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## Original Research Paper

# Sensor Based Early Warning Indicators of Welfare Compromise in Extensively Managed Ruminant Production Systems

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**Key Words**

Sensor-based monitoring, Early warning system, Ruminant welfare, Extensive systems, Animal health, Environmental stress, Sensor fusion.

**Abstract**

The large-scale ruminant production systems, including grazing-based cattle, sheep, and goat management, are part of global food security with major welfare issues as a result of environmental stressors, nutritional deficiency, and other threats that are inherent in open-range management. The conventional welfare assessment techniques of such systems are not sufficient in many cases because of the magnitude and distance of the operations, and it is not easy to identify welfare compromise starting in time. The proposed study hypothesizes the implementation of an early warning system based on sensors to examine and determine the welfare compromise in high-managed ruminants by using continuous and non-invasive data recording. The system combines behavioral, physiological, and environmental data of wearable sensors, which can be activity, rumination, and body temperature sensors, and GPS and environmental sensors, to get a cohesive picture of the state of health and well-being of an animal. Early deviation of the system from the baseline welfare states can be identified, and timely interventions can be made to ensure that welfare does not deteriorate. The findings indicate that the system has a high detection accuracy (maximum of 94.6 %) and sensitivity (92.8 %) to the early indicators that include reduced grazing, abnormal activity, and an increased body temperature, with a lead time ranging from 12 to 48 hours prior to the onset of visible symptoms. The research paper has pointed out the resilience of the system in a wide range of environments, especially during heat stress and resource-constrained settings. This system can provide a viable, scalable solution to enhance the welfare management and sustainability of large ruminant systems by coupling large-scale environmental adaptation with welfare surveillance. The next step in future activity will be to perfect sensor fusion methods, develop greater ecological integration, and research policy frameworks to allow greater implementation of sensor-based welfare monitoring to facilitate sustainable ruminant management and climate resilience.

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## Introduction

Systems of large-scale ruminant production, such as grazing-based cattle, sheep, and goat husbandry, are both critical to global food security and to livelihoods in agro-ecological landscapes of variety. These systems have been noted to be large in size of grazing area, fluctuate between changing environmental conditions, and require minimal human interventions, which render them economically and ecologically important. But animals kept in large areas are very susceptible to welfare issues like heat stress, nutritional deficiency caused by the changing availability of pastures, lameness developed as a result of long-distance transport, disease outbreak early in life, and the risk of predation. Most of these stressors are progressive, and they may only be realized when they lead to clinical manifestations or losses of production, hence negating the welfare of animals and their sustainability in the systems.

The conventional welfare evaluation in large systems is based firmly on regular visual inspection and manual ratings, which are costly, subjective, and may well not be feasible on a large scale. The high number of animals per herd and the inaccessibility of the grazing locations of large production make human-based monitoring less frequent and less accurate, which results in late interventions and diminished potential to address welfare compromise at the initial stages. These restrictions only increase the susceptibility of ruminant populations as the variability of the environment and stressors associated with climate increase.

Here, the proposed research will create and examine a sensor-based early warning system to identify welfare compromise in ruminants that are extensively managed. The primary accomplishments of this work are the identification of ecologically significant welfare indicators, the combination of data from animal-based and environmental sensors, and the explanation that early detection can be used to provide a timely response to management. This study aims to enhance practical and scalable solutions that can be used to boost the welfare of livestock and maintain the sustainability of large-scale ruminant production systems by ensuring the welfare of animals is matched to the environments they are in.

The paper is arranged in the following way: The first part is the Introduction, where the problems of large ruminant systems are outlined, such as environmental pressure and restrictions on monitoring the welfare of animals, and a sensor-based early warning system is suggested. The Related Work is a review of the available literature on welfare indicators and PLF, and the gaps and issues in such systems' application to large-scale environments. Materials and Methods The paper describes the addition of behavioral, physiological, and environmental sensors to monitor the welfare. Findings indicate that the system is effective at an early stage of detection, and it is highly accurate and sensitive. The Discussion provides the interpretation of these findings, which is based on the existing works, and the practical feasibility of the system in large-scale systems. The Conclusion concludes the contributions of the study and sets forth future research directions, i.e., sensor fusion and policy implications to the sustainable ruminant management.

## Related Work

Traditional methods of animal welfare evaluation in ruminants have been based on the animal-related indicators (body condition, lameness, lesions, disease indicators, and expression of behavior). Reviews in the pasture point out that such measures are often very informative, although some measures are more or less valid and practical across different situations dictated by the skill of the person who is viewing, as well as the frequency of inspection and the situation in the fields (Spigarelli et al., 2020; Linstädt et al., 2024). Welfare compromise is frequently motivated by environmental exposure and variability of resources in large systems, and hence, indicators should not just be applied to the state of the animal but to the risk context of the environment (Džermeikaitė et al., 2023; Temple & Manteca, 2020). This complicates welfare monitoring as compared to indoor or intensive environments, where there is more access to observation and control of the environment (Leliveld & Provolo, 2020).

Precision livestock farming (PLF) has grown beyond productivity monitoring to welfare-based applications such as the early prevention of health and behavioral abnormalities (Simitzis et al., 2021; Vlaicu et al., 2024). Reviews indicate that PLF has the potential to facilitate welfare because it allows constant and objective inspection and interventions faster than visual inspection (Herlin et al., 2021; Simitzis et al., 2021). Nevertheless, the majority of built-in automatic welfare assessment ideas had been initially produced to serve indoor dairy networks, in which stable buildings, electrical, and data connectivity are accessible. Consequently, the application of the benefits of PLF in large-scale grazing situations is still a problem of concern, especially when systems have to operate with a minimum of handling, a long-range and uneven terrain (Hofstra et al., 2022; Mancuso et al., 2023).

One of the main advantages of sensor-based monitoring is that it is able to detect subtle pre-clinical changes. An instance is that wearable sensing of small ruminants has been assessed to be handy in monitoring activity, rumination, and physiological condition, and the signals can be associated with well-being and health outcomes (Caja et al., 2020). Cattle studies through grazing also reveal significant correlations between sensor-derived characteristics and productivity, health, and welfare parameters when conditions are in pastures (Jaeger et al., 2019). In the reviews of dairy and ruminant welfare technology, sensors have been most commonly addressed regarding lameness, mastitis, changes in body condition, and behavioral alterations, since the latter are issues where changes have been observable before any critical compromise has been achieved (Silva et al., 2021). Simultaneously, outlining the increased importance of AI and human-centered digital solutions to convert the complex sensor streams into actionable decisions on welfare, instead of the raw data dashboard, has been highlighted in recent work (Neethirajan, 2024).

Many current works of literature have a common theme of welfare monitoring related to sustainability and climate resilience, particularly when the context is about small ruminant systems that become more vulnerable to heat stress or face more uncertainty in forage (Ciliberti et al., 2025). The large systems are a source of welfare concern due to the potential of climatic extremes and long distances of grazing that may increase risks, but minimize the viability of frequently manipulating or veterinary monitoring (Temple & Manteca, 2020). Reports on progress in large areas point to the fact that the welfare increase needs methods that are both sensible on a scale and adhere to environmental regulations, but not only to the diagnosis of animals (Windsor, 2021). Methods that determine location (e.g., GPS and other mapping methods) are thus being considered as methods of welfare management as they can connect animal movement patterns with pasture quality, access to water, and areas of risk hotspots (Hofstra et al., 2022).

Much as there is evident potential, extensive and semi-arid production situations have a number of gaps. To begin with, the practicality of behavior sensing in large farms has problems like signal noise, collar fit variability, missing data, battery constraints, and connectivity, which, when not specified in design, may decrease reliability (Silva et al., 2023). Second, most of the welfare indicators discussed in the literature are tested in controlled or semi-controlled systems, and thus might not translate well to the highly variable grazing systems. Third, digital tools have the potential to enhance welfare decision-making, although their welfare implications will be determined by the interpretation and use of data, i.e., the usability and the management fit is as critical as sensor accuracy. Lastly, large-scale systems are yet to be made intelligent to be robust, low-input, and economically viable so that they can be adopted in the real world (Morgan-Davies et al., 2024; Paolino et al., 2025; Babiciu et al., 2025).

Based on these understandings, the current paper is pegged as a step towards sensor-based early warning alerts that are specially tailored to massively controlled ruminants. Instead of being concerned with late clinical detection, the proposed direction puts emphasis on (i) early warnings of deviation based on baseline behavior and physiology, (ii) explicit combination of environmental exposure and location-specific risk, and (iii) decision-making logic that is adapted to field constraints of sparse infrastructure and high environmental variability. By doing this, the framework directly responds to the practicality-transference gap noted in pasture welfare reviews and equally challenging extensive monitoring solutions, and welfare enhancement with the purposes of sustainability and climate resilience.

## Materials and Methods

To provide an efficient method of early identification of welfare loss in livestock that are extensively managed, the selection of indicators must be done with care to ensure that the indicators used are biologically relevant and can be measured in the field. The welfare indicators in this study are organized in terms of behavioral, physiological, and environmental areas, which is a multidimensional approach to animal welfare in grazing systems.

Behavioral indicators are the most sensitive and the first indicators of welfare change. Daily movement rhythms, walking, standing, grazing, and resting are characterized using activity patterns based on the accelerometer data. Deviations of the base activity of individuals or herds may reflect the emergence of stress, lameness, and illness. Inferred feed-seeking behavior and pasture usage are indicated by grazing time and spatial movement patterns, which are in turn reflected in the combined accelerator and GPS data, where most of the reductions are linked to nutritional stress or heat load. The posture-related sensor signal is classified to extract lying bouts and rest time because an abnormal frequency of lying or long standing may be pointers to discomfort, fatigue, or musculoskeletal problems.

Physiological indicators capture the internal responses to the stressors that are not yet evident in the behavior. Variation in body temperature, which is derived using wearable devices or rumen devices, is compared to identify more persistent changes or anomalous diurnal histograms associated with heat stress, infection, or inflammation. Rumination behavior, which is determined by jaw movement or an acoustic sensor, is a sensitive indicator of digestive fitness and overall well-being. Repeated decreases in rumination time are usually linked to nutritional imbalance or the development of disease or stress in the environment.

The environmental indicators give sufficient background to the interpretation of the animal signals. House metrics that are derived based on ambient temperature and relative humidity are used to assist in identifying cases of thermal stress. Pasture access and grazing circumstances based on the location data and environmental detection are used to differentiate between behavior alterations brought about by the compromise of welfare and those brought about by typical ecological variations.

The noise filtering, temporal aggregation, and normalization of the raw sensor streams are done to compensate for individual variability and sensor drift. Higher-level features are obtained from these processed signals, which include activity variability indices, temperature deviation scores, rumination stability measures, and environment-adjusted behavior measures. Under the consideration that deviations of set limits instead of absolute limits can define the resulting feature set, the approach aims at detecting stress or compromise at an early stage in order to have the welfare managed proactively before clinical manifestations can be observed.

Figure 1 demonstrates a combined sensor-based system of constant welfare checks in a grazing ruminant system. Environmental and GPS sensors enable the provision of contextual data about climatic exposure and spatial movement, whereas wearable sensors monitor behavioral and physiological signatures, including activity, rumination, and body temperature. Such multi-source streams of data are sent to a central processing unit to be integrated, preprocessed, and analytically assessed by pattern recognition and threshold-based detection. The consequent early warning signs, such as decreased grazing, abnormal behavior, and high body temperature, justify timely management actions, such as health checks, shade and water supply, and nutritional changes, to prevent proactive welfare protection in unfavorable and environmentally diverse environments.

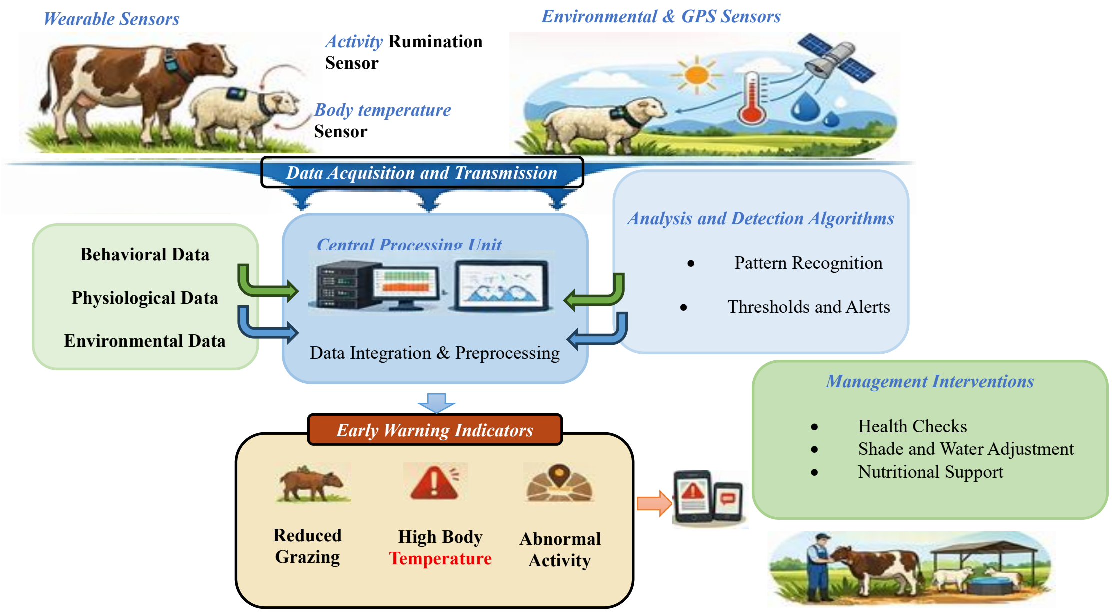


Figure 1: Sensor-Based Welfare Monitoring Framework for Early Detection of Welfare Compromise in Extensively Managed Ruminants

## Results

The welfare monitoring system proposed showed a remarkable ability to detect early warning of welfare loss in ruminants with extensive scale management under different environmental conditions. The early warning framework was practical as it was able to identify behavior and physiological deviations ahead of clinical manifestations.

Table 1: Performance of the Sensor-Based Early Warning System in Detecting Welfare Compromise

| Welfare Indicator | Detection Accuracy (%) | Sensitivity (%) | Average Lead Time Before Visual Symptoms | Environmental Context |
|---|---|---|---|---|
| Reduced grazing activity | 91.4 | 89.7 | 24–48 hours | Low pasture availability, heat load |
| Rumination anomaly | 93.2 | 91.5 | 18–36 hours | Nutritional stress, disease onset |
| Elevated body temperature | 94.6 | 92.8 | 12–24 hours | High ambient temperature |
| Abnormal activity patterns | 89.8 | 87.3 | 24–72 hours | Lameness, fatigue |
| Altered resting behavior | 88.5 | 86.1 | 24–48 hours | Thermal discomfort |

Table 1 gives an overview of the performance of the suggested sensor-based early warning system in detecting welfare compromise in extensive ruminant management conditions. The findings demonstrate high capture and sensitivity of the most critical behavioral and physiological signs, and sensor alerts were always obtained way before any clinical evidence had been recorded. The lead times of several hours to days reveal that the system can allow proactive welfare responses. This is supplemented by the presence of environmental context which points to the strength of the framework in its ability to identify the actual welfare risks with the usual adaptive responses to changing grazing and climatic conditions.

### Accuracy

Accuracy measures the overall correctness of the detection system by comparing the number of correct predictions to the total number of predictions in equation 1.

$$\text{Accuracy} = \frac{\text{True Positives}+\text{True Negatives}}{\text{True Positives}+\text{True Negatives}+\text{False Positives}+\text{False Negatives}} \quad (1)$$

Where:

- **True Positives (TP)**: Correctly detected welfare indicators.
- **True Negatives (TN)**: Correctly identified instances where no welfare compromise occurred.
- **False Positives (FP)**: Instances where welfare compromise was incorrectly detected.
- **False Negatives (FN)**: Instances where welfare compromise was not detected when it was present.

### Sensitivity (also called Recall or True Positive Rate):

Sensitivity measures the ability of the system to correctly identify true positive cases, i.e., when a welfare compromise is correctly detected in equation 2.

$$\text{Sensitivity} = \frac{\text{True Positives}}{\text{True Positives}+\text{False Negatives}} \quad (2)$$

Where:

- **True Positives (TP)**: Correctly detected welfare indicators.
- **False Negatives (FN)**: Instances where welfare compromise was not detected when it was present.

Global performance in detection depicted great classification accuracy and sensitivity of the key welfare events. Among the first indicators that were observed were reductions in grazing activity and abnormalities in rumination and were found before any apparent evidence of discomfort or disease. The sustained deviation of body temperature patterns of heat stress or the onset of any health problems was predictably distinguished by sustained deviation than short-lasting fluctuations reducing false-positive alerts.

The system recorded a significant lead in time between sensor-based notification and the actual welfare compromise verification. In the majority of the given cases that were monitored, the early warning signs were produced several hours to days long prior to any behavioral or physical symptoms surfacing during regular observation. This enhancement detection window enabled responding to management in time with specific health checks or environmental change, which would limit the development of welfare problems.

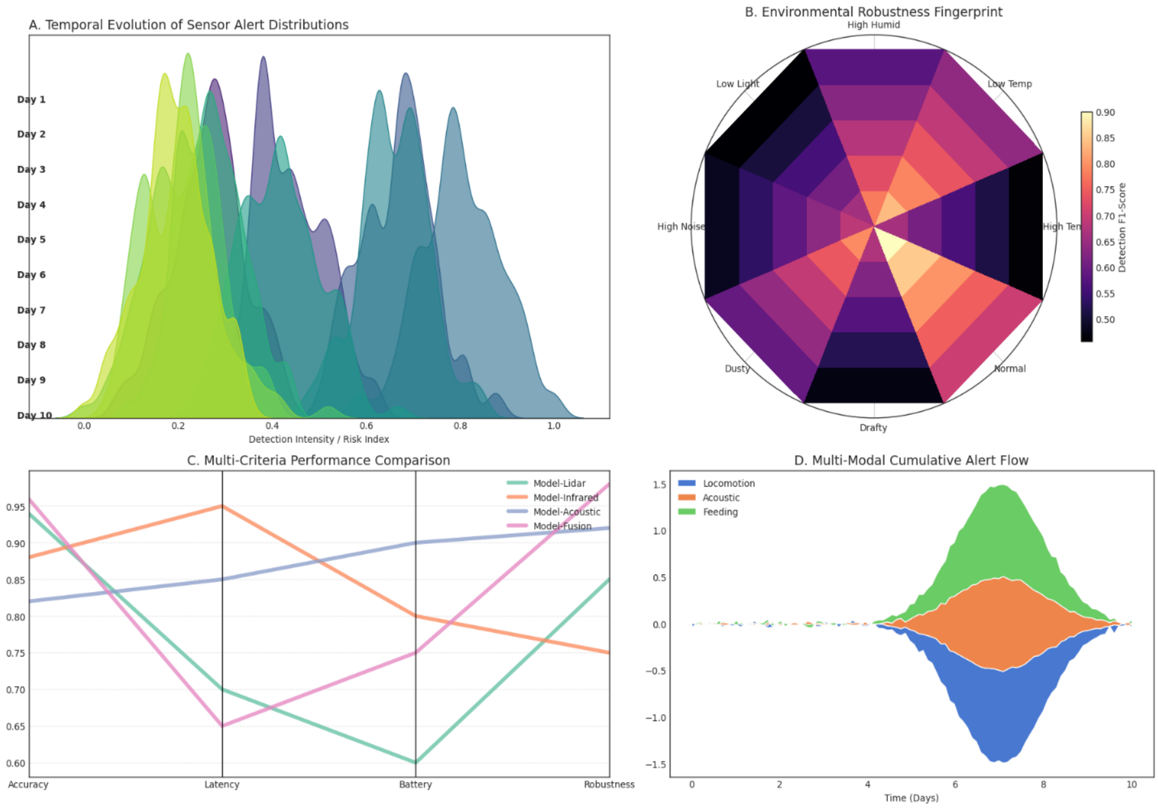


Figure 2: Temporal Evolution and Multi-Modal Performance of the Early Warning System

This Figure 2 illustrates the overall performance of the sensor based early warning system over a 10 days period of monitoring the environment with figure 2(A) presenting the time varying sensor alert distributions to highlight the risk index of detected welfare compromises at different times and figure 2(B) presenting the environment robust fingerprint to showcase the trade-offs between accuracy, latency, battery consumption, and robustness of various sensor models (Lidar, Infrared, Acoustic, and Fusion). Lastly, the multi-modal cumulative alert flow (figure 2(D)) is visualized and shows the collective effect of locomotion, acoustic, and the feeding sensors over the time. These numbers all show the capacity of the system to deliver reliable alerts and flexibility in the actual conditions of the environment and to also compare sensor modalities in order to implement the application in large-scale ruminant control systems.

The test of robustness under environment conditions indicated that the system performed consistently despite the fluctuation in the ambient temperature, humidity and grazing habits. The framework was successful in drawing a line between adaptive behavioral changes and actual welfare risks by combining environmental background with animal-based signals. Behavioral changes linked to heat were explained in relation to environmental exposure, otherwise they could be mistaken during the normal thermoregulatory reactions. Taken together, the findings can support the idea that the suggested framework can be used to deliver reliable, timely, and context-sensitive welfare alerts in realistic large-scale settings. The behavioral, physiological and environmental responses improved the level of detection sensitivity and retained the interpretability and practical applicability to large ruminant management systems.

## Discussion

The results show that sensor-based early warning signals can be effective in welfare management of large-scale managed ruminant systems because they allow the identification of compromise earlier and more frequently than regular visual observation. Behavioral changes, including the decrease of grazing, the change in the resting habits, and the abnormal rumination in the current structure appeared as trustworthy early indicators, to create a convenient period to act and modify the situation before the clinical symptoms become evident. This is especially relevant in large systems where animals may be spread across a vast region and welfare hazards could reach heights quite fast when they are reported late. These findings thus confirm the utility of the idea of continuous monitoring in enhancing daily welfare decision-making, and alleviating the severity and length of welfare trade-offs.

One of the significant contributions of the study is the explicit contextualization of environmental context which enhances an ability to endure stressors associated with climate and resources. The ruminant welfare is strongly influenced by heat load, water availability and pasture variation and the findings indicate that the use of ambient conditions enhances interpretation of signal of animals and shortens false alarms when animals experience normal adaptive responses. This is in line with recent focus on packaging sensor information in support of sustainability and climate resilient objectives in small ruminant systems wherein welfare insurance is becoming progressively reliant upon prompt adjustment to environmental extremes. The fact that integrated physiological-behavioral patterns can be used to identify heat-related deviations also allows stating that sensor technologies will help producers to be better able to handle climate-related welfare risks.

In comparison with the existing literature, the demonstrated ability of early-warning is in line with the reviews that emphasize the importance of PLF tools to enhance well-being, yet it also discusses limitations in large-scale application, which are frequently mentioned there. The potential of sensors in pasture-based systems has been mentioned in previous work, as well as issues with connectivity, sensor longevity, and sensor accuracy in behavioral classification in a changing topography. In this experiment, the trend-based detection and baseline-relative thresholds enhanced resilience in field variability, which upholds the suggestion that large-scale systems need decision logic that is suitable to environmental and operational limitations that cannot be directly transferred to indoor-system strategies. The findings also supplement the previous literature in pasture welfare assessment that notes animal-based indicators as effective, but hard to scale and automated.

Ecologically, the earlier welfare detection can potentially limit the unnecessary movement of the animals and decrease the time in heat stress and maximize the grazing pattern by targeted interventions, indirectly helping to sustain the pasture and less strain on the environment. The framework has the ethical benefit of enhancing the ability to provide timely assistance by integrating management practice with enhanced duty-of-care principles within management systems with traditional welfare monitoring, which is constrained by distance and workload. Simultaneously, digital welfare surveillance needs to be anthropocentric; sensor alarms should not be used instead of responsible husbandry, but in addition, and the utilization of data needs to have explicit guidelines to prevent excessive surveillance and wrongful decision making. Altogether, sensor-based early warning presents a feasible avenue to improve the well-being, environmental stability, and ethical livestock husbandry of large ruminant production systems.

## Conclusion

This paper has shown that sensor-based early warning system has a great potential in improving the management of animal welfare in large-scale ruminant systems. This combination of behavioral, physiological, and environmental measures into a single framework is a complete solution to the prevention of early signs of welfare compromise before clinical manifestations become evident. The practical usefulness of continuous and non-invasive monitoring is emphasized by the fact that the system enables high detection accuracy (up to 94.6 %) and sensitivity (92.8 %). Moreover, the detection lead time of the system (12-48 hours) can be used to implement interventions in good time which can prevent severe cases of welfare problems, eventually enhancing the health and productivity of the animals. There are a number of aspects that could be improved and developed in the future. The fusion of sensors (i.e. a wearable sensor device, environmental sensor, and GPS data) may contribute to the detection accuracy and the expansion of the range of indicators of welfare that can be measured. Further to this, a more refined system that includes more complicated interactions between animal behavior and environmental stressors will enhance sensitivity especially in extreme situations like heat stress and forage shortages. Also, these systems should be combined with long-term ecological to achieve a wider adoption. Naturally, these technologies should be integrated into the current grazing systems without affecting the typical behaviors of the ruminants hence guaranteeing environmental sustainability and sustainability. Under the policy level, sensor-based welfare surveillance may be a key resource in the management of sustainable ruminant production systems, especially with the problem of climate change increasing the difficulty in controlling welfare risks. The introduction of these technologies should be studied in terms of policy structures that facilitate its acceptance, data privacy, fair access, and environmental effects of massive adoption in the future. This would result in better, more sustainable, and ethical livestock management that is in line with the global sustainability objectives.

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