18(1s), Spring 2026

Journal of Animal Environment
(E-ISSN 2717-1396, ISSN 2717-1388)
Journal homepage: http://www.aejournal.ir

Original Research Paper

Precision Livestock Farming Technologies for Reducing Greenhouse Gas Emissions in Agriculture

Pratik Durgawale[*1], Kashish Gupta[2], Harshini R[3], Hardik Kumar[4], Anjali Adhikari[5], Maftuna Rabbimova[6]

[1]Krishna Institute of Science and Technology, Krishna Vishwa Vidyapeeth "Deemed to be University", Taluka-Karad, Dist-Satara, Pin-415 539, Maharashtra, India. (Pratik Durgawale) | Email: pratikpdurgawale@gmail.com

[2]Department of Biotechnology and Microbiology, Noida international University,Uttar Pradesh (Kashish Gupta) | ORCID: https://orcid.org/0000-0001-5627-4792 | Email: kashish.gupta@niu.edu.in

[3]Assistant Professor, Computer Science, Meenakshi College of Arts and Science, Meenakshi Academy of Higher Education and Research, Tamilnadu, India (Harshini R) | Email: harshinir@maher.ac.in

[4]School of Pharmaceutical Sciences, CT University, Punjab, 142024, India (Hardik Kumar)

[5]Asst Prof, Agriculture Departmernt, Dev Bhoomi Uttarakhand University, Dehradun (Anjali Adhikari) | ORCID: https://orcid.org/0009-0007-3516-3079 | Email: soa.anjali@dbuu.ac.in

[6]Assistant, Department of Radiation Diagnostics and Therapy, Samarkand State Medical University, Samarkand, Uzbekistan (Maftuna Rabbimova) | ORCID: https://orcid.org/0009-0009-7792-2752 | Email: rabbimovamaftuna1995@mail.ru

Abstract: Precision Livestock Farming (PLF) has emerged as an innovative system to maximize livestock production and minimize greenhouse gas (GHG) emission through the intelligent use of monitoring, automation and data. This review summarizes the latest developments in PLF technologies and how these technologies are helping to advance livestock production in a climate-smart way. It provides an overview of the significant livestock GHG sources, their environmental impacts, and the methane and nitrous oxide sources from manure, as well as the enteric CH4 sources, and energy use. The review also examines the use of sensor-based technologies including wearable devices, Internet of Things (IoT) platforms, smart collars and biometric monitoring systems, for real-time monitoring of animal health, behaviour and emission-related measurements. AI, machine learning, and deep learning analysis of livestock performance and prediction, disease detection and estimation of methane emissions and optimization of resources. In addition, precision health and reproduction management are discussed to achieve better feed efficiency, reduce the waste of resources and increase the sustainability of production. Implementation challenges are also addressed, such as high investments, interoperability, cyber security, data ownership, and skills limitations that hinder broad implementation. In summary, incorporating PLF technologies with AI, advanced sensing, digital agriculture is a viable strategy to create an environmentally sustainable, economically viable, low carbon livestock production system that will contribute to global climate mitigation and resilient agriculture.

Keywords: Precision Livestock Farming; Greenhouse Gas Emissions; Artificial Intelligence; Internet of Things; Methane Mitigation; Sustainable Agriculture

I. Introduction

Livestock production is a core pillar of the global food and agriculture system that supplies food, nutrition, jobs and economic livelihoods for billions of people around the world. The sector plays a major role in providing meat, milk, eggs, fibre and other animal-based products to ensure food security and the livelihoods of rural people. The situation has become more severe however, due to the increasing population, urbanization, changing food habits and greater global demand for animal protein, livestock production systems have been intensified. The intensification, besides improving productivity, has also created environmental pressures, such as GHGs emissions, resource depletion, ecosystem degradation, etc. This often means that agricultural sustainability is a crucial challenge for today's agriculture in terms of livestock production. Livestock agriculture is considered as a major source of anthropogenic green house gas (GHG) emissions, in particular through enteric CH4 emissions from ruminant digestion, manure management CH4 emissions, manure and soil interactions and CO_2 from energy use and feed production [1]. The global warming potential of

***Corresponding Author:**
Received: 24th April, 2026; Revised: 11th May, 2026; Accepted: 24th May, 2026; Available Online: 6th June, 2026
(DOI): 10.70102/AEJ.2026.18.1s.61

methane over 100 years is much higher than that of carbon dioxide and addressing livestock's emissions is an important measure to mitigate climate change. International initiatives such as the Paris Agreement and the United Nations Sustainable Development Goals (SDGs) highlight the need to cut down on emissions in agriculture while ensuring food production is sustainable. Traditional livestock raising methods are based on regular checks, using pen records, and blanket management that can mask differences among animals in health, nutrition and behavior. These practices can result in inefficient use of feed, late disease diagnosis, waste of feed resources and elevated GHG emissions. However, the digital revolution in agriculture has created new possibilities to address these challenges by providing the ability to monitor livestock continuously, make decisions in real time, and manage livestock operations with precision. Precision Livestock Farming (PLF) is a new technology strategy that combines the application of sophisticated sensing technologies, IoT, AI, machine learning (ML), computer vision, robotics, cloud computing and automated control systems to optimize livestock production. PLF is continuously gathering and analysing real-time data on animal health, feeding behaviour, movement, physiological status, environmental conditions and productivity [2]. These technologies, which rely on data, help to make informed management decisions that benefit animal welfare, boost production efficiency, decrease operational costs, and minimize environmental impact.

The use of wearable sensors, smart collars, environmental monitoring systems, unmanned aerial technologies and automated feeding equipment have made monitoring livestock more accurate. At the same time, AI and deep learning algorithms allows for predictive analytics in disease diagnosis, reproductive management, feed optimisation, methane emission estimation, and behavioural analysis. PLF technologies can help minimise feed waste, optimise feed conversion efficiency, facilitate better manure management and reduce greenhouse gas emissions across livestock systems [3]. Although significant progress has been made, the use of PLF is still limited by a number of technical, economic and organizational problems. Despite all these benefits, the implementation costs, infrastructure needs, interoperability between the different technologies and the security of data and the need for trained staff are still limiting the spread of adoption – especially for SMEs. These obstacles are best overcome through multidisciplinary teamwork, supportive policies, harmonisation of data frameworks and low-cost technologies. The aim of this review is to consider the contribution of Precision Livestock Farming technologies to the reduction of GHGs in various livestock production systems [4]. It addresses key emission sources, sensor-based monitoring technologies, the use of artificial intelligence in emissions monitoring, smart health and reproduction management and the main implementation challenges. Moreover, future research directions are emphasized, and the possibility of combining smart digital technologies with strategies for climate-smart livestock management to achieve environmentally sustainable, economically viable, and resilient agricultural production systems is discussed.

II. Overview of Precision Livestock Farming for Sustainable Agriculture

Precision Livestock Farming combines sensors, Internet of Things (IoT) technology, artificial intelligence, automation, and data analytics to help track the health, behaviour, nutrition and environment of livestock at all times. It enables intelligent and real-time farm management, which leads to improved productivity, animal welfare, and resource utilization, as well as to environmentally sustainable and climate-smart livestock production and to evidence-based decision making.

A. Concept and evolution of precision livestock farming

Precision Livestock Farming (PLF) is a cutting-edge livestock management system that uses digital technologies to continually track and monitor, analyse and optimise animal production by real time acquisition of the data and intelligent decision making. PLF combines sensors, communication networks, artificial intelligence, automation and the cloud to track individual animals throughout their entire production cycle, unlike traditional livestock management practices that rely on periodic observations and manual actions [5]. The idea was developed in the late 1990s in the context of precision agriculture and has gradually developed with the progress of Internet of Things (IoT), machine learning and computer vision, wearable devices, robotics and big data analytics. Incorporation of modern PLF systems allows for continuous monitoring of animal health, feeding habits, reproduction, animal welfare, productivity and environmental conditions, while providing the ability for timely intervention to improve operational efficiency. The uptake of PLF technologies globally is gaining momentum due to growing worries on climate change, greenhouse gas emissions, animal welfare, antimicrobial resistance, and resource sustainability [6]. In this context, PLF has emerged as an essential part of climate-smart agriculture with the benefits of optimized production, reduced environmental footprint, increased returns on investment and sustainable livestock production, all thanks to the evidence-based approach to management.

B. Principles of Data-Driven Livestock Monitoring and Management

Data-driven livestock monitoring is underpinned by the ability to collect, integrate, analyse and interpret biological, behavioural, physiological and environmental data to inform decision making for livestock management. Today's PLF systems collect real-time data from wearable sensors, environmental monitoring devices, automated feeders, milk analyzers, cameras and positioning systems that continually analyze farm and animal performance. These data sets are scattered and sent over wireless communication systems to cloud or edge computing applications, where sophisticated analytical algorithms turn raw data into useful information. Predictive analytics can help to identify disease, stress, reproductive events, nutrition deficiencies and abnormal behavior before clinical signs appear [7]. Decision-support systems then suggest best feeding schedules, exact medication, environmental changes, breeding plans and manure management measures, all according to the needs of the individual animal. This personalized management strategy leads to higher feed conversion efficiency, less waste of resources, better animal welfare and lower greenhouse gas emissions. Continuous monitoring also enhances traceability, productivity measurement, regulatory compliance and the support of livestock production sustainability, by implementing scientific, evidence-based and adaptive management practices in a variety of production environments [8].

C. Integration of Sensors, Artificial Intelligence, and Automation Technologies

Technological backbone of Precision Livestock Farming is the integration of sensors, AI and automation technologies in order to enable intelligent and autonomous livestock management. Physiological, behavioral and environmental data is collected continuously from livestock and livestock production facilities via wearable biosensors, accelerometers, GPS, temperature sensors, microphones, environmental sensors and computer vision systems. These data streams are sent over IoT networks to cloud or edge computing services where AI and ML algorithms are used to process complex data patterns for health monitoring, disease prediction, estrus detection and feed optimization, and methane emission estimation. Management decisions are made and carried out in automated systems such as robotic feeders, precision milking machines, ventilation controllers, manure handling machines and climate control machines with little human intervention [9]. This integration of sensing technology, smart analytics, and automation leads to a more efficient operation, fewer man-hours needed, better animal welfare, more efficient use of resources, and fewer environmental impacts. The table 1 summarizes the list of recent technologies, applications, outcomes and limitations of the PLF technologies comprehensively. Thus, integrated PLF technologies create a very responsive data-driven and sustainable livestock system that can contribute to climate smart agriculture and long term environmental sustainability.

PLF Technology	Livestock Type	Data Source	Primary Objective	Key Findings	Limitation
Precision Livestock Farming framework [10]	Multiple livestock	Sensor networks	Improve animal monitoring	Established PLF principles for sustainable livestock management	Limited AI integration
IoT and smart sensing [11]	Dairy cattle	Wearable and environmental sensors	Real-time livestock monitoring	Improved health detection and farm automation	High deployment cost
Precision monitoring systems [12]	Dairy cattle	Accelerometers, cameras	Animal welfare assessment	Enhanced welfare and productivity monitoring	Sensor calibration challenges
Automated feeding technologies	Dairy cattle	Feeding sensors	Optimize feed efficiency	Reduced feed wastage and improved production	Infrastructure dependency
Smart wearable devices [13]	Dairy livestock	Biometric sensors	Continuous physiological monitoring	Early disease and estrus detection	Battery life limitations

Precision dairy farming [14]	Dairy cattle	Farm management data	Improve farm productivity	Better operational efficiency and management decisions	Limited interoperability
IoT livestock platform [15]	Cattle and sheep	Environmental and animal sensors	Intelligent livestock management	Improved remote monitoring and traceability	Cybersecurity concerns
Artificial Intelligence in PLF	Multiple livestock	Multisource sensor data	Intelligent decision support	Higher prediction accuracy for animal health	Large data requirements
Smart agriculture technologies	Multiple livestock	IoT devices	Digital agriculture applications	Improved precision farming efficiency	Integration complexity
Cloud-enabled smart farming	Livestock farms	Wireless sensor networks	Automated farm operations	Efficient resource management and scalability	Network reliability dependency

Table 1. Related Studies on Precision Livestock Farming for Sustainable Agriculture

III. Sources of Greenhouse Gas Emissions in Livestock Production

The primary sources of GHG emissions from livestock are enteric methane fermentation, manure decomposition, nitrous oxide emission from manure-soil interactions, and carbon dioxide emissions from farm activities that require a lot of energy. Knowing these emission pathways can guide targeted mitigation measures based on precision technologies, better nutrition, effective manure management, and sustainable practices of livestock production to be more climate resilient.

A. Enteric methane emissions from ruminant animals

Enteric methane is the biggest source of GHGs from livestock production, especially ruminants like cattle, buffaloes, sheep and goats. Methane is generated by microbial fermentation of fibrous feed materials in the rumen under anaerobic conditions by specialized methanogenic archaea which produce methane from hydrogen and carbon dioxide. Most methane produced is lost from the atmosphere by eructation, and less by respiration and manure. Methane has a much higher global warming potential than carbon dioxide over 100 years, so enteric fermentation is a major driver of the climate change effects of agriculture. A variety of factors affects methane production such as the type of animals, age, body weight, animal health, feed composition, forage quality and digestibility, feeding rate, rumen microflora and flora in the rumen. Methane is typically larger in quantity and feed conversion efficiency (FCR) is typically lower when poor quality forage and inefficient feeding practices are used.

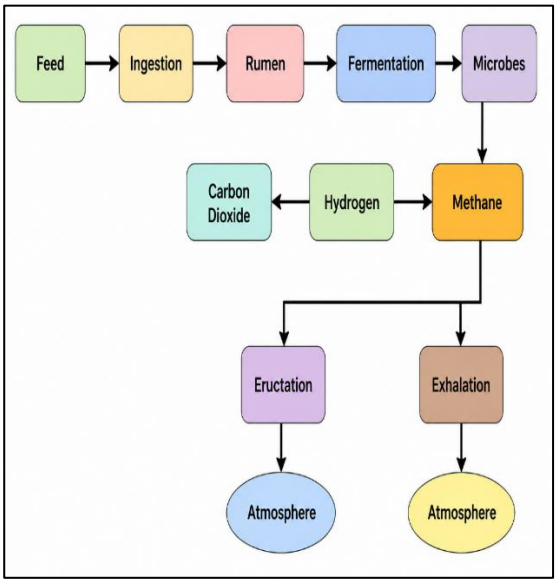


Figure 1. Enteric Methane Emission Pathway in Ruminant Animals Through Rumen Fermentation and Methanogenesis

Precision Livestock Farming technologies such as wearable sensors, automated feeding systems, artificial intelligence, and rumen monitoring technologies, provide a continuous assessment of feeding behaviour, digestive efficiency, and animal metabolism. These technologies enable precision nutrition approaches to be delivered that maximize feed efficiency, productivity, minimize methane emissions and optimize environmental sustainability of livestock systems.

B. Methane Generation from Manure Storage and Management Systems

The other important source of CH4 emissions is livestock manure management, including anaerobic

treatment and storage of manure. When the manure decomposes, microorganisms decompose the organic matter without oxygen, creating methane gas that is released to the atmosphere. The amount of emissions is dependent on factors such as the type of manure, moisture content, storage time, temperature, oxygen availability and management. Most liquid manure storage systems, lagoons, pits and slurry tanks generate significantly higher methane emissions compared to solid manure storage systems as they provide anaerobic conditions suitable for the growth of methanogenic microorganisms for long periods of time. The manure accumulation has also been worsened with the increase in livestock intensification and proper management of manure is important for mitigation of climate change. Precision Livestock Farming technologies aid in continuous manure storage monitoring by providing sensors for the Internet of Things that monitor storage condition, such as temperature, moisture, pH, gas concentration and storage characteristics. AI algorithms process these data to fine-tune manure management, aeration plans, biogas capture and wastewater treatment systems. Combining renewable energy production via anaerobic digesters, automated manure management and precision monitoring can lower methane emissions. By doing so, intelligent manure management benefits the environment, increases nutrient recycling rate, reduces odors and reduces GHG emissions in livestock production.

C. Nitrous Oxide Emissions from Livestock Waste and Soil Interactions

The main sources of NOx emissions from livestock production are the conversion of nitrogen compound that occurs in animal manure, urine and applied organic fertilisers. Under a range of soil moisture and oxygen levels, microbial nitrification and denitrification processes transform ammonium and nitrate into nitrous oxide, after being deposited on grazing lands or applied to agricultural soils. N2O has an extremely high global warming potential and a long residence time in the atmosphere; it is one of the most important agriculture-related greenhouse gases. Soil properties, rainfall, irrigation, temperature, nitrogen content, manure application rates, grazing intensity, and crop management systems are important factors affecting emission intensity. High nitrogen application rates and poor use of manure lead to significant amounts of nitrous oxide and to lower nutrient-use efficiency. Precision Livestock Farming technologies combine environmental sensors, soil monitoring equipment, satellite data and Artificial Intelligence to provide ideal nutrient management and manure application timing. Nitrogen availability, soil moisture dynamics and emission risks are estimated with predictive models, which allow for site-specific nutrient management strategies aimed at minimizing N losses. These smart solutions optimize fertilizer use, boost soil health, lower GHG emissions, and enable sustainable livestock and crop production in an integrated agriculture system, all while helping to shrink the environmental footprint of agriculture.By optimizing fertilizer use, improving soil health, lowering GHG emissions, and enabling sustainable livestock and crop production within an integrated agriculture system, these smart solutions help to shrink the environmental footprint of agriculture.

D. Energy Consumption and Carbon Footprint of Livestock Operations

In addition to the biological emissions, livestock production is also responsible for large amounts of carbon dioxide emissions due to energy use in several production activities. Electricity and fossil fuel power systems are widely employed to ventilate houses, light up interiors, feed and milk livestock, pump water, cool and heat homes, handle manure, process feed, move animals, and refrigerate. The carbon footprints of animal production systems are further expanded by the operations of feed manufacturing, fertilizer production, and transportation all along livestock production chains. Intensive livestock operations require more energy due to using mechanical equipment, climate controlled buildings, and high tech production systems. Ways to achieve energy efficiency are not only to lower production costs but also to reduce greenhouse gas emissions from fossil fuel combustion. Precision Livestock Farming technologies play a key role in optimizing energy use by intelligent monitoring, automated process control, predictive maintenance and real-time resource management. Smart energy management systems use sensors from the Internet of Things, artificial intelligence, and a cloud-based analytics platform to control the ventilation, light, feeding and equipment systems depending on actual production needs. The use of renewable energy sources such as solar energy and biogas from animal waste further reduces reliance on fossil fuels. All these innovations contribute to lower carbon emission, better efficiency in operations, economic sustainability and climate smart livestock production system.

IV. Sensor-Based Technologies for Emission Monitoring and Control

These sensor-based technologies track conditions such as livestock health, behavior, methane indicators, and environmental conditions around the clock, through sensors on livestock, sensors in the environment, smart collars and Internet of Things platforms. Real-time data collection enables timely interventions, feeding optimization, intelligent manure management, lower GHG emission, better

animal welfare and sustainable precision livestock farming.

A. Wearable sensors for animal health and behavioral monitoring

With the advent of sensor technologies that can be worn, the PLS has become a vital part of the agricultural landscape, allowing for the continuous monitoring of animal health, behaviour and physiological status in real time. The devices are lightweight, attached to animals via ear tags, leg bands, neck belts or harnesses and use various sensors, including accelerometers, gyroscopes, temperature, heart rate, respiration, and rumination detectors. The continuous data collection enables farmers to observe animals feeding, moving, resting, their body temperature, their stress and their reproductive status, without disturbing them. Abnormal behavioral patterns are often the first signs of disease, nutrient deficiencies or environmental stress and can be used for early detection and prevention of loss of productivity. As shown in Figure 2, the continuous monitoring of livestock's health and behavior are achievable in an efficient manner using wearable sensors. Feed efficiency improves with better health management and fewer unnecessary medicines which indirectly reduces GHG emissions from poor production systems.

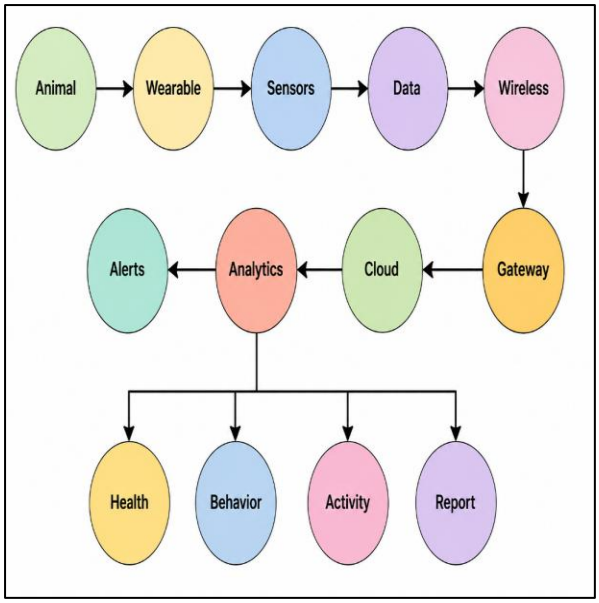


Figure 2. Wearable Sensor-Based Smart Livestock Health and Behavioral Monitoring Framework

Wearable sensors also offer valuable information for the optimization of feeding programmes, heat stress detection, monitoring grazing behaviour and animal welfare. The gathered data is sent to cloud or edge computing systems, where AI algorithms analyse the information in advance and provide timely alerts. As a result, the application of wearable sensing technologies has the potential to enhance the productivity of livestock, aid in climate-smart management, lower operational costs, and help create more environmentally-friendly agricultural practices.

B. Internet of Things (IoT)-Based Livestock Monitoring Systems

The Internet of Things (IoT) has revolutionized livestock management, creating a network that enables real-time data exchange and analysis from smart devices with animals and their surroundings. IoT-based livestock monitoring systems connect all the environmental sensors, wearable sensors, automated feeding systems, water monitoring, climate sensors, surveillance, and communication gateways into a single digital environment. These devices are able to measure continuously parameters like temperature, humidity, gas concentration, feed intake, water consumption, animal movements, housing conditions etc. The wireless communication technologies, such as LoRaWAN, Wi-Fi, Bluetooth Low Energy, Zigbee and cellular networks enable the reliable transmission of data to the cloud or edge computing. These datasets are then analyzed using AI and big data to detect health issues, feeding strategies, environment conditions, and methane emission risks. Automated alerts allow for quicker management interventions, helping to reduce resource wastage, improve animal welfare and production efficiency. The IoT Systems also enable predictive maintenance of farm equipment, automated control of ventilation systems, precision management of manure, and intelligent energy optimization. IoT technologies help to cut greenhouse gas emissions, enhance operational sustainability, boost traceability and ease the shift toward climate-smart and digitally connected livestock production systems.

C. Smart Collars and Biometric Sensing Devices

Smart collars and biometric sensing devices offer cutting-edge features to help monitor individual animal physiology, behavior and movement on a continuous basis, which are essential tools in Precision Livestock Farming. Most smart collars are combined with Global Positioning System (GPS) receivers, accelerometers, gyroscopes, microphones, temperature sensors, rumination monitors, and wireless communication modules, which can collect a whole suite of behavioral and physiological data. As these systems continuously monitor the grazing patterns, feeding frequency, walking activity, rumination, resting periods, social interactions, and location, farmers are able to determine if abnormal behavior is happening, which could be related to illness, nutritional stress,

reproductive cycles or environmental challenges. Biometric sensing devices also determine physiological parameters like heart rate, breathing rate, temperature, blood oxygen levels and metabolism, giving deeper insights into animal health and welfare. These multidimensional data are used to forecast disease outbreaks, identify when sows are in heat, predict methane, plan grazing, and increase the efficiency of feed utilization through AI algorithms. The real time notifications enable timely veterinary intervention and precise management decisions that help to minimize resource wastage and boost productivity. Cloud integration, mobile apps, and farm management systems allow for remote management and automation. Thereby, smart collars and biometric sensing technologies can contribute to the sustainability of livestock, animal welfare, decrease in greenhouse gas emission and to data-driven and climate resilient agricultural production systems.

V. Artificial Intelligence and Data Analytics in Precision Livestock Farming

The application of AI and data analytics in livestock management revolutionizes the farming industry, incorporating predictive modeling, deep learning, computer vision, and decision support systems. These technologies enhance disease diagnosis, behavior detection, methane prediction, feed optimization, reproductive management and resource efficiency, and lower GHG emissions to enable intelligent, climate smart farming production systems that are more sustainable.

A. Machine learning models for livestock performance prediction

The use of machine learning (ML) has turned it into a tool invaluable for analytical purposes in Precision Livestock Farming (PLF) and is used to predict animal performance through the processing of a lot of biological, behavioural, environmental and production data. The algorithms used for supervised learning such as Random Forest, Support Vector Machine, Decision Tree, Extreme Gradient Boosting, Artificial Neural Networks, and ensemble models are used to analyse complex relationship between the feed intake, body weight, milk yield, reproductive performance, health status, environmental conditions and genetic characteristics. These predictive models can extract patterns that aid in the decision making process of nutrition management, disease prevention, breeding selection, and productivity improvement. The dynamic learning from historical and real-time data allows for adaptive predictions in a changing production environment. By providing accurate performance forecasts, farmers can ensure that feed is being used optimally, waste of resources is minimised, animal welfare is maximised and production costs are kept low, while the productivity of the animal is kept high. The future is promising as machine learning, sensor networks, cloud computing, and farm management software are integrated into the system, furthering the automation and real-time decision making capabilities. Therefore, machine learning-based livestock performance prediction helps to optimize operations, enhance livestock production sustainability, lower emissions of greenhouse gases from resource mismanagement, and helps to promote evidence-based resource optimization for climate-smart livestock production.

B. Deep Learning Approaches for Animal Behavior Recognition

However, deep learning has greatly improved animal behaviour recognition by automatically learning and extracting high order features from images, videos, audio recordings or sensor-generated time-series data without relying on intensive manual feature engineering. Convolutional Neural Networks (CNNs), Recurrent Neural Networks (RNNs), Long Short-Term Memory (LSTM) networks, Vision Transformers (ViTs) and hybrid deep learning architectures are able to recognize feeding, grazing, rumination, resting, locomotion, aggression, lameness and social interactions accurately. Computer vision systems with cameras, and wearable sensors, to track movement and physiological information complement each other to achieve multimodal behavior analysis of livestock. Detecting abnormal behavior at an early stage allows disease, stress, injury, reproductive events, and nutritional deficiencies to be detected before signs and symptoms of the disease are observed. Automated Behavioural Recognition saves labour, boosts animal welfare and optimises management efficiency due to timely interventions. Instead, deep learning algorithms get better and better at predicting with every new addition to the training set, which is gathered under a broad assortment of conditions and environments. It enables them to be integrated with edge computing, cloud platforms, and automated farm management systems, providing real-time data for decision-making and optimizing resource usage to improve greenhouse gas emissions and sustainable livestock production, all through intelligent behavioral monitoring.

C. AI-Based Methane Emission Prediction and Optimization

By incorporating animal physiology, nutrition, environmental factors, and production data into sophisticated predictive models, AI harnesses the power of prediction and mitigation of methane emissions with impressive results. The algorithms of machine learning, deep learning and hybrid AI,

analyze the composition of rations, ruminating activity, the body weight, milk output, heat from the body, methane sensor readings, and rumen activity to precisely estimate methane generation. These predictive models can highlight emission trends and assess the impact of nutritional formulations, feed additives, grazing management, animal genetics and health on methane emissions. The continuous monitoring via the wearable sensors and the Internet of Things provides real-time data that allows the feed to be adjusted dynamically, together with the management of farm activities. The precision nutrition approach is optimized using artificial intelligence to suggest precision nutrition plans, methane reducing feed supplements, better grazing management plans and efficient manure management techniques to reduce GHG emissions while maintaining productivity. Combined with digital twins, cloud computing, and decision support systems, predictive accuracy and automated management are further improved. In Table 2, the various techniques, datasets, applications, outcomes, and limitations of AI are summarized. AI-powered methane prediction can therefore play a crucial role in optimizing feed use, minimize environmental footprint, decrease production costs, boost sustainability, and help producers and policymakers meet GHG mitigation targets for contemporary farming.

AI/Data Analytics Technique	Application Area	Livestock Type	Key Outcome	Limitation	Future Scope
Machine Learning	Smart livestock farming	Multiple livestock	Improved health prediction and automated monitoring	High-quality data requirement	Explainable AI integration
ML, Big Data Analytics	Precision agriculture	Mixed farming	Enhanced decision-making accuracy	Data heterogeneity	Unified agricultural platforms
Big Data Analytics	Farm management	Dairy and mixed farms	Improved predictive farm management	Data governance issues	Standardized data sharing
Convolutional Neural Networks (CNN)	Animal behavior recognition	Poultry, cattle	High-accuracy behavior classification	High computational demand	Edge AI deployment
Deep Learning	Animal welfare monitoring	Dairy cattle	Accurate welfare assessment	Limited field validation	Real-time monitoring systems
IoT + AI Analytics	Precision livestock monitoring	Cattle, sheep	Continuous livestock supervision	Network dependency	Intelligent autonomous farms
Decision Support Systems	Precision Livestock Farming	Multiple livestock	Improved farm management efficiency	Limited predictive capability	AI-driven autonomous decisions
Predictive Analytics	Dairy herd management	Dairy cattle	Better productivity prediction	Limited interoperability	Integrated cloud platforms

Table 2. Related Studies on Artificial Intelligence and Data Analytics in Precision Livestock Farming

VI. Smart Livestock Health and Reproduction Management

Smart livestock management integrates wearable sensors, AI systems, and automated monitoring solutions for early detection of diseases, effective health management, reproductive efficiency, and enhanced productivity. In the end, the continuous physiological and behavioural monitoring reduces the waste of resources, improves the welfare of animals, helps to minimise the environmental impact and contributes to sustainable livestock production by making informed decisions and taking action beforehand.

A. Early disease detection using sensor-based monitoring

One of the major benefits of Precision Livestock Farming is the ability to detect disease early, allowing for on-going monitoring of animals' health using sophisticated sensor technologies and intelligent data analysis. The physiological and behavioural data of single animals are continuously recorded using wearable sensors, smart ear tags, rumination monitors, thermal imaging cameras, accelerometers, heart rate sensors, respiration monitors and body temperature sensors. These data are sent to the cloud or edge computing systems where they are analyzed by AI and machine learning algorithms which look for subtle abnormalities that can sometimes precede visible symptoms of the clinical disease. Progressive changes in feeding behaviour, movement patterns, rumination rate, body temperature and activity level are signs of onset of infectious diseases, metabolic disorders, lameness, mastitis, respiratory diseases or heat stress. Automated alert systems will alert farmers and vets immediately and will enable quick diagnosis and targeted treatment, preventing disease spreading within the herd. Early intervention will help to reduce mortality, decline in production, avoid the use of unnecessary antibiotics and enhance overall animal welfare. A healthy animal will have improved feed conversion efficiency and productivity which will decrease the amount of greenhouse gas (GHG) emissions from inefficient production. Therefore, the use of sensors in disease monitoring is important for sustainable livestock management as it contributes to: better health of livestock, lower operation cost, better biosecurity, and better environmental responsible production of agricultural goods by proactive health care management.

B. Reduction of Resource Wastage Through Predictive Health Management

Predictive health management involves using AI, machine learning and constant monitoring via sensors, as well as predicting health issues before they have a major impact on animal productivity and farm resources. Predictive systems use information about the physiology, behavior, environment, and past health data to predict disease risk, and then make interventions to prevent that disease. Body temperature, feed intake, water consumption, activity, rumination and environmental stress are continuously monitored and an accurate assessment of the health deterioration is made early. This proactive approach maximizes the veterinary medicines, feed, labor, water and energy used and reduces unnecessary expenditure. Strategies of targeted treatment play a vital role in reducing overuse of antibiotics, the cost of medicines and environmental impact from drug residues. Better health management also translates to better feed conversion efficiency, lower mortality rates, quicker recovery times and more production. Decision support systems (DSS), which are computer-based systems that use artificial intelligence, offer tailored advice for nutrition, vaccination, housing management and environmental control that are specific to individual animal conditions. Therefore, predictive health management can drastically minimize resource wastage, boost the economic profitability, decrease the greenhouse gas emissions from inefficient livestock production and support livestock farming in a sustainable manner with efficient use of agricultural resources while taking care of the environment.

Hire a beekeeper to monitor your hives and provide the bees with a synthetic food source.Have a beekeeper inspect your bees and feed a synthetic food source.

C. Precision Reproduction Monitoring and Productivity Improvement

Wearable sensors, smart collars, accelerometers, pedometers, body temperature monitors, and activity tracking devices monitor continuously behavioral and physiological changes related to estrus, ovulation, pregnancy and calving. These multi-dimensional datasets are then used by a suite of artificial intelligence algorithms to make precise predictions of optimal breeding windows, to identify animals with reproductive issues and to alert vets to animals that need care. The use of automated estrus detection significantly improves insemination timing, conception rates, reduces reproductive failure and shortens calving interval relative to the use of visual detection. Continuous reproductive monitoring also allows for early pregnancy diagnosis, a postpartum health assessment, and evaluation of the animals' reproductive performance, providing management interventions that can be undertaken at the right time to improve the chances for a successful cow herd. Figure 3 shows intelligent reproduction monitoring for supporting decisions with precision to increase productivity. Better reproductive efficiency decreases the number of non-productive animals, decreases utilization of feed and resources and increases the number of animals productive for longer.

Improved reproductive performance will improve overall production efficiency and help to avoid unnecessary maintenance costs, which will also help decrease GHG emissions per livestock product. Precision reproduction technologies, therefore, reinforce sustainable agriculture of livestock by boosting genetics improvement, farm profitability, efficient use of resources, animal welfare, and

sustainable agricultural development, through intelligent livestock breeding systems.

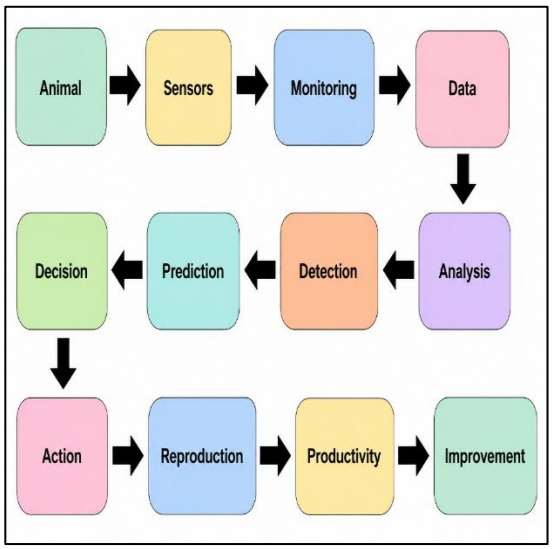


Figure 3. Precision Reproduction Monitoring and Productivity Improvement Framework Using Intelligent Sensor-Based Decision Support

VII. Challenges and Limitations of Precision Livestock Farming Adoption

The main obstacles for PLF adoption are the financial investment required, lack of digital infrastructure, technical complexity, cybersecurity risks, data privacy concerns, interoperability of data and a lack of farmer training. This is why it is crucial to overcome these challenges using technologies that are affordable, platform standardisation, capacity building and supportive policies, to make them practisable, and sustainable, on a large scale.

A. High implementation and maintenance costs

Although Precision Livestock Farming (PLF) has many advantages it is not used broadly because of the high implementation and maintenance costs. The implementation of a comprehensive PLF system involves significant investments in wearable sensors, smart collars, environmental monitoring instruments, automatic feeding systems, robotic milking systems, communication networks, cloud computing and AI software. Other costs include system installation, system calibration, software licensing, equipment upgrades, technical support and periodic maintenance. Financial constraints are a significant obstacle for small and medium-scale livestock producers to invest in these new technologies, especially in developing countries, given the scarcity of capital. Moreover, the technological progress may become so fast that equipment life cycles will be shortened, leading to high replacement costs and long-term cost reduction. Other operational costs for data storage, internet connectivity, cybersecurity and skilled staff also add to the total cost of ownership. Technology accessibility can be enhanced through the implementation of government incentives, financial assistance programs, cooperative models of technology sharing and cost-efficient sensor development. Lowering implementation costs is critical to the uptake of PLF on farms, the competitiveness of farms, and to sustain livestock production with lower GHG emissions and higher resource efficiency.

B. Data Privacy, Security, and Ownership Issues

Precision Livestock Farming can produce a lot of data on animal health, farm operations, environmental factors, production performance and management practices. Though these datasets offer valuable insights for intelligent decision-making, they also have a number of concerns in relation to data privacy, cyber security and data ownership. Sensitive farm information could be compromised with unauthorized access, cyberattacks, data manipulation, ransomware incidents, or unintentional information leakage, which could impact production activities. If proper encryption, authentication and access control are not provided then the use of cloud-based storage and Internet of Things communication networks exposes the data to security risk. One of the other key challenges is the bilateral sharing of ownership of agricultural data produced by sensors, AI platforms, equipment manufacturers and cloud service providers. Farmers are often confused with respect to who they are responsible to, who owns their operational information or who is commercializing it. In addition to this lack of standardised legal frameworks and transparent data governance policies further adds to the challenges of technology adoption. By adopting secure communication protocols, blockchain-based data management systems, and privacy-focused AI, and by establishing robust cybersecurity measures, business trust can be enhanced. Regulatory policies and well-defined ownership rights are crucial to safeguarding agricultural data and fostering its broader use, alongside digital livestock technologies.

C. Requirement of Technical Expertise and Infrastructure

Adequate technical expertise and technical support and a reliable infrastructure are essential for successful implementation of Precision Livestock Farming. To make the most of these technologies, farmers need to have a solid understanding of how these sensors, IoT devices, AI software, cloud-based systems, automated equipment, and digital tools work. Insufficient training and lack of digital literacy can be a barrier to technology acceptance,

especially for small-scale producers and rural farming communities. Internet connectivity, wireless communication networks, electricity as a power source, cloud computing resources and services of maintenance are also necessary for smooth operation of the system. But in many agricultural areas, digital infrastructure is still lacking, and real-time monitoring and automated management are still challenging. This compounded by technical glitches, sensor calibration, software compatibility, and equipment maintenance needs adds to the complexity of operations. Educational programs, farmer training, technical advice and user friendly software interfaces can make technology adoption and operational efficiency better. The construction of rural digital infrastructure and broadband connectivity is also the foundation of intelligent agriculture, which needs to be supported by government investment. Increased technical capacity and infrastructure will widen the spread of Precision Livestock Farming, enhance sustainability, productivity and environmental performance.

D. Interoperability Challenges Among Different Technologies

Precision Livestock Farming systems continue to have a large challenge from interoperability. Today, farms are likely to be using sensors, wearables, automation, communication systems, artificial intelligence software and farm management software from various manufacturers. Oftentimes, the underlying communication protocols, data formats and software architectures are proprietary, incompatible and independent, posing a challenge to seamless integration. Without interoperability, data sharing is not efficient, systems can't scale, implementation is harder and comprehensive farm-wide decision-making becomes more difficult. Farmers might be required to use several software platforms for the different devices, which can cause data silos, duplication of data and high expenses in operations. Other inconsistencies in data standards also hinder the performance of machine learning models that need datasets to be integrated and of good quality to make accurate predictions and optimizations. The use of a common set of communication protocols, open application programming interfaces (APIs), interoperable data models, and common agricultural data standards can greatly boost technology compatibility. Edge computing architectures and cloud-based integration platforms also help to ensure secure data transfer between different systems. Better interoperability will improve the operational efficiency, make technology deployment easier, improve the use of data for decision making and speed up the adoption of sustainable Precision Livestock Farming in different types of agricultural production.

VIII. Conclusion

Precision Livestock Farming (PLF) is a paradigm shift in the way livestock farming can be done to be environmentally sustainable and climate smart, which uses advanced sensing technology, artificial intelligence, sensor networks (IoT), data analysis, and automation. These technologies facilitate a system of continuous monitoring of animal health, behaviour, nutrition, reproduction and environmental parameters, which allows the making of informed decisions for improved productivity and lower GHG emissions. Smart methane monitoring, manure management, feed utilisation and energy use adds a big part to reducing the footprint of livestock farming. In addition, machine learning and deep learning models are used to enhance methane emission estimation, behavioral recognition, reproductive management, and disease prediction to ensure precision interventions that maximize resource use and animal well-being. Nevertheless, the adoption of widespread deployment is hindered by the cost of implementation, technical complexity, lack of interoperability, lack of digital infrastructure, data privacy and cybersecurity. The solutions to these challenges will come from coordinating a combination of researchers, policy-makers, technology developers and livestock producers on the creation of common platforms, cost-effective sensing technologies, secure data governance models and farmer training programs. In future, special attention should be drawn to the use of explainable artificial intelligence (XAI), digital twins, edge computing, integration of blockchain and autonomous decision-making systems to further improve sustainability. Overall, Precision Livestock Farming offers a promising route towards low carbon, resilient, resource efficient and economically sustainable livestock production to contribute to global climate mitigation goals and sustainable agriculture development.

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