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Precision Livestock Farming (PLF) for Grazing Animals: Technologies, Applications, and Future Directions

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Rising global demand for animal products, declining farm labour, and shrinking grazing lands have created an urgent need for more efficient livestock management systems. Precision Livestock Farming (PLF) addresses this challenge through real-time, automated monitoring using sensors, algorithms, and data-driven decision support tools. This article reviews the major PLF technologies applied to grazing cattle, small ruminants, pigs, and poultry, evaluating their scientific performance and commercial readiness. Technologies like Radio Frequency Identification (RFID), Global Positioning Systems (GPS), accelerometers, virtual fencing, Unmanned Aerial Vehicles (UAVs), and Convolutional Neural Networks (CNNs) consistently achieve monitoring accuracy above 90% in field conditions. However, widespread adoption remains limited by economic constraints, poor rural infrastructure, and insufficient cost-benefit evidence. Future PLF development must prioritise economic viability, user-friendly design, and species-inclusive research.

Keywords: animal welfare; behaviour monitoring; GPS; grazing animals; IoT; Precision Livestock Farming; RFID; virtual fencing;

Introduction

The global livestock sector faces a convergence of pressures: rising demand for animal products, a shrinking agricultural workforce, and progressive loss of grazing land to crop production. Grazing land constitutes approximately 60% of the world's agricultural area and sustains nearly 360 million cattle and over 600 million sheep and goats, supporting the livelihoods of more than 200 million people (FAO, 2013). Average milk and dairy consumption has risen steadily and is projected to increase by 50% by 2050 relative to 2010 levels (Thornton, 2010). Against this backdrop, individual animal monitoring, the cornerstone of effective welfare and productivity management, has become increasingly difficult at scale.

Precision Livestock Farming (PLF) offers a technologically mediated solution. Defined as the use of real-time, continuous monitoring and control systems employing sensors, data loggers, and computer algorithms for early problem detection and individual animal awareness, PLF represents a paradigm shift from reactive, population-level herd management to proactive, data-driven animal care (Berckmans, 2017). Potential benefits include improvements in animal health and welfare, reductions in labour and veterinary costs, more effective pasture management, and gains in both economic and environmental sustainability. This article reviews the principal PLF technologies applied to grazing animals across species, assesses their field performance, and identifies the key barriers and research priorities shaping the future of the field.

Key PLF Technologies and Their Performance

RFID and Identification Systems

Radio Frequency Identification (RFID) is among the most widely deployed PLF technologies, offering cost-effective, remote, and continuous individual animal identification.

Tags deployed as ear tags, rumen boluses, or injectable transponders store data on age, breed, weight, reproductive status, and medical history, which readers installed around the farm capture automatically. In grazing cattle, commercial RFID-based systems have demonstrated consistently high performance: the MooMonitor+ achieved 94% accuracy for grazing behaviour and 97% for rumination; the RumiWatch noseband sensor attained 96% and 98%, respectively (Werner *et al.*, 2017). Water intake monitoring via RFID reached 100% detection efficiency, while individual welfare assessment achieved 93% accuracy. For small ruminants, RFID is mandatory in the European Union and forms the foundation for recording milk yield, reproductive efficiency, growth performance, and medical treatments (Tzanidakis *et al.*, 2023).

GPS, GIS, and Accelerometers

Grazing animals frequently range over vast and topographically complex terrain, making conventional tracking methods inadequate. GPS collars, often combined with Geographic Information Systems (GIS) and tri-axial accelerometers, address this challenge by providing continuous positional data alongside behavioural classification. Turner *et al.* (2000) demonstrated 95% location detection accuracy and 94.8% grazing activity classification in a GPS-GIS collar system for cattle. When GPS is combined with accelerometers, behavioural classification accuracy improves further. Riaboff *et al.* (2020) achieved 98% accuracy in distinguishing grazing, walking, ruminating, resting, and lying behaviours while simultaneously correlating these patterns with pasture site characteristics. Four-year seasonal tracking studies have revealed systematic spatial preferences. Animals congregate near shade during hot months and range widely in cooler periods, providing actionable insight for pasture rotation and infrastructure planning (Tzanidakis *et al.*, 2023).

Virtual Fencing

Virtual fencing (VF) replaces physical barriers with GPS-linked collars that deliver an audio alert when an animal approaches a digitally defined boundary; if the animal ignores the warning, a mild electrical stimulus follows. Animals typically learn within days to respond to the audio cue alone. The boundary exists only in software and can be repositioned remotely, enabling flexible pasture rotation, riparian zone protection, and real-time grazing management without fence construction or dismantling. Multiple field studies have reported strong performance: Boyd *et al.* (2022) achieved 96% success in excluding cattle from ecologically sensitive burned land; other deployments have recorded efficiency rates as high as 99.8% (Campbell *et al.*, 2020). The technology also supports biodiversity conservation by enabling dynamic protection of biotopes and watercourses. Cost comparison with conventional barbed wire fencing (approximately $8,000/km annually) reveals that VF can deliver long-term savings for large-scale operations, though the upfront investment of approximately $12,500 per base station and $40 per collar lease per year remains a deterrent for smaller farms (Tzanidakis *et al.*, 2023).

IoT, CNN, and Emerging Technologies

Internet of Things (IoT) sensor architectures are increasingly integrating multiple data streams into unified farm management platforms. Accelerometer-based IoT systems have achieved overall behavioural classification accuracy exceeding 90%, with 96.98% specificity for normal walking behaviour. Neural network models applied to collar accelerometer data have verified feeding, walking, drinking, rumination, and resting behaviours with average accuracy above 98%, with potential for early disease and oestrus detection (Tzanidakis *et al.*, 2023). Convolutional Neural Networks (CNNs) applied to UAV aerial imagery have approached 100% accuracy in cattle detection under challenging lighting conditions (Barbedo *et al.*, 2019). An innovative concept using kinetic energy harvesting, converting the natural locomotion of animals into electrical power for wearable sensors, addresses battery limitations in remote deployment environments and represents a promising frontier for off-grid PLF applications.

PLF Across Species: Small Ruminants, Pigs, and Poultry

While cattle farming has led PLF adoption, the technology is expanding across species. For sheep and goats, wearable tri-axial accelerometers have been validated for classifying grazing, ruminating, resting, and locomotion behaviours, and can contribute to welfare assessment, lameness detection, and mating score measurement. Acoustic sensors mounted on the head of animals distinguish bite from chew jaw movements, enabling non-intrusive estimation of feed intake. Walk-over-weighing (WoW) platforms installed along animal access corridors record individual body weights automatically, while automated drafters sort animals into management groups based on weight, pregnancy status, or medical treatment need, substantially reducing manual handling (Tzanidakis *et al*., 2023). UAV-based flock surveys offer remote monitoring in mountainous terrain, and camera systems using the YOLOv5m deep learning architecture have achieved 99.49% precision in distinguishing predators such as the Iberian wolf from livestock guardian dogs in real time (Del Castillo *et al*., 2022).

For free-range poultry, a sector transformed by the European Union's 2012 ban on battery cages, image and video analysis accounts for more than 42% of welfare assessment PLF systems, reflecting the non-intrusive and low-cost nature of camera-based monitoring (Rowe *et al*., 2019). RFID systems track individual hen range use, feeding behaviour, stress responses, and welfare metrics over extended periods. Advanced applications include automatic egg collection robots, dead bird detection algorithms, and GPS-guided livestock guardian dogs for fox deterrence. For extensively managed pigs, GPS and accelerometer-based monitoring have documented foraging patterns, social grouping, and wallowing behaviour, revealing clear associations between environmental conditions and activity associations with direct welfare implications. Despite these advances, PLF adoption in the pig and poultry sectors remains limited by the small commercial scale of extensive operations and the continued absence of rigorous cost-benefit data.

Barriers to Adoption and Future Research Priorities

Despite the technical maturity of PLF systems, commercial adoption across grazing sectors remains low and is concentrated predominantly in cattle production. Multiple interacting barriers sustain this gap. Economic constraints are paramount: high upfront hardware and installation costs, combined with a near-total absence of rigorous farm-scale cost-benefit analyses in the scientific literature, make it difficult for producers and agricultural lenders alike to justify investment. Poor rural digital infrastructure, unreliable electricity, limited broadband, and patchy mobile coverage restrict the deployment of connected PLF systems, particularly in developing-world contexts where grazing livestock represent the most critical food security assets.

Cultural factors also play a significant role. Research among Irish dairy farmers documented a strong association between emotional attachment to traditional management practices and resistance to PLF adoption (Rieple & Snijders, 2018). Unresolved animal welfare concerns, particularly regarding electrical stimuli in virtual fencing, represent both an ethical consideration and a commercial risk, despite multiple studies finding no significant negative effects on animal behaviour or performance: software complexity and the absence of farmer-friendly interfaces further limit uptake among producers without technical backgrounds.

Future research should prioritise: (i) rigorous, multi-system cost-benefit analyses across diverse production contexts; (ii) longitudinal welfare assessments of aversive-stimulus technologies; (iii) development of low-power sensor architectures, including kinetic energy harvesting, for remote deployment; (iv) expansion of CNN training datasets to improve breed and species generalisation; and (v) co-design of farmer-friendly software platforms that lower technical barriers to entry. Equally important is the development of extension and policy frameworks that translate research findings into accessible guidance for producers at all scales.

Conclusion

Precision Livestock Farming has matured from a research concept into a field with demonstrated, high-accuracy applications across cattle, small ruminants, pigs, and poultry. RFID systems routinely achieve individual identification and behaviour monitoring accuracy above 90%; GPS-accelerometer combinations deliver equivalent performance in spatial and behavioural classification; virtual fencing demonstrates consistent field effectiveness of 95-100%; and AI-based imaging is approaching near-perfect accuracy in animal detection and real-time predator identification. These technologies collectively offer a credible pathway to more humane, productive, and environmentally sustainable grazing systems. Yet the gap between technical capability and commercial adoption remains wide and persistent. Bridging it will require coordinated action across research institutions, technology developers, extension services, and policymakers with a focus on economic evidence, inclusive design, and infrastructure investment. PLF will fulfil its potential not when the technology improves further, but when it becomes accessible and financially viable for the full diversity of farmers it is designed to serve.

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