ASSESSING BEEF CATTLE WELFARE VIA SMART WEARABLE SENSORS IN INTENSIVE AND EXTENSIVE FARMING SYSTEMS

D. N. Enea[1*], D. C. Popa[1], R. A. Popa[1], L. Vidu[1], E. Pogurschi[1], M. Marin[1], A. Vulpe[2], A.-I. Nicodim[1]

[1]University of Agronomic Sciences and Veterinary Medicine of Bucharest, 59 Marasti Blvd, District 1, Bucharest, Romania
[2]BEAM INNOVATION SRL, Romania

Abstract

Beef cattle welfare is traditionally assessed through periodic visual inspection, a subjective and discontinuous method. This review examines smart wearable sensors, including accelerometers, GNSS collars, and physiological monitors, as continuous alternatives for welfare assessment, using the Five Domains Model as a framework, and compares performance in intensive versus extensive systems. Evidence on sensor validation, behavior classification, GPS/GNSS tracking, virtual fencing, and heat stress and lameness monitoring was synthesized across seven thematic areas. Results show behavior-classification technology has reached reasonable maturity, increasingly validated on beef-specific breeds, but formal validation and translation of sensor output into welfare outcomes remain markedly less developed for extensive systems and beef cattle relative to dairy cattle. Mapping this gap, the review offers an original, system-specific synthesis guiding future validation priorities.

Key words: *beef cattle welfare, wearable sensors, precision livestock farming, intensive and extensive systems*

INTRODUCTION

Beef cattle production is a cornerstone of global animal agriculture, providing a major source of animal protein and supporting rural livelihoods worldwide, and the sector faces growing scientific and public scrutiny regarding the welfare of the animals it depends upon [1]. Historically, welfare assessment on commercial farms has relied on periodic visual inspection and clinical scoring performed by trained assessors, an approach that is labor-intensive, subjective, and inherently discontinuous, offering only a snapshot of an animal's condition at the moment of observation [2]. As herd sizes increase and the ratio of stockpeople to animals declines, the capacity to detect early and subtle deviations from normal behavior through human observation alone diminishes, creating demand for continuous, objective monitoring tools able to complement conventional assessment protocols [3].

Precision Livestock Farming (PLF) has emerged as a response to this demand, encompassing automated technologies, including wearable sensors, environmental monitoring equipment, and remote sensing that enable continuous, individual-level data collection on behavior and physiology [4]. Among these, wearable devices such as accelerometer-equipped collars, ear tags, leg bands, and boluses have attracted particular interest, as they can be deployed directly on the animal and record activity, posture, rumination, and body temperature without requiring constant human presence [5]. Linking this stream of sensor-derived

*Corresponding author: danut-nicolae.enea@usamv.ro
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data to the animal's actual welfare state, however, requires a conceptual framework capable of translating behavioral and physiological signals into meaningful welfare outcomes. The Five Domains Model, most recently updated to incorporate the quality of human-animal interactions, structures welfare assessment around nutrition, environment, health, behavior, and the resulting affective state, and is increasingly used as the reference grid against which sensor-based monitoring tools are evaluated [6].

A growing body of evidence supports the use of accelerometer-based sensors for classifying core behavioral indicators in cattle, including grazing, rumination, standing, lying, and locomotion, with several validation studies reporting good to excellent agreement against direct visual observation, even under the more variable conditions of pasture-based grazing systems [5, 7]. Global navigation satellite system (GNSS) collars, often paired with accelerometers, further extend monitoring capacity to spatial behavior, enabling continuous tracking of grazing patterns, resource use, and, more recently, the identification of behavioral changes associated with disease and other welfare concerns [8]. Wearable technologies have also been applied to monitor thermoregulatory responses to heat stress, a condition that increasingly compromises both productivity and welfare as extreme heat events become more frequent under climate change [9]. Collectively, these applications illustrate the breadth of physiological and behavioral information that can now be captured non-invasively and continuously at the individual animal level.

Despite this progress, the deployment and performance of wearable welfare-monitoring technologies differ markedly between intensive and extensive beef cattle systems. PLF tools have been developed and validated predominantly under the controlled conditions typical of intensive housing, where reliable connectivity, short transmission distances, and easy animal access facilitate both data collection and device maintenance [4]. Extensive systems, in which animals are raised largely outdoors and which account for approximately two-thirds of the world's agricultural land, present a fundamentally different set of constraints, including limited battery autonomy, inconsistent network coverage, larger inter-animal distances, and higher computational costs for on-device data processing [3, 4]. These constraints are especially relevant to beef cattle, a large proportion of which, unlike dairy cattle are raised under extensive or semi-extensive grazing systems for at least part of their production cycle [1].

A further limitation concerns the validation status of commercially available sensors. Systematic reviews indicate that only a small minority of wearable devices marketed for livestock welfare monitoring have undergone rigorous external validation against a recognized reference standard, with validation rates reported as low as 14% among sensors identified through market searches [2]. Moreover, the existing validation literature remains disproportionately concentrated on dairy cattle housed in intensive systems, leaving beef specific applications and particularly their performance under extensive, pasture-based conditions comparatively underexplored [2, 3].

Given these gaps, the present review aims to synthesize current evidence on the use of smart wearable sensors for assessing beef cattle welfare, with particular attention to how sensor performance, validation status, and practical applicability differ between intensive and extensive farming systems, in order to identify the methodological and technological priorities needed to advance objective, continuous welfare assessment across the diversity of beef production systems.

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MATERIAL AND METHOD

Evidence for this review was gathered through targeted searches of Web of Science, Scopus, PubMed, ScienceDirect, and MDPI Open Access, using combinations of terms such as wearable sensors, accelerometer, beef cattle welfare, precision livestock farming, virtual fencing, GNSS tracking, heat stress monitoring, and lameness detection, joined through Boolean operators. The search prioritized peer-reviewed journal articles published between 2000 and 2026, spanning both validation studies (e.g., sensor performance against direct observation or physiological reference measures) and conceptual or systematic reviews of welfare-monitoring technology. Sources unrelated to cattle, lacking a clear description of sensor deployment, or offering no verifiable methodological detail were excluded from the final selection.

The resulting corpus of 26 sources was grouped into seven recurring themes that emerged from the literature itself rather than from a predefined outline: conceptual welfare-assessment frameworks, the validation status of commercial sensor technologies, accelerometer-based behavior classification, operational differences between intensive and extensive management, GPS/GNSS and virtual-fencing applications, heat-stress monitoring, and lameness detection. Because beef-specific evidence is still comparatively limited, closely related dairy cattle studies were retained where the sensor technology and behavioral indicators were directly transferable, and this distinction is flagged explicitly wherever it affects the interpretation of results.

RESULTS AND DISCUSSIONS

1. Conceptual framework linking sensor data to welfare outcomes

The Five Domains Model provides the dominant conceptual structure for translating raw sensor output into welfare-relevant conclusions, organizing assessment around nutrition, physical environment, health, behavior, and the resulting mental or affective state of the animal, and has been progressively extended since its original formulation to explicitly incorporate positive welfare states alongside welfare compromise [6, 10]. Wearable sensors most directly populate the behavioral and health domains, capturing indicators such as lying time, feeding duration, rumination, and locomotion, which are established correlates of physical condition and, indirectly, of affective state (figure 1) [6].

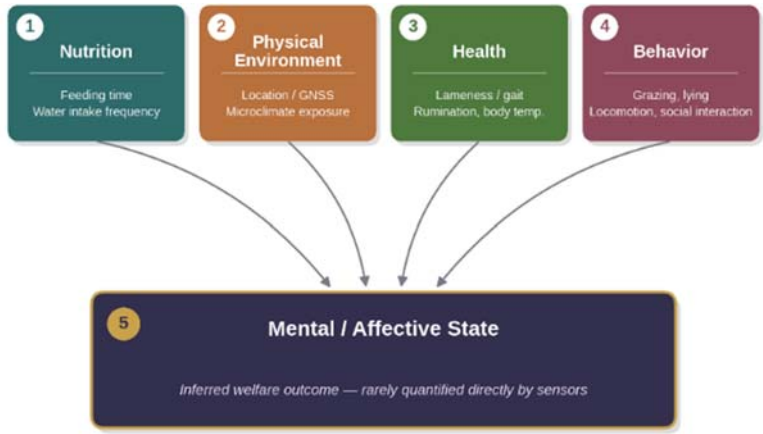


Figure 1 The Five Domains Model mapped to wearable-sensor indicators used in beef cattle welfare assessment

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No equivalent domain-by-domain audit has yet been published for beef cattle specifically, but the closest available benchmark comes from a systematic review applying the Five Domains framework retrospectively to 71 published studies of on-animal sensors in sheep, a comparably farmed ruminant species: it found that 90.1% of sensor applications addressed the Behaviour domain, while only 25.4% addressed the health domain and a further 25.4% addressed the Mental State domain directly [11]. In the absence of a cattle-specific equivalent, this cross-species evidence is used here only as an illustrative benchmark, and it points to a structural imbalance plausibly shared across ruminant welfare-sensor research more broadly: sensors overwhelmingly document what an animal does, far less often what condition it is in, and only rarely what it may be experiencing. Broader reviews of cattle welfare across production systems support this framework while emphasizing that welfare challenges and their behavioral expression differ substantially between intensive and extensive management, reinforcing the need for system-specific interpretation of sensor-derived indicators rather than a single universal threshold applied across contexts [1].

2. Validation status of commercially available wearable sensors

A key finding consistently reported across the reviewed literature is the low proportion of commercially marketed sensors that have undergone rigorous external validation. A systematic review screening over 1,100 publications identified 129 commercially available technologies for dairy cattle welfare monitoring, of which only 18 (approximately 14%) had been validated against an independent reference standard, with accelerometer-based devices showing the highest validation rate among sensor types at around 30% (table 1, figure 2) [2].

Table 1 Validation status of commercially available sensor technologies for cattle welfare monitoring (adapted from Stygar et al., 2021)

Parameter	Value
Publications screened	>1,100
Commercial technologies identified	129
Externally validated technologies	18 (14%)
Accelerometer validation rate	~30%
Studies meeting full validation criteria	42 (describing 30 instruments)

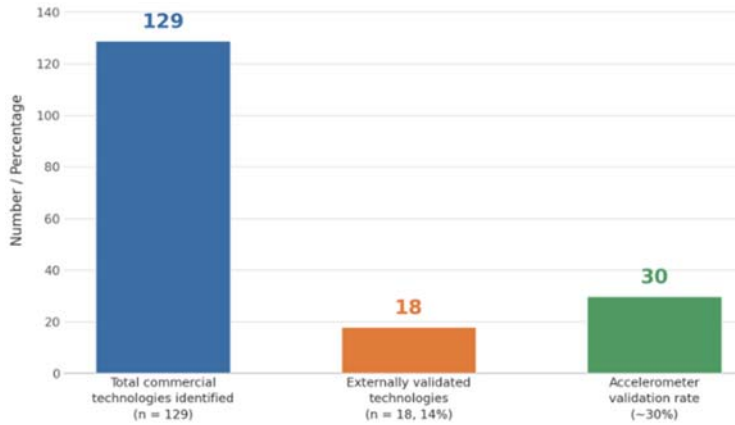


Figure 2 Validation status of commercially available sensor technologies for monitoring (adapted from Stygar et al. 2021)

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A complementary classification and review effort focused specifically on intelligent wearable devices and biosensors for cattle health monitoring collected and classified 54 studies according to sensor type, measured health parameter, body attachment site, and data collection method, concluding that sample sizes were frequently modest, that most trials were conducted indoors to control for environmental interference, and that wireless transmission reliability and device durability remained recurring practical obstacles [12]. This pattern is consistent with the validation gap identified for lameness-detection systems, where automated approaches are formally classified into four levels of technological maturity (table 2) [13].

Table 2 Four-level maturity scheme for automated lameness detection systems (adapted from Alsaaod et al., 2019)

Level	Description	Evidence status in reviewed literature
I	Sensor technique capable of acquiring raw data	Well documented
II	Raw data processed via a specific, validated algorithm	Well documented
III	Demonstrated diagnostic performance vs. reference standard (locomotion/lesion score)	Documented, moderate-to-high agreement [14, 15]
IV	Decision-support system with real-time early warning	Not yet documented under commercial conditions

More recent evaluations of artificial-intelligence-based lameness detection confirm that automated systems drawing on gait analysis via accelerometers, weighing platforms, acoustic analysis, radar sensors, and computer vision are now able to classify lame versus non-lame cows with generally adequate reliability, although the majority of validation studies continue to rely on visual mobility scoring rather than confirmed foot lesion records as the ground truth, and remain concentrated in dairy herds [14]. Commercial video-surveillance systems for automatic lameness detection have also undergone initial field validation on working dairy farms, illustrating that level III validation is achievable outside experimental settings, though comparable field-scale validation for beef systems has not yet been reported [16]. A dedicated review of accelerometer-based lameness detection further confirms that leg- and neck-mounted devices can reliably flag gait asymmetries associated with lameness on commercial farms, but again almost exclusively in dairy contexts [15].

3. Composition and thematic distribution of the reviewed evidence base

The 26 verified sources retained for this review were distributed across seven thematic clusters reflecting both the conceptual and applied dimensions of wearable sensor use in beef cattle welfare assessment (figure 3), confirming that the technical feasibility of behavior classification and the constraints of intensive-versus-extensive deployment are comparatively well documented, whereas the direct translation of sensor output into welfare-domain scores for beef cattle specifically remains a less consolidated area of the literature.

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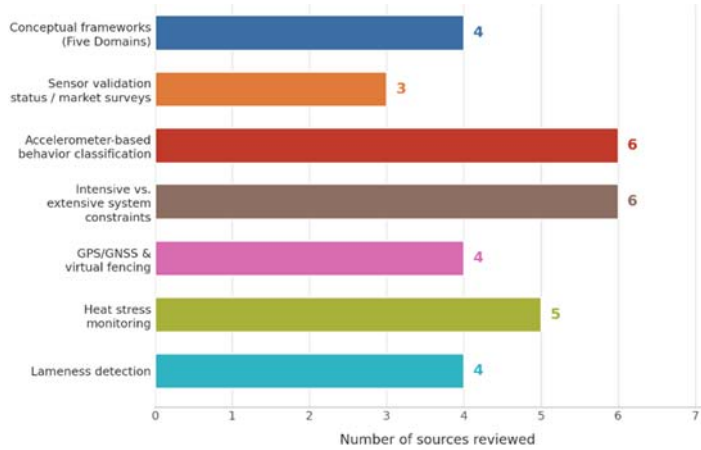


Figure 3 Distribution of the reviewed sources across the seven thematic clusters addressed in this review

4. Accelerometer-based behavior classification in beef cattle

Triaxial accelerometers mounted on collars, ear tags, or legs are the most extensively validated sensor modality for classifying core behavioral states in beef cattle, including grazing, rumination, lying, standing, and locomotion. Studies using machine learning classifiers, most commonly Random Forest, Support Vector Machine, decision trees, and k-nearest neighbour algorithms, report high overall classification accuracy, although performance varies according to behavior frequency, collar placement, and the resampling strategy applied to the training dataset (table 3) [5, 7, 17, 18, 19, 20, 21].

Table 3 Reported characteristics of accelerometer-based behavior classification studies in beef cattle

Study	System / breed	Behaviors classified	Algorithm(s)	Key finding
Poulopoulou et al., 2019 [5]	Grazing beef cattle	General activity budget	Automated activity sensors	Reliability of automated sensors confirmed under grazing conditions
Watanabe et al., 2021 [7]	Grazing (Nelore, Brazil)	Grazing, ruminating, idle, walking, feeding, water consumption	RF, SVM, NBC	RF + resampling improved detection of rare behaviors
Versluijs et al., 2023 [17]	Free-ranging, forested (Norway); beef crossbreds	10 behaviors (feeding, resting, walking, scratching, etc.)	Random forest	Pre-processing choices materially affect accuracy
Lund et al., 2026 [18]	Virtual fencing (Angus)	Grazing/feeding, ruminating, lying, standing, locomotion	Random forest	Mean accuracy = 0.87 (range 0.83–0.90)
Parsons et al., 2024 [20]	Grazing (Brahman-cross, USA)	Grazing, resting, walking	Random forest	10-s smoothing window improved accuracy
Simanungkalit et al., 2021 [21]	Penned beef cattle (Angus)	Licking, eating, standing, lying	DT, RF, SVM, kNN	Neck-collar and ear-tag both acceptable (88% / 98% accuracy)
Bretas et al., 2023 [19]	Grazing beef cattle, weed-encroached pasture	Grazing, resting, traveling	GPS/GIS classification	GPS-based activity linked to freedom to express normal behavior

Note: *RF = Random Forest; SVM = Support Vector Machine; NBC = Naïve Bayes Classifier; DT = Decision Tree; kNN = k-Nearest Neighbour; GIS = Geographic Information System*

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A consistent finding across these studies is that infrequent but welfare-relevant behaviors, such as drinking, licking, or resting bouts, are more difficult to classify reliably than dominant behaviors like grazing, and require targeted resampling, feature-selection, or dual sensor placement (neck-collar plus ear-tag) strategies to avoid underrepresentation in training datasets [7, 21]. Studies conducted under free-ranging or rugged terrain conditions further show that pre-processing choices, including smoothing window length and collar orientation, materially affect classification outcomes, underscoring that models validated under one set of environmental and topographic conditions do not necessarily generalize to another [17, 20]. Notably, several of these studies worked with beef breeds directly, Nelore, Angus, Brahman-cross, and mixed European beef crossbreds, partially offsetting the dairy-dominated bias identified in the validation literature more broadly, and suggesting that accelerometer classification pipelines developed for beef cattle, including under free-ranging conditions, are becoming increasingly robust to real-world topographic and behavioral variability [7, 17, 18, 19, 20, 21].

5. Applications in extensive and rangeland systems: GPS/GNSS tracking and virtual fencing

Extensive systems introduce operational constraints largely absent from intensive housing, including battery longevity, network connectivity, larger inter-animal distances, and the computational cost of on-device processing, all of which affect the practical deployment of wearable welfare-monitoring tools (table 4, figure 4) [3, 4, 22].

Table 4 Distinguishing operational and validation characteristics of intensive versus extensive beef cattle systems relevant to wearable sensor deployment

Dimension	Intensive systems	Extensive systems
Network connectivity	Reliable Wi-Fi/LAN	Limited/no coverage; satellite or LoRa required
Transmission distance	Short	Long, herd dispersed over large area
Animal accessibility	Frequent (maintenance, battery change)	Infrequent; battery autonomy critical
Validation study coverage	High (mostly dairy)	Sparse (mostly beef/rangeland)
GNSS accuracy	Minimal terrain interference	Reduced by rugged/forested terrain [17]
Share of global agricultural land	Smaller	~two-thirds of global agricultural land [3, 4]

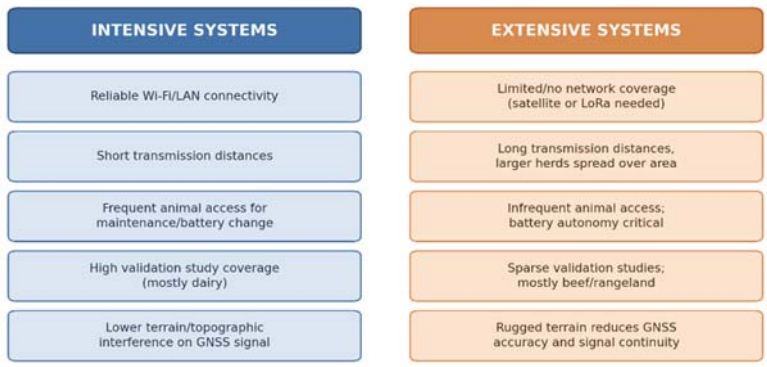


Figure 4 Comparative operational constraints for wearable sensor deployment in intensive versus extensive beef cattle farming systems

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GPS technology applied to beef cattle grazing management dates back over two decades: an early foundational study demonstrated that lightweight GPS collars recording animal position at 5-minute intervals, combined with geographic information system (GIS) analysis, could characterize spatial and temporal grazing behavior and forage utilization patterns on pasture [23]. This approach has since been extended to more complex rangeland management questions, including the monitoring of cattle behavioral responses to weed encroachment in grazing systems, where GPS-derived activity budgets (grazing, resting, traveling time) were used as a proxy for the animal's freedom to express normal behavior, one of the foundational welfare principles most directly challenged in degraded extensive pasture [19]. GNSS collars combined with accelerometers have also been used to detect behavioral deviations associated with disease and other welfare concerns under rangeland conditions, including a documented case in which reduced activity was recorded in the days preceding visual detection of illness in a grazing heifer [8].

Virtual fencing technology, which combines GNSS positioning with audio and mild electrical cues delivered through a collar in place of physical fencing, has emerged as a particularly active application area for extensive beef systems, and reviews of pasture-based PLF technologies identify battery lifespan, transmission range, service coverage, and economic affordability as the principal constraints on its wider adoption [22]. Behavioral studies of habituated cattle managed under virtual fencing report no pronounced disruption of normal behavioral time budgets relative to conventional management, suggesting that, once animals are habituated, the welfare cost of the containment method itself may be limited [17, 18]. However, this evidence remains drawn from a small number of herds and breeds, and longer-term or larger-scale validation across diverse extensive contexts is still lacking [17, 18].

6. Physiological monitoring: heat stress

Wearable and semi-invasive sensors, including ear tags, boluses, implantable biosensors, and neck- or head-mounted accelerometer/noseband devices, have been applied to monitor thermoregulatory behavioral and physiological responses associated with heat stress, a welfare and productivity concern expected to intensify under climate change [9]. Reviews of this literature emphasize that minimally invasive, continuous monitoring platforms are likely to become central to future heat-stress management, integrating behavioral indicators alongside physiological signals into composite risk indices [9].

Field studies support this direction: activity-sensor monitoring of 40 dairy cows in Spain under summer conditions showed that increasing Temperature-Humidity Index (THI) produced increased general activity, altered feeding patterns, and decreased rumination and resting behavior, effects the authors proposed could form the basis of an automatic early-warning system for heat stress [24]. Similarly, RumiWatch noseband sensors deployed on Lithuanian Black-and-White cows detected significant reductions in drinking time (-51.16%) and chewing rate (-12.9%), alongside a 16.99% increase in general activity, once THI exceeded a threshold of 72, confirming that jaw-movement and activity sensors can detect physiologically meaningful heat-stress responses at the individual level [25]. At the physiological level, implantable subdermal biosensors combined with wearable RFID scanners have been shown to track core body temperature in real time with values closely tracking vaginal (core) temperature measurements, and machine-learning models were able to predict core body temperature from subdermal readings and THI data, offering a minimally invasive

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route to individualized heat-stress monitoring [26]. This asymmetry toward dairy cattle is particularly relevant for beef cattle raised extensively in warm climates, where shade and water access may be limited and where the animal cannot be relocated as readily as in a housed system.

7. Physiological monitoring: lameness detection

Lameness detection represents one of the most methodologically mature applications of sensor-based welfare monitoring, with kinematic, kinetic, and indirect (behavior-based) detection methods evaluated against visual locomotion or lesion scoring as the reference standard [13]. While reported agreement between automated and human assessment is generally moderate to high, and commercial video-surveillance systems have begun to undergo field-level validation on working farms [16], the persistent absence of validated level IV early-warning systems under commercial conditions, combined with the near-total concentration of this evidence base in dairy cattle, represents a clear translational gap for beef production systems, particularly those managed extensively where early intervention is logistically more difficult [13, 14, 15].

Synthesis

Taken together, the evidence indicates that wearable sensor technologies for beef cattle welfare assessment have reached a reasonable level of technical maturity for core behavior classification (grazing, rumination, lying, licking), increasingly validated on beef-specific breeds and under free-ranging conditions [7, 17, 18, 19, 20, 21], but that formal validation, physiological monitoring, and translation into welfare-domain scores remain markedly less developed for extensive, beef-specific contexts than for intensive, dairy-dominated ones [2, 11, 12, 13, 14, 15, 16]. This asymmetry, consistently visible across all seven thematic clusters summarized in figure 3, constitutes the central evidence gap that motivates continued research effort in this area.

CONCLUSIONS

Wearable sensor technology for classifying core behavioral indicators of beef cattle welfare has matured to a point where it can reliably support practical, on-farm welfare monitoring. The scientific challenge has therefore shifted away from sensing and classification accuracy and toward the meaningful translation of behavioral output into standardized welfare judgments, a shift with direct implications for how future research and development efforts should be prioritized.

The conceptual bridge between raw behavioral data and actual welfare state is still underdeveloped, with existing frameworks applied unevenly across welfare domains. Strengthening this bridge, rather than further refining behavior-classification performance in isolation, represents the most valuable direction for advancing both the scientific understanding and the practical utility of sensor-based welfare assessment in beef cattle.

A persistent gap between commercially available sensors and scientifically validated instruments, compounded by a species imbalance favoring dairy over beef systems. This has practical consequences for end users, who currently have limited means of distinguishing reliable technologies from unproven ones. Closing this gap is essential for enabling farmers and veterinarians to adopt these tools with confidence.

Because intensive and extensive beef production systems differ fundamentally in their deployment conditions, technologies validated in one context cannot be assumed to perform equivalently in the other. Given the global importance of extensive grazing systems to beef production, prioritizing direct, side-by-side validation across both system types is a practical necessity for ensuring that sensor-based welfare monitoring can be meaningfully and equitably applied across the diversity of real-world beef farming contexts.

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