized when mainstream approaches assume uniform large-scale adoption. If meaningful animal agency is to be fully realized, design processes must include stakeholders from diverse farming contexts, integrating multi-species preferences, environmental constraints, and local cultural norms.

Overall, I have shown that the call for greater animal agency goes beyond minor welfare improvements to challenge the underlying assumptions of livestock production. Returning some measure of autonomy to animals could shift the structure of farming toward a more ethically grounded and ecologically mindful enterprise. By sustaining a focused conversation about the ethics and utility of PLF, and by encouraging multi-stakeholder participation, the field can move toward innovations that genuinely enhance both productivity and the self-determination of farmed species.

One remaining question is how to translate these insights into clear, enforceable guidelines that balance technological development, economic feasibility, and genuine animal empowerment. While scattered examples of good practice exist, scaling them up requires not only improved engineering but also robust policy frameworks and cultural acceptance. Ultimately, by continuing to refine AI algorithms that adapt to animals' self-initiated behaviors and by expanding pilot programs that test flexible housing designs, the industry might truly reconcile ethical obligations with the operational realities of feeding a growing population. It will require a concerted effort, but the potential reward is a future in which animals are no longer silent recipients of technology but active participants in shaping their own welfare.

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: Not Applicable.

Conflicts of Interest: The authors declare that they have no competing interests.

Funding: This work is kindly sponsored by the Natural Sciences and Engineering Research Council of Canada (RGPIN 2024-04450), Nova Scotia Department of Agriculture (NSDA), and the Department of NB Agriculture (NB2425-0025).

Author Contributions: SN is the sole author of this paper and sole contributor to writing the manuscript.

References

1. Neethirajan S. SOLARIA-Sensor-driven resilient and adaptive monitoring of farm animals. *Agriculture*. 2023;13(2):436. https://doi.org/10.3390/agriculture13020436
2. **de Boer J, Aiking H. Considering how farm animal welfare concerns may contribute to more sustainable diets. *Appetite*. 2022;168:105786.** https://doi.org/10.1016/j.appet.2021.105786
3. **Ammann J, Mack G, El Benni N, Jin S, Newell-Price P, Tindale S, Hunter E, Vicario-Modrono V, Gallardo-Cobos R, Sánchez-Zamora P, Miškolci S. Consumers across five european countries prioritise animal welfare above environmental sustainability when buying meat and dairy products. *Food Qual. Prefer.* 2024;117:105179.** https://doi.org/10.1016/j.foodqual.2024.105179

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

4. Neethirajan S, Kemp B. Digital livestock farming. *Sens. Bio-Sens. Res.* 2021;32:100408. https://doi.org/10.1016/j.sbsr.2021.100408
5. Neethirajan S, Scott S, Mancini C, Boivin X, Strand E. Human-computer interactions with farm animals—enhancing welfare through precision livestock farming and artificial intelligence. *Front. Vet. Sci.* 2024;11:1490851. https://doi.org/10.3389/fvets.2024.1490851
6. Lou S, Hu Z, Zhang Y, Feng Y, Zhou M, Lv C. Human-cyber-physical system for industry 5.0: a review from a human-centric perspective. *IEEE Trans. Autom. Sci. Eng.* 2024;22:494-511. https://doi.org/10.1109/TASE.2024.3360476
7. Shneiderman B. *Human-centered AI*. Oxford University Press; 2022.
8. Mazarakis A, Bernhard-Skala C, Braun M, Peters I. What is critical for human-centered AI at work?–toward an interdisciplinary theory. *Front. Artif. Intell.* 2023;6:1257057. https://doi.org/10.3389/frai.2023.1257057
9. Zhang L, Guo W, Lv C, Guo M, Yang M, Fu Q, Liu X. Advancements in artificial intelligence technology for improving animal welfare: current applications and research progress. *Anim. Res. One Health*. 2024;2(1):93-109. https://doi.org/10.1002/aro2.44
10. Neethirajan S. Artificial intelligence and sensor innovations: enhancing livestock welfare with a human-centric approach. *Hum. Centric Intell. Syst.* 2024;4(1):77-92. https://doi.org/10.1007/s44230-023-00050-2
11. Chang F, Gu Z, Shi Z, Tang W. Advancing cattle health monitoring through ACI-driven wearable sensor technology: a case study of leg-worn system development. *Proc. Tenth Int. Conf. Anim. Comput. Interact.* 2023 Dec;pp.1-13. https://doi.org/10.1145/3637882.3637893
12. Gehlot A, Malik PK, Singh R, Akram SV, Alsuwian T. Dairy 4.0: Intelligent communication ecosystem for the cattle animal welfare with blockchain and IoT enabled technologies. *Appl. Sci.* 2022;12(14):7316. https://doi.org/10.3390/app12147316
13. Wolfert S, van Wassenaer L, van der Burg S, Ryan M, Klerkx L, Rijswijk K, McCampbell M, Athanasiadis I, Beers G. *Navigating the twilight zone: pathways towards digital transformation of food systems.* Wageningen University & Research; 2021.
14. Lupton D. *The internet of animals: human-animal relationships in the digital age.* John Wiley & Sons; 2023.
15. Nelson XJ, Taylor AH, Cartmill EA, Lyn H, Robinson LM, Janik V, Allen C. Joyful by nature: approaches to investigate the evolution and function of joy in non-human animals. *Biol. Rev.* 2023;98(5):1548-1563. https://doi.org/10.1111/brv.12965
16. Wemelsfelder F. Boredom and laboratory animal welfare. In: Rollin BE, editor. *The experimental animal in biomedical research.* CRC Press; 2024. pp. 243-272.
17. Mancini C, Hirsch-Matsioulas O, Metcalfe D. Politicising animal-computer interaction: an approach to political engagement with animal-centred design. *Proc. Ninth Int. Conf. Anim. Comput. Interact.* 2022 Dec; pp.1-11. https://doi.org/10.1145/3565995.3566034
18. McGraw EB, Bosco C, Brey L, Nippert-Eng C. Dogs or not dogs? Examining ACI authors' reporting on animal participants' willingness to engage in research: a spotlight on mediated and contingent consent. *Proc. Tenth Int. Conf. Anim. Comput. Interact.* 2023 Dec; pp. 1-13. https://doi.org/10.1145/3637882.3637888
19. Neethirajan S. The use of artificial intelligence in assessing affective states in livestock. *Front. Vet. Sci.* 2021;8:715261. https://doi.org/10.3389/fvets.2021.715261
20. Neethirajan S. The role of sensors, big data and machine learning in modern animal farming. *Sens. Bio-Sens. Res.* 2020;29:100367. https://doi.org/10.1016/j.sbsr.2020.100367
21. Neethirajan S. Affective state recognition in livestock—artificial intelligence approaches. *Animals.* 2022;12(6):759. https://doi.org/10.3390/ani12060759

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

22. Hannan J, editor. *Meatsplaining: the animal agriculture industry and the rhetoric of denial*. Sydney University Press; 2020.
23. Neethirajan S. Transforming the adaptation physiology of farm animals through sensors. *Animals.* 2020;10(9):1512. https://doi.org/10.3390/ani10091512
24. Ekesbo I, Gunnarsson S. *Farm animal behaviour: characteristics for assessment of health and welfare*. 2nd ed. CABI; 2018.
25. Torgerson-White L. Animal emotion in farmed animal welfare assessment. In: Vonk J, Shackelford TK, editors. *Encyclopedia of Animal Cognition and Behavior.* Cham: Springer International Publishing; 2022. pp. 272-279.
26. Webster J. *Animal welfare: understanding sentient minds and why it matters.* John Wiley & Sons; 2022.
27. Hausberger M, Lesimple C, Henry S. Detecting welfare in a non-verbal species: social/cultural biases and difficulties in horse welfare assessment. *Animals.* 2021;11(8):2249. https://doi.org/10.3390/ani11082249
28. Blaxter T, Åsbjer E, Fraanje W. *Animal welfare and ethics in food and agriculture.* Oxford, UK; Uppsala, Sweden; Wageningen, the Netherlands: TABLE. 2024. https://doi.org/10.56661/f2d8f4c7
29. van der Laan S, Breeman G, Scherer L. Animal lives affected by meat consumption trends in the G20 countries. *Animals.* 2024;14(11):1662. https://doi.org/10.3390/ani14111662
30. Littlewood KE, Heslop MV, Cobb ML. The agency domain and behavioral interactions: assessing positive animal welfare using the five domains model. *Front. Vet. Sci.* 2023;10:1284869. https://doi.org/10.3389/fvets.2023.1284869
31. Neethirajan S. From predictive analytics to emotional recognition-the evolving landscape of cognitive computing in animal welfare. *Int. J. Cogn. Comput. Eng.* 2024;5:123-131. https://doi.org/10.1016/j.ijcce.2024.02.003
32. Molnár M. Transforming intensive animal production: challenges and opportunities for farm animal welfare in the european union. *Animals.* 2022;12(16):2086. https://doi.org/10.3390/ani12162086
33. Drummond EJ. *A sheep in wolf's clothing? the role of animal welfare science in european union farm animal welfare legislation* [Doctoral dissertation]. University of Leeds. 2022.
34. Špinka M. Animal agency, animal awareness and animal welfare. *Anim. Welf.* 2019;28(1):11-20. https://doi.org/10.7120/09627286.28.1.011
35. Mellor DJ, Beausoleil NJ, Littlewood KE, McLean AN, McGreevy PD, Jones B, Wilkins C. The 2020 five domains model: including human–animal interactions in assessments of animal welfare. *Animals.* 2020;10(10):1870. https://doi.org/10.3390/ani10101870
36. Browning H, Veit W. Freedom and animal welfare. *Animals.* 2021;11(4):1148. https://doi.org/10.3390/ani11041148
37. Browning H, Veit W. Animal welfare, agency, and animal–computer interaction. *Animals.* 2025;15(2):219. https://doi.org/10.3390/ani15020219
38. Abdai J, Miklósi Á, editors. *An introduction to ethorobotics: robotics and the study of animal behaviour.* Taylor & Francis; 2024.
39. Liu CY, Yin B. Affective foundations in AI-human interactions: insights from evolutionary continuity and interspecies communications. *Comput. Hum. Behav.* 2024;161:108406. https://doi.org/10.1016/j.chb.2024.108406
40. Nawroth C, Langbein J, Coulon M, Gabor V, Oesterwind S, Benz-Schwarzburg J, Von Borell E. Farm animal cognition—linking behavior, welfare and ethics. *Front. Vet. Sci.* 2019;6:24. https://doi.org/10.3389/fvets.2019.00024
41. Rault JL, Camerlink I, Goumon S, Mundry R, Špinka M. The joint log-lift task: a social foraging paradigm. *Front. Vet. Sci.* 2021;8:745627. https://doi.org/10.3389/fvets.2021.745627

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

42. Lage CA, Wolmarans DW, Mograbi DC. An evolutionary view of self-awareness. *Behav. Process.* 2022;194:104543. https://doi.org/10.1016/j.beproc.2021.104543
43. Maffezzini N, Turner SP, Bolhuis JE, Arnott G, Camerlink I. Third-party intervention and post-conflict behaviour in agonistic encounters of pigs (sus scrofa). *Front. Zool.* 2023;20(1):28. https://doi.org/10.1186/s12983-023-00508-w
44. Collarini E, Capponcelli L, Pierdomenico A, Cordoni G, Norscia I. Balancing welfare and habitat damage in pigs (sus scrofa) under extensive farming: an ethological approach for determining the effects of group composition and environmental enrichment. *Front. Ethol.* 2024;3:1450585. https://doi.org/10.3389/fetho.2024.1450585
45. Rørvang MV, Nawroth C. Advances in understanding cognition and learning in cattle. In: Endres M, editor. *Understanding the behaviour and improving the welfare of dairy cattle.* Burleigh Dodds Science Publishing; 2021. pp.17-35.
46. Cornips L, van Koppen M. Multimodal dairy cow–human interaction in an intensive farming context. *Lang. Sci.* 2024;101:101587. https://doi.org/10.1016/j.langsci.2023.101587
47. Stenfelt J, Yngvesson J, Rørvang MV. A calm companion lowers fear in groups of dairy cows. *J. Dairy Sci.* 2022;105(8):6923-35. https://doi.org/10.3168/jds.2022-21796
48. Nogues E. *Social behaviour of dairy cattle: inter-individual differences and implications for welfare* [Doctoral Dissertation]. University of British Columbia (Vancouver). 2023.
49. Langbein J, Moreno-Zambrano M, Siebert K. How do goats “read” 2D-images of familiar and unfamiliar conspecifics?. *Front. Psychol.* 2023;14:1089566. https://doi.org/10.3389/fpsyg.2023.1089566
50. Bushby EV, Friel M, Goold C, Gray H, Smith L, Collins LM. Factors influencing individual variation in farm animal cognition and how to account for these statistically. *Front. Vet. Sci.* 2018;5:193. https://doi.org/10.3389/fvets.2018.00193
51. Raoult CM, Osthaus B, Hildebrand AC, McElligott AG, Nawroth C. Goats show higher behavioural flexibility than sheep in a spatial detour task. *R. Soc. Open Sci.* 2021;8(3):201627. https://doi.org/10.1098/rsos.201627
52. Muhammad M, Stokes JE, Manning L. Positive aspects of welfare in sheep: current debates and future opportunities. *Animals.* 2022;12(23):3265. https://doi.org/10.3390/ani12233265
53. Tahamtani F, Pedersen I, Toinon C, Riber AB. Learning ability in broilers: does environmental enrichment help?. *Proc. 52nd Congr. Int. Soc. Appl. Ethol.* Canada: Wageningen Academic Publishers. 2018. p. 154.
54. Loconsole M, De Agrò M, Regolin L. Young chicks rely on symmetry/asymmetry in perceptual grouping to discriminate sets of elements. *Proc. R. Soc. B.* 2021;288(1957):20211570. https://doi.org/10.1098/rspb.2021.1570
55. Campbell DL, Lee C. A perspective on strategic enrichment for brain development: is this the key to animal happiness?. *Front. Vet. Sci.* 2021;8:720422. https://doi.org/10.3389/fvets.2021.720422
56. Clarke C, Knights D. Milking it for all it’s worth: unpalatable practices, dairy cows and veterinary work?. *J. Bus. Ethics.* 2021:1-6. https://doi.org/10.1007/s10551-020-04666-3
57. Webster J, Margerison J, editors. *Management and welfare of farm animals: the UFAW farm handbook.* 6th ed. John Wiley & Sons; 2022.
58. Webber S, Cobb ML, Coe J. Welfare through competence: a framework for animal-centric technology design. *Front. Vet. Sci.* 2022;9:885973. https://doi.org/10.3389/fvets.2022.885973
59. Jensen EH, Jensen MB, Neave H, Bateson M. Measuring motivations and preferences in dairy cattle: a scoping review. *UFAW Online Anim. Welf. Conf.* 2023. p.42.
60. Hernandez E, Llonch P, Turner PV. Applied animal ethics in industrial food animal production: exploring the role of the veterinarian. *Animals.* 2022;12(6):678. https://doi.org/10.3390/ani12060678

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

61. Hennessy DA, Marsh TL. Economics of animal health and livestock disease. In: Barrett CB, Just DR, editors. *Handbook of agricultural economics*. Elsevier. 2021. Vol. 5: pp. 4233-4330. https://doi.org/10.1016/bs.hesagr.2021.10.005
62. Dawkins MS. Smart farming and artificial intelligence (AI): how can we ensure that animal welfare is a priority?. *Appl. Anim. Behav. Sci.* 2025;283:106519. https://doi.org/10.1016/j.applanim.2025.106519
63. Garner R. *Animals, politics and morality*. Manchester University Press; 2024. https://doi.org/10.7765/9781526183743
64. Rutledge-Prior S. Addressing the will theory challenge to animal rights. *Polit. Stud.* 2024:00323217241253555. https://doi.org/10.1177/00323217241253555
65. Stucki S. Animal warfare law and the need for an animal law of peace: a comparative reconstruction. *Am. J. Comp. Law*. 2023;71(1):189-233. https://doi.org/10.1093/ajcl/avad018
66. Webster J. Animal welfare: freedoms, dominions and "a life worth living". *Animals*. 2016;6(6):35. https://doi.org/10.3390/ani6060035
67. EFSA AHAW Panel (EFSA Panel on Animal Health and Welfare), Nielsen SS, Alvarez J, Bicout DJ, Calistri P, Canali E, Drewe JA, Garin-Bastuji B, Gonzales Rojas JL, Schmidt CG, Herskin MS. Welfare of broilers on farm. *EFSA J.* 2023;21(2):e07788. https://doi.org/10.2903/j.efsa.2023.7788
68. Misztal I, Lourenco D. Potential negative effects of genomic selection. *J. Anim. Sci.* 2024;102:skae155. https://doi.org/10.1093/jas/skae155
69. Bhoj S, Tarafdar A, Singh M, Gaur GK. Smart and automatic milking systems: benefits and prospects. In: Sehgal S, Singh B, Sharma V, editors. *Smart and sustainable food technologies*. Springer, Singapore; 2022. pp. 87-121. https://doi.org/10.1007/978-981-19-1746-2_4
70. Marumo JL, Fisher DN, Lusseau D, Mackie M, Speakman JR, Hambly C. Social associations in lactating dairy cows housed in a robotic milking system. *Appl. Anim. Behav. Sci.* 2022;249:105589. https://doi.org/10.1016/j.applanim.2022.105589
71. Papakonstantinou GI, Voulgarakis N, Terzidou G, Fotos L, Giamouri E, Papatsiros VG. Precision livestock farming technology: applications and challenges of animal welfare and climate change. *Agriculture*. 2024;14(4):620. https://doi.org/10.3390/agriculture14040620
72. Neethirajan S, Reimert I, Kemp B. Measuring farm animal emotions—sensor-based approaches. *Sensors*. 2021;21(2):553. https://doi.org/10.3390/s21020553
73. Vigors B, Ewing DA, Lawrence AB. The importance of farm animal health and natural behaviors to livestock farmers: findings from a factorial survey using vignettes. *Front. Anim. Sci.* 2021;2:638782. https://doi.org/10.3389/fanim.2021.638782
74. Alonso ME, González-Montaña JR, Lomillos JM. Consumers' concerns and perceptions of farm animal welfare. *Animals*. 2020;10(3):385. https://doi.org/10.3390/ani10030385
75. Moran D, Blair KJ. Sustainable livestock systems: anticipating demand-side challenges. *Animal*. 2021;15:100288. https://doi.org/10.1016/j.animal.2021.100288
76. Neethirajan S. Metaverse for enhancing animal welfare-leveraging sensor technology and ethical considerations. *J. Emerg. Comput. Technol.* 2024;4(1):6-14. https://doi.org/10.57020/ject.1460995
77. Jiang B, Tang W, Cui L, Deng X. Precision livestock farming research: a global scientometric review. *Animals*. 2023;13(13):2096. https://doi.org/10.3390/ani13132096
78. Dhaliwal Y, Bi H, Neethirajan S. Bimodal data analysis for early detection of lameness in dairy cows using artificial intelligence. *J. Agric. Food Res.* 2025;21:101837. https://doi.org/10.1016/j.jafr.2025.101837

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 June 2025 doi:10.20944/preprints202506.0694.v1

79. **Rivero MJ, Grau-Campanario P, Mullan S, Held SD, Stokes JE, Lee MR, Cardenas LM. Factors affecting site use preference of grazing cattle studied from 2000 to 2020 through GPS tracking: a review.** ***Sensors.*** **2021;21(8):2696.** https://doi.org/10.3390/s21082696
80. **Herlin A, Brunberg E, Hultgren J, Högberg N, Rydberg A, Skarin A. Animal welfare implications of digital tools for monitoring and management of cattle and sheep on pasture.** ***Animals.*** **2021;11(3):829.** https://doi.org/10.3390/ani11030829
81. **George AS, George AH. Optimizing poultry production through advanced monitoring and control systems.** ***Partn. Univers. Int. Innov. J.*** **2023;1(5):77-97.** https://doi.org/10.5281/zenodo.10050352
82. **Andrade RR, Tinoco ID, Damasceno FA, Ferraz GA, Freitas LC, Ferreira CD, Barbari M, TELES CG. Spatial analysis of microclimatic variables in compost-bedded pack barn with evaporative tunnel cooling.** ***An. Acad. Bras. Ciênc.*** **2022;94(3):e20210226.** https://doi.org/10.1590/0001-3765202220210226
83. **Hofstetter D, Fabian E, Lorenzoni AG. Ammonia generation system for poultry health research using arduino.** ***Sensors.*** **2021;21(19):6664.** https://doi.org/10.3390/s21196664
84. **Neethirajan S. Rethinking poultry welfare-multifactorial and digital approaches to enhance animal well-being.** ***SSRN.*** **2024.** http://dx.doi.org/10.2139/ssrn.5034840
85. **Xiong Y.** ***Engineering solutions to address several current livestock and poultry housing challenges*** **[Doctoral dissertation]. University of Illinois at Urbana-Champaign; 2019.**
86. **Kopler I, Marchaim U, Tikász IE, Opaliński S, Kokin E, Mallinger K, Neubauer T, Gunnarsson S, Soerensen C, Phillips CJ, Banhazi T. Farmers' perspectives of the benefits and risks in precision livestock farming in the EU pig and poultry sectors.** ***Animals.*** **2023;13(18):2868.** https://doi.org/10.3390/ani13182868
87. **Aerts J, Kolenda M, Piwczyński D, Sitkowska B, Önder H. Forecasting milking efficiency of dairy cows milked in an automatic milking system using the decision tree technique.** ***Animals.*** **2022;12(8):1040.** https://doi.org/10.3390/ani12081040
88. **Robertson B, Riley M. "It's good to show happy cows": understanding farmer–livestock relations through social media.** ***Soc. Cult. Geogr.*** **2024;25(9):1417-1450.** https://doi.org/10.1080/14649365.2024.2329656
89. **Baur P, Iles A. Inserting machines, displacing people: how automation imaginaries for agriculture promise 'liberation' from the industrialized farm.** ***Agric. Hum. Values.*** **2023;40(3):815-833.** https://doi.org/10.1007/s10460-023-10435-5
90. **Prause L. Digital agriculture and labor: a few challenges for social sustainability.** ***Sustainability.*** **2021;13(11):5980.** https://doi.org/10.3390/su13115980
91. **McCaig M, Dara R, Rezania D. Farmer-centric design thinking principles for smart farming technologies.** ***Internet of Things.*** **2023;23:100898.** https://doi.org/10.1016/j.iot.2023.100898
92. Monteiro A, Santos S, Gonçalves P. Precision agriculture for crop and livestock farming—brief review. *Animals.* 2021;11(8):2345. https://doi.org/10.3390/ani11082345
93. Schillings J, Bennett R, Wemelsfelder F, Rose DC. Digital livestock technologies as boundary objects: investigating impacts on farm management and animal welfare. *Anim. Welf.* 2023;32:e17. https://doi.org/10.1017/awf.2023.16

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

© 2025 by the author(s). Distributed under a Creative Commons CC BY license.