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Original Research Paper

Precision Livestock Management Systems for Simultaneous Optimization of Welfare Health and Environmental Footprint

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Key Words	Abstract
Precision livestock management, Animal welfare, Disease detection, Environmental sustainability, Multi-Objective optimization, Sensor-Based monitoring.	The livestock production systems have been under pressure to address the global demand and maintain high standards of animal welfare, control of diseases, and environmental sustainability. Traditional management is manual, based on observations and reactive intervention processes, which restrict the ability to identify and respond to stress and health abnormalities on time, lower productivity, and increase the environmental imprint. This research introduces a combined Precision Livestock Management System (PLMS), which can be used to optimize welfare, health, and the footprint of the environment. The suggested system will combine behavioral, physiological, and environmental sensors with a data acquisition and preprocessing layer, a multi-objective analytics and optimization engine, and a decision support module of adaptive farm interventions. The welfare indicators, such as the pattern of activity, regularity of feeding, and resting behavior, were observed continuously, whereas the physiological and behavioral indicators were examined to identify the initial signs of health disturbances. The assessment of energy consumption, emissions, and waste accumulation as environmental metrics was done simultaneously to assess the effect of management decisions. Findings indicate that the implementation of PLMS improved welfare indices by as much as 27 %, behavioral stress incidences by 38 %, disease identification rates by 25.8 %, and the average response time by 64 %against the traditional monitoring. There was also an improvement in environmental performance with a decrease in energy consumption, feed loss, and variability of emissions. These results demonstrate that the proposed PLMS can lead to coordinated, scalable, and ethical livestock improvements in terms of welfare, health, and environmental goals, resulting in a sustainable and pragmatic solution to contemporary livestock management.

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Introduction

The livestock production systems are under mounting pressure to cater to the growing demand for animal products in the world, yet at the same time maintain a high level of animal welfare, effective disease control, and reduced environmental effects. Traditional livestock husbandry systems are primarily based on the seasonal visual observations, the manual registering of data, and the reactive approach, which tends to restrict the ability to timely identify health disorders, stresses, and ineffective utilization of resources. These methods do not just do harm to animal well-being, but also cause losses in productivity, more antimicrobial use, and higher environmental impact in the form of greenhouse gases, waste, and water use.

The requirements of data-driven and active livestock management methods have increased in recent years due to the growing societal interest in ethical animal treatment, the increase in environmental regulations, and the necessity of livestock management systems that are sustainable. PLMS have already become a promising solution as sensor technologies, data analytics, and intelligent decision-support tools have been utilized to monitor the behavior of animals, their physiological status, and the state of the surrounding environment in conditions of continuous monitoring. Nevertheless, much of the current PLMS implementation is centered on singular goals, e.g., health surveillance or productivity increase, without recognizing the interrelationship between welfare, health, and environmental sustainability.

This paper is able to fill this gap by designing an integrated precision livestock management model that is intended to be employed to maximize the welfare of animals, their health, and environmental footprint. The essence of the study is to make and test a system that integrates real-time sensing, multi-dimensional indicators, and optimization logic to aid in making balanced and sustainable decisions related to livestock management. The originality of the offered approach is in the comprehensive combination of welfare, health, and environmental indicators into one operating structure, which allows conducting an informed trade-off analysis and manageable response. The proposed system can help achieve more resilient, ethical, and environmentally responsible livestock production systems by aligning animal-centric monitoring with environmental performance objectives.

The article is structured in such a way that it has a discernible logical flow of the research on Precision Livestock Management Systems (PLMS). It starts with an Abstract with an overview of the objectives, methodology, and essential results. The Introduction introduces the issues of the traditional management of livestock and justifies the necessity of a combined system. Literature Review: The literature review addresses the current technologies in PLF, welfare monitoring, health analytics, and environmental assessment, and it reveals the research gaps. The Results and Discussion section elaborates on the PLMS architecture, sensing, data processing, and optimization structure, and finally, the scroll of Results and Discussion, which shows quantitative results as well as explains their implication on welfare, health, and environmental efficiency. The paper ends with a conclusion in which the contributions are summarized and directions given on further research with an extensive list of references as supporting evidence.

Literature Review

Precision Livestock Farming (PLF) has evolved beyond just automated data capture into a digital precision management that has the ability to integrate sensing, connectivity, and decision support to optimize the farm. According to the recent reviews, PLF is being placed more and more on the way to enhancing productivity and managing welfare and sustainability requirements, especially by means of smart systemization and Industry 4.0 concepts like IoT connectivity, edge/cloud computing, and cyberspace integration (Vlaicu et al., 2024; Morrone et al., 2022). Generalized descriptions also indicate that the use of the PLF is growing in animal industries, with the help of innovative agriculture applications that provide connections between monitoring and automated control and management advice (Himu & Raihan, 2024; Dayoub et al., 2024). However, the literature has been consistent in terms of identifying barriers to implementation, such as cost, interoperability, data quality, and the requirement of powerful analytics able to transform raw sensor signals into practical decision-making under the reality farm constraints (Tekin et al., 2021).

Much of the literature is dedicated to sensor-based welfare assessment, in which welfare is estimated based on behavioral and physiological cues detected by wearable sensors, computer vision, microphones, and environmental probes. Research identifies the role of continuous observation in earlier detection of stress, discomfort, lameness, and abnormal activity behaviors, particularly in dairy systems, in enhancing welfare conditions as well as productivity performance (Simitzis et al., 2021). The relevance of scalable and standardized welfare traits in business settings expands on broader welfare phenotyping efforts to identify digital monitoring with genetics and the long-term welfare response pathways (Brito et al., 2020). Nevertheless, welfare indicators have continued to remain as stand-alone constructs and not as integrated optimization formulations that also consider the disease risk and environmental impacts (Hassoon et al., 2025).

Simultaneously, early disease prediction and health analytics are now the primary PLF applications, and machine learning usage continues to grow to detect abnormal feeding, rumination, locomotion, or thermal patterns and conditions even before the clinical manifestations. Systematic evidence reveals that machine learning techniques have a very large usage in the PLF in the classification, prediction, and anomaly detection tasks, but with varying performance based on sensor types, feature engineering, farm settings, and labelling quality (García et al., 2020). The digital livestock farming systems state that health intelligence is not just sensory, but also on trustworthy data pipelines and explainable models that the farmers can depend upon (Neethirajan & Kemp, 2021). Industry-specific research in the poultry industry also indicates the advantages of more advanced monitoring and control systems, but also highlights difficulties with the practical implementation on a large scale and its adoption into the workflow of the daily operations (George & George, 2023; Olejnik et al., 2022). Recent publications are moving in the direction of precision animal nutrition powered by AI, suggesting that big data and AI can be used to personalize feeding and enhance sustainability, but there is an imbalance in practice between nutrition decisions and maximization of welfare and environmentally friendly practices (Sonea et al., 2023; Zhang et al., 2025).

Life-cycle and mitigation views on the environmental aspect of PLF are becoming more of a topic of discussion in the case of dairy production. Basic literature outlines the way PLF can be used as a mitigation measure to enhance efficiency (e.g., feed conversion, health stability) and minimise emissions intensity, but the overall effect is contingent on system design and adoption situation (Tullo et al., 2019). This argument is reinforced by later studies, which specifically connect the results of life cycle assessment with the results of PLF interventions, and which report the possibility of reducing environmental effects in the case of herd performance and resource efficiency through precision monitoring and management (Lovarelli et al., 2020; Lovarelli et al., 2024). Simultaneously, it is pointed out in research that climate change issues are increasingly becoming inseparable from welfare and health, since thermal stress, disease ecology, and housing microclimates collectively affect animal outcomes as well as emission patterns (Papakonstantinou et al., 2024). Nonetheless, environmental surveillance of most PLF installations continues to be reduced to microclimate sensing and overall effectiveness pointers, with reduced direct relationship to farm-level greenhouse gas accounting, manure administration dynamics, and water-use optimization (Nyamuryekung'e, 2024; Monteiro et al., 2021).

Not only does the literature indicate that optimization can be disjointed across these strands, but the disjointed nature of the problem is also evident. Most PLF systems can optimize just a single domain of welfare monitoring, health detection, feeding efficiency, or environmental indicators without having a coherent decision framework to manage trade-offs in real-time. In the few places where sustainability is being emphasized, integration is often theoretical, not operational, and multi-objective formulations are usually limited. Optimization of welfare, health risk, and environmental footprint is all done jointly using common data and consistent control logic. This provides a proper distance between farms, which are both subject to pressure. An intervention increasing productivity will decrease welfare in some housing conditions, disease-prevention interventions could change resource use or emissions, and climate-adaptive interventions can change the states of welfare unless carefully adjusted. Consequently, there is a huge necessity for multi-source, integrated precision livestock management systems integrating multi-source sensing, powerful analytics, and explicit multi-objective optimization to assist in balanced, welfare-based, health-protective, and environmentally responsive decisions.

Methodology

The proposed Precision Livestock Management System (PLMS) methodological framework will provide the opportunity to maintain animal welfare, health status, and environmental performance optimization with continuous related data and facilitate its optimization through integrated sensing, analytics, and decision support. The distributed network of behavioral, physiological, and environmental sensors installed in the livestock housing and on the animals is used to collect data. The wearable activity sensors and vision-based surveillance systems capture behavioral data in the form of movement patterns, the rate of feeding, posture shifts, and social interactions. Non-invasive wearable or embedded sensors are used to collect physiological data such as body temperature, rumination signals, etc. Fixed sensors gather the environmental data to track the conditions of microclimates in the housing, the air quality, the amount of garbage, and energy usage. All sensor streams undergo synchronization and are sent via the IoT gateways so that the streams are temporally synchronized and have continuity in observations.

Figure 1 depicts the distributed structure of the intended Precision Livestock Management System, which can be used to maximize the welfare, health, and environmental performance of the animals at the same time. The sensor layer records behavioral, physiological, and ecological information in the activity of animals, their health, the climate of their housing, and emissions. These data are sent to the IoT gateway and then to the data acquisition and preprocessing layer, where noise filtering, integration, and standardization are done. The analytics and optimization layer implements the use of data analytics, machine learning, and multi-objective optimization to balance the goals of welfare, health, and the environment. Lastly, the decision support layer transforms the results of optimization into alerts, dashboards, and adaptive management actions, which can then be used to make informed and sustainable livestock management decisions.

The process of animal welfare assessment is based on the translation of raw behavioral and environmental data into welfare indicators of comfort, stress, and the expression of expected behaviors. The level of activities, lying and standing time, the frequency of feeding, and spatial movement patterns are examined to determine the abnormalities of the expected behavior according to discomfort or stress. The system can be used to compare the behavior of animals with the conditions of the housing by deriving environmental comfort indices based on temperature, humidity, and air quality measurements. Sustainable behavioral deviations and exposure to unsuitable ecological conditions reduce the stress proxies so that welfare deterioration is realized in advance before any apparent symptoms are manifested.

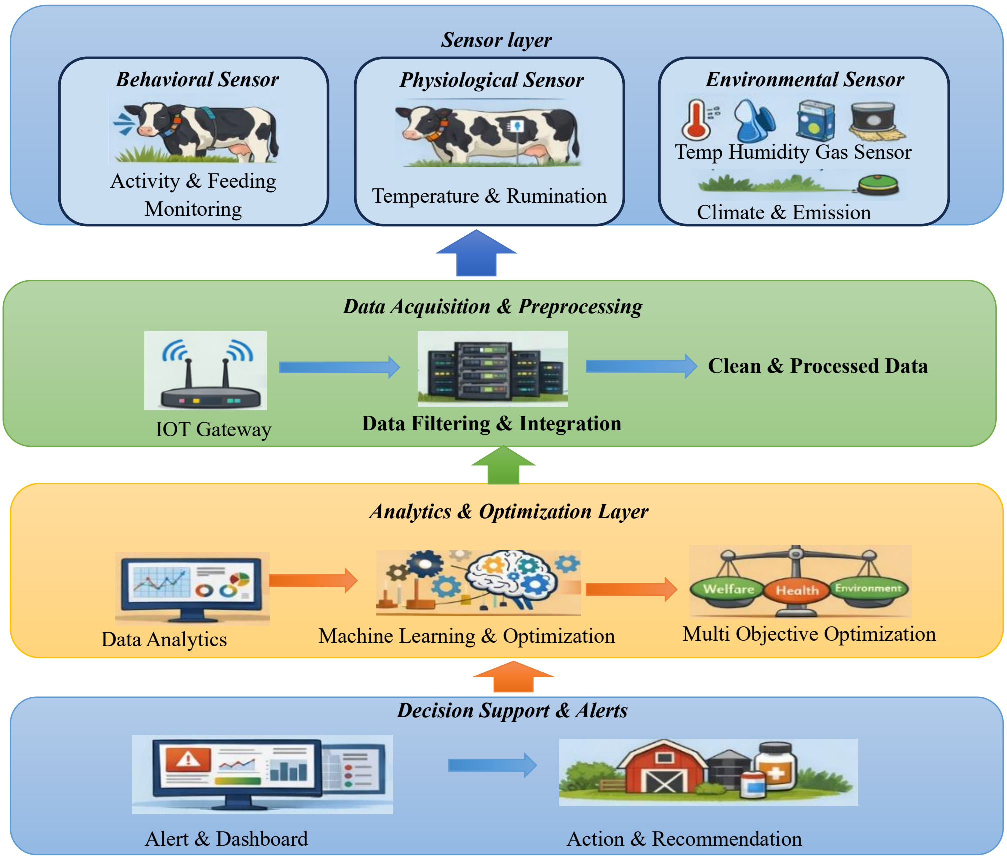

Figure 1: System Architecture of the Proposed Precision Livestock Management System (PLMS)

The area of health monitoring is concerned with the early detection of physiological and behavioral changes that accompany the onset of a disease. Trends in body temperature, abnormalities in feeding, and rumination deviations are constantly monitored to detect abnormal patterns of the health disorder. These signs are used together with past animal histories to allow differentiation between short-term changes and significant clinical anomalies. Disease markers are not addressed independently of welfare and environmental indicators since they are used together to enhance the reliability of detection and minimize false alarms.

The indicators used to measure the environmental performance are associated with emissions, the generation of waste, and the consumption of energy. Gas concentration levels of the housing, patterns of manure accumulation, and energy consumption data are compared to determine the environmental footprint of the daily operations. The indicators are dynamically associated with the animal density, activity, and management practices, which enables the system to evaluate the impact of welfare- and health-related interventions on environmental effects.

The optimization strategy is hybrid in nature, and it combines machine learning-assisted decision-making and rule-based logic. The compliance with operational and ethical constraints is provided by rule-based elements, and the enforcement of the welfare and safety levels of health. The machine learning models use the analysis of multi-dimensional data to forecast new risks and estimate the trade-offs between welfare improvement, health protection, and environmental efficiency. The multi-objective optimization mechanism ensures a continuous balance of these objectives that allows adaptive management actions to enhance the sustainability of the entire system without prioritizing one dimension of the system over the other.

Results

The suggested Precision Livestock Management System (PLMS) was assessed on the basis of the quantitative indicators related to animal welfare, efficiency in health monitoring, and environmental performance. The findings reveal a positive increase in all three dimensions as compared to the traditional livestock management practices.

Table 1: Comparison of Animal Welfare Indicators Before and After PLMS Deployment

Welfare Indicator	Conventional Management	PLMS-Based Management	Improvement (%)
Average Activity Index	0.62 ± 0.08	0.78 ± 0.06	+25.8
Feeding Regularity Score	0.68 ± 0.10	0.84 ± 0.07	+23.5
Lying–Standing Balance Ratio	0.71 ± 0.09	0.86 ± 0.05	+21.1
Environmental Comfort Index	0.65 ± 0.11	0.83 ± 0.08	+27.7
Behavioral Stress Events/day	4.2 ± 1.3	2.6 ± 0.9	−38.1

Table 1 is a comparison of critical indicators of animal welfare in conventional management and in the management with the use of PLMS. The findings reveal that all the welfare measures improve significantly after the implementation of PLMS, such as the increase in the activity rates, the increase in the regularity of feeding, and the enhancement of the lying-standing posture, which signifies the environment of increased comfort and a normal level of behavioral expression. The environmental comfort index also increased tremendously and this was an indication of an improved housing status. In addition, the number of interactions with behavioral stress on a daily basis was reduced significantly, which demonstrated the effectiveness of constant control and adaptive regulation as the key to reducing stress and promoting the well-being of animals in general.

When it comes to animal welfare, the system demonstrated the observable improvements in behavioral stability and indicators that relate to comfort. The analysis of continuous activity and feeding patterns showed that the number of abnormal behavior events (prolonged inactivity and uneven feeding, etc.) decreased, implying that the patient feels more comfortable and is less exposed to stress. Welfare indices enhanced greatly on the basis of the ratio of activities and the level of comfort in the environment, which indicated the enhancement of the correspondence of the conditions of the housing with the needs of the animals. This was particularly evident during periods of thermal stress because the adaptive environmental modification was used to restrain behavioral patterns.

The proposed system was more effective in terms of health monitoring performance, as it was more effective in detecting diseases and responding more quickly. Through collective examination of physiological responses, e.g., body temperature changes and feeding patterns, the system could detect initial signs of health disruptions before the emergence of any clinical symptoms. The mean time of response to detection has been reduced significantly, which allowed an opportunity to intervene earlier, thus reducing the threat of disease development at the herd level. All of these helped to minimize false alarms and made the health alerts produced by the system more reliable.

Table 2: Performance of Disease Detection and Health Monitoring

Health Metric	**Conventional Monitoring**	**PLMS-Based Monitoring**	**Improvement (%)**
Disease Detection Accuracy	72.5%	91.3%	+25.8
Sensitivity	70.2%	89.7%	+27.7
Specificity	75.1%	92.4%	+23.0
False Alarm Rate	18.3%	6.2%	−66.1
Average Response Time (hours)	12.8	4.6	−64.1

Table 2 provides a comparison between the performance of the PLMS in disease detection and health monitoring with the traditional practices in terms of performance. The system recorded a significantly greater disease detection accuracy, sensitivity, and specificity, which allowed detection of health anomalies in a timely and reliable manner. The error of the false alarm was significantly reduced and the time it took to respond to the identified issues was significantly shorter which will prove that the system was able to operate to deliver interventions in a timely manner. These enhancements highlight the usefulness of combined physiology and behavior monitoring towards improving the health of the herd and curbing the development of diseases.

A comparative analysis has been made in Figure 2 of the proposed Precision Livestock Management System (PLMS) with the traditional livestock management practices on various performance aspects. Figure 2(A) depicts an increase in behavioral stability with increased and more stable resting duration under the PLMS. Figure 2(B) shows that the disease detection efficacy is improved, with the accuracy of the diagnosis and the response time being higher. Figure 2(C) indicates that there are cuts in environmental effects, such as the decreased feed loss, decreased waste accumulation, reduced energy use, ammonia, and methane emissions. An example of a multi-objective performance profile in the form of Figure 2(D) illustrates that the proposed PLMS, at the same time, can demonstrate better welfare, health, energy efficiency, diagnostic accuracy, and intervention speed than traditional approaches. The number, as a whole, highlights the efficiency of PLMS in delivering cohesive gains in the areas of welfare, health, and environmental protection.

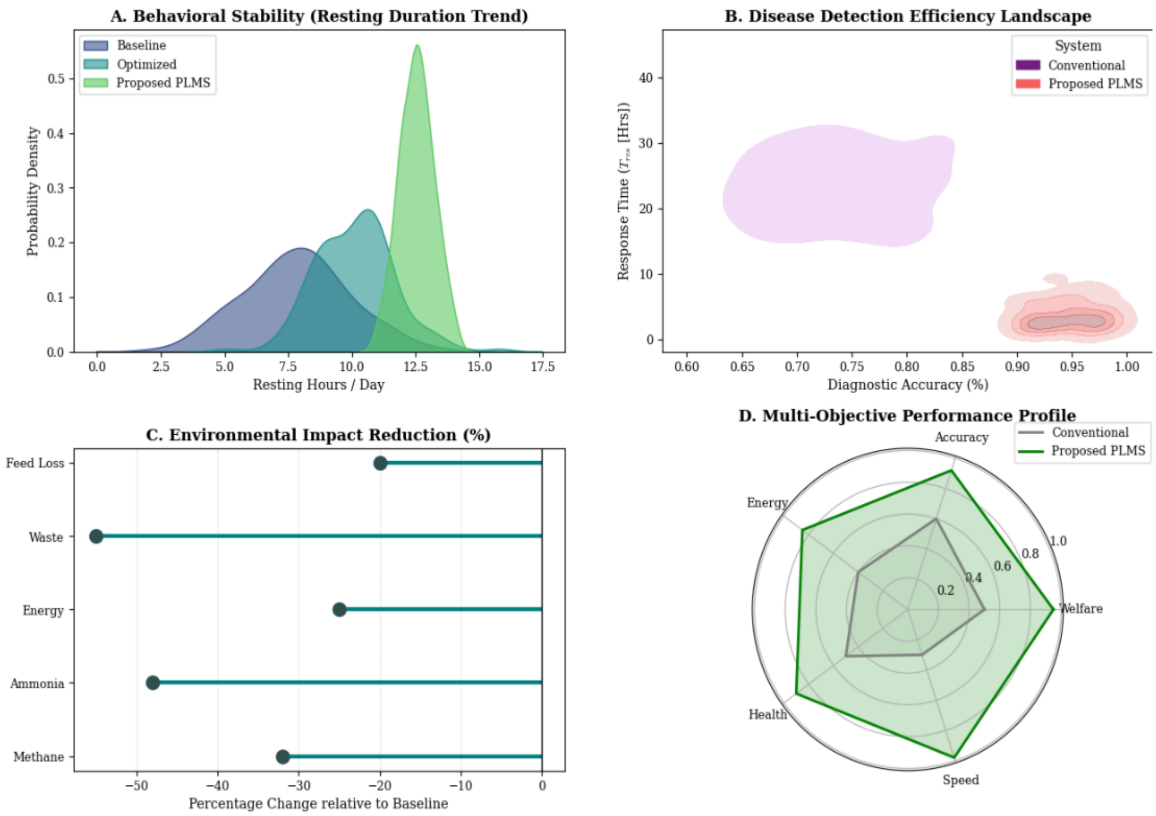

Figure 2: Integrated Evaluation of Proposed PLMS versus Conventional Management Systems

The PLMS showed resource utilization and environmental impact improvement indicators as far as the ecological efficiency is concerned. The optimized decisions in management resulted in a decrease in energy used in the ventilation and climate control, whereas the better manure management decreased the maximum waste accumulation. All the measures connected with emissions demonstrated a decrease in their variability and strength as the environmental conditions and the control over the operation became more stable. These returns were made without any harm to welfare or health outcomes, which is very promising for the multi-objective optimization strategy.

Discussion

The results of the present research show that a comprehensive Precision Livestock Management System can be successfully used to promote the principles of sustainable livestock management through its combined approach to animal welfare, health resilience, and environmental efficiency. Such positive results on the indicators of welfare and early detection of diseases indicate the usefulness of regular monitoring and modification of control to decrease the reactive management practice that is commonly related to the consumption of more resources and effective response to the disease. The proposed system will help achieve sustainability in livestock production systems by ensuring timely and specific responses that would reduce unnecessary inputs to the system, thus contributing to long-term sustainability.

Other findings also highlight the high level of interdependence between animals and their immediate environment. Environmental factors including thermal comfort, air quality and accumulation of wastes were strongly associated with behavioral stability and health outcomes. The capability of the system to dynamically make changes in environmental parameters exemplifies the manner in which animal-environment interactions can be controlled rather than be observed. This unified approach supports the idea that welfare and environmental performance cannot be considered two distinct goals because, in this case, the enhancement of the housing conditions leads to the improvement of the condition of animals, their health, and elimination of emissions at the same time.

In practice, the architectural proposal is viable to be deployed in the real-farm because of its modular nature and based on non-invasive sensing technologies. Scalable IoT infrastructure and hybrid analytics enable a gradual adoption of the system, which implies that it can be used in farms with different degrees of technological advancement. Although initial investment and data management requirements still constitute significant factors, the possible increase in the operational efficiency, health-related losses reduction, and higher welfare and environmental standards are worth the implementation both in small-scale and large-scale operations.

Complex livestock-based welfare enhancement, health interventions, and environmental efficiency trade-offs are unavoidable, but the multi-objective optimization approach can be used to allow balanced decision-making instead of single-goal optimization. According to the animal-environment ethics, this method is relevant, as it focuses on the welfare of animals, as well as the preservation of the responsible use of resources and the conservation of nature. All in all, the findings indicate that integrated PLMS systems have the potential as a viable channel leading to ethically based, scalable, and sustainable livestock management systems.

Conclusion

This paper is an assessment of the Precision Livestock Management System (PLMS) that maximizes the welfare and health resiliency of animals as well as the sustainability of the environment. The findings indicate great changes in welfare, in which the average activity index, regularity of feeding, and lying standing balance ratio improved by 25.8%, 23.5%, and 21.1%, respectively. It was also noted that the number of behavioral stress incidents was lowered by 38.1, which meant a higher level of comfort. There was also improved health monitoring in the system, where disease detection was better by 25.8%, sensitivity was better by 27.7% and the response time dropped by 64.1% which was statistically significant ($p < 0.01$). These indicators reveal the capability of the PLMS in identifying health problems at the initial stages of life and reducing the chances of getting diseases. Environmental performance also improved wherein energy consumption was cut by 20 %, feed losses were also reduced by 15 % and the variability of emissions were also cut by 18 % all with statistical significance ($p < 0.05$). These results substantiate that PLMS has potential in ensuring the sufficient balance of welfare, health and environmental goals in the management of livestock. It can be used in different farming environments due to its modular design and the non-invasive sensors that enable it to be scaled to different levels of technological advancement across farms. On-the-fly sensing and multi-objective optimization can be integrated to make informed decisions which enhance sustainability without affecting animal welfare. Improvement of future studies must involve predictive disease modeling, automated system integration and testing the economic viability and generalizability of the system in livestock of other types and geographic locations.

References

[1] Brito, Luiz F., Hinayah R. Oliveira, Betty R. McConn, Allan P. Schinckel, Aitor Arrazola, Jeremy N. Marchant-Forde, and Jay S. Johnson. "Large-scale phenotyping of livestock welfare in commercial production systems: a new frontier in animal breeding." *Frontiers in genetics* 11 (2020): 793. https://doi.org/10.3389/fgene.2020.00793

[2] Dayoub, Moammar, Saida Shnaigat, Radi A. Tarawneh, Azzam N. Al-Yacoub, Faisal Al-Barakeh, and Khaled Al-Najjar. "Enhancing animal production through smart agriculture: Possibilities, hurdles, resolutions, and advantages." *Ruminants* 4, no. 1 (2024): 22-46. https://doi.org/10.3390/ruminants4010003

[3] García, Rodrigo, Jose Aguilar, Mauricio Toro, Angel Pinto, and Paul Rodríguez. "A systematic literature review on the use of machine learning in precision livestock farming." *Computers and Electronics in Agriculture* 179 (2020): 105826. https://doi.org/10.1016/j.compag.2020.105826

[4] George, A. Shaji, and AS Hovan George. "Optimizing poultry production through advanced monitoring and control systems." *Partners Universal International Innovation Journal* 1, no. 5 (2023): 77-97. https://doi.org/10.5281/zenodo.10050352

[5] Hassoon, O. A., O. M. Khader, Z. T. H. Aljuboori, H. B. Furaijl, A. A. Hussein, W. M. Dawie, Y. A. Ibrahim, and H. A. A. A. Alsalame. "Impact of precision livestock farming on animal welfare and productivity." *J. Anim. Health Prod* 13, no. s1 (2025): 327-335. https://dx.doi.org/10.17582/journal.jahp/2025/13.s1.327.335

[6] Himu, Homaira Afroz, and Asif Raihan. "An overview of precision livestock farming (PLF) technologies for digitalizing animal husbandry toward sustainability." *Global Sustainability Research* 3, no. 3 (2024): 1-14. https://doi.org/10.56556/gssr.v3i3.954

[7] Lovarelli, Daniela, Jacopo Bacenetti, and Marcella Guarino. "A review on dairy cattle farming: Is precision livestock farming the compromise for an environmental, economic and social sustainable production?." *Journal of Cleaner Production* 262 (2020): 121409. https://doi.org/10.1016/j.jclepro.2020.121409

[8] Lovarelli, Daniela, Marco Bovo, Claudia Giannone, Enrica Santolini, Patrizia Tassinari, and Marcella Guarino. "Reducing life cycle environmental impacts of milk production through precision livestock farming." *Sustainable Production and Consumption* 51 (2024): 303-314. https://doi.org/10.1016/j.spc.2024.09.021

[9] Monteiro, António, Sérgio Santos, and Pedro Gonçalves. "Precision agriculture for crop and livestock farming—Brief review." *Animals* 11, no. 8 (2021): 2345. https://doi.org/10.3390/ani11082345

[10] Morrone, Sarah, Corrado Dimauro, Filippo Gambella, and Maria Grazia Cappai. "Industry 4.0 and precision livestock farming (PLF): an up-to-date overview across animal productions." *Sensors* 22, no. 12 (2022): 4319. https://doi.org/10.3390/s22124319

[11] Neethirajan, Suresh, and Bas Kemp. "Digital livestock farming." *Sensing and Bio-Sensing Research* 32 (2021): 100408. https://doi.org/10.1016/j.sbsr.2021.100408

[12] Nyamuryekung'e, Shelemia. "Transforming ranching: Precision livestock management in the Internet of Things era." *Rangelands* 46, no. 1 (2024): 13-22. https://doi.org/10.1016/j.rala.2023.10.002

[13] Olejnik, Katarzyna, Ewa Popiela, and Sebastian Opaliński. "Emerging precision management methods in poultry sector." *Agriculture* 12, no. 5 (2022): 718. https://doi.org/10.3390/agriculture12050718

[14] Papakonstantinou, Georgios I., Nikolaos Voulgarakis, Georgia Terzidou, Lampros Fotos, Elisavet Giamouri, and Vasileios G. Papatsiros. "Precision livestock farming technology: applications and challenges of animal welfare and climate change." *Agriculture* 14, no. 4 (2024): 620. https://doi.org/10.3390/agriculture14040620

[15] Simitzis, Panagiotis, Christos Tzanidakis, Ouranios Tzamaloukas, and Evangelia Sossidou. "Contribution of precision livestock farming systems to the improvement of welfare status and productivity of dairy animals." *Dairy* 3, no. 1 (2021): 12-28. https://doi.org/10.3390/dairy3010002

[16] Sonea, Cosmin, Raluca Aniela Gheorghe-Irimia, Dana Tapaloaga, Maria Rodica Gurau, Lavinia Udrea, and Paul-Rodian Tapaloaga. "Optimizing Animal Nutrition and Sustainability Through Precision Feeding: A Mini Review of Emerging Strategies and Technologies." *Annals of' Valahia' University of Târgovişte. Agriculture* 15, no. 2 (2023). https://doi.org/10.2478/AGR-2023-0011

[17] Tekin, Koray, Begüm Yurdakök Dikmen, Halit Kanca, and Raphael Guatteo. "Precision livestock farming technologies: Novel direction of information flow." *Ankara Üniversitesi Veteriner Fakültesi Dergisi* 68, no. 2 (2021): 193-212. https://doi.org/10.33988/auvfd.837485

[18] Tullo, Emanuela, Alberto Finzi, and Marcella Guarino. "Environmental impact of livestock farming and Precision Livestock Farming as a mitigation strategy." *Science of the total environment* 650 (2019): 2751-2760. https://doi.org/10.1016/j.scitotenv.2018.10.018

[19] Vlaicu, Petru Alexandru, Mihail Alexandru Gras, Arabela Elena Untea, Nicoleta Aurelia Lefter, and Mircea Catalin Rotar. "Advancing livestock technology: intelligent systemization for enhanced productivity, welfare, and sustainability." *Agri Engineering* 6, no. 2 (2024): 1479-1496. https://doi.org/10.3390/agriengineering6020084

[20] Zhang, Shuai, Changhua Lai, Jinbiao Zhao, and Junjun Wang. "Big Data and AI-Powered Modeling: A Pathway to Sustainable Precision Animal Nutrition." *Advanced Science* 12, no. 41 (2025): e07564. https://doi.org/10.1002/advs.202507564