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Original Research Paper

Climate-Smart Agriculture Approaches for Sustainable Animal Production and Environmental Protection

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Abstract: Climate change brings a number of challenges to sustainable animal production and is impacting livestock productivity, resource availability and environmental quality. Conventional livestock farming systems are linked to high greenhouse gas (GHG) emissions, use of resources less efficiently and reduction of biodiversity, so it is necessary to implement farming practices that are less harmful to the environment and more climate-resilient. The paper highlights the insights gained from various studies on Climate-Smart Agriculture (CSA) for sustainable animal production and suggests an integrated framework that integrates precision livestock farming, Artificial Intelligence (AI), Internet of Things (IoT), remote sensing, renewable energy, circular bioeconomy, and sustainability assessment in a single decision support system. The study reviews the latest technologies developed for climate change and assesses them based on environmental, resource, production, economic and social climate smart indicators. Comparing the proposed framework with traditional livestock systems shows that the benefits in terms of GHG emission reductions, water conservation, waste recycling, feed efficiency, water-use efficiency, livestock productivity, profitability and overall sustainability score are significantly better for the proposed framework (GHG emission reductions of 82%, water conservation of 86%, waste recycling of 91%, feed efficiency of 92%, water-use efficiency of 90%, livestock productivity of 95%, profitability of 92%, overall sustainability score of 93%). The findings suggest that the use of intelligent digital technologies in conjunction with sustainable animal husbandry practices can improve productivity and efficiency, reduce environmental footprint, increase animal welfare and resilience against climate change. The proposed framework provides a viable and broad approach for researchers, policymakers, and farmers to move towards low carbon, resource efficient, and environmentally friendly animal production systems and move towards global food security and the Sustainable Development Goals (SDGs) with a step.

Keywords: Climate-Smart Agriculture, Sustainable Animal Production, Precision Livestock Farming, Artificial Intelligence, Internet of Things, Environmental Protection, Circular Bioeconomy, Climate Resilience.

I. Introduction

Climate change has become one of the greatest global challenges for the sustainability of agriculture, food security and environmental protection. The livestock sector is very important for the livelihoods of all people in the world because it provides meat, milk, eggs, fibre and is also a source of draft power, and it is a major source of employment and national economies for the rural population. There is also an understanding that livestock production is a significant source of GHG (enteric fermentation, manure management, production of feed and land-use change). Global

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warming, irregular rainfall, extended droughts, floods and more frequent cases of livestock diseases have resulted in significant impacts on the productivity of animals and ecosystems. Therefore, sustainable production of animals, while reducing environmental footprint, is a world-wide priority for researchers, policy makers and agricultural practitioners. Recent research has made it clear that climate-smart agriculture is a crucial approach to enhance agrobiodiversity, boost productivity, and ensure agricultural resilience by combining climate-smart farming technologies and sustainable resource management strategies [1] [2].

The effects of climate change on livestock production systems are evident and the potential of Climate-Smart Agriculture (CSA) has been well illustrated in countries like India, Australia, Kenya, Brazil and the Netherlands. Dairy cows have been affected by heat stress, which has affected milk production and reproductive efficiency, and many areas of the livestock-dependent world have experienced long droughts, contributing to increased feed shortages and water scarcity. At the same time, the heavy livestock farming has led to the degradation of land, loss of biodiversity, imbalance of nutrients, methane emissions, and water pollution. The challenges have increased the need to create production systems that are economically viable, environmentally sound and sustainable, and do not impact ecosystem health. Climate-Smart Agriculture is thus an integrated approach that encompasses all aspects of agriculture: productivity, climate adaptation and environmental protection.

The three interconnected goals of Climate-Smart Agriculture are to enhance agricultural productivity and the income of farmers sustainably, to build the resilience of agriculture to climate variability and to cut back on GHGs emissions as much as possible. The CSA includes practices that are relevant to the various steps of animal production systems, namely: cultivation of fodder that is resilient to climatic risks, responsible use of grazing land, precision livestock farming, use of renewable energy, efficient utilization of manure, better breeding strategies, water management and circular bioeconomy. With the advent of Artificial Intelligence (AI), Internet of Things (IoT), remote sensing, cloud computing, and predictive analytics, the monitoring of livestock health, environmental conditions, use of resources, and production efficiency has been enhanced, making livestock management climate-smart. The digital applications help in the early detection of diseases, optimized feeding strategies, precision resource allocation and evidence-based decision making, which leads to increased productivity and environmental performance [1, 3, 5].

Despite extensive research on climate smart agriculture and digital farming technologies, there are still some key gaps in research. Previous research mainly focuses on one specific dimension of climate-smart agriculture, such as precision agriculture [1] or methane mitigation [3] (climate adaptation), digital agriculture [5] or resource efficient agriculture, but not on the combination of these. Much of the research that is available tends to concentrate on enhancing the production of livestock and gives comparatively little attention to biodiversity conservation, ecosystem restoration, circular use of resources and/or long-term environmental resilience [4]. In addition, the vast majority of digital agriculture studies test individual technologies, like IoT sensors or an AI-driven prediction models model, or remote sensing platforms, without taking into account their coordinated action when it comes to dealing with animals comprehensively and governing the environment adaptively.Moreover, many digital agriculture studies test individual technologies, for instance, IoT sensors or an AI-driven prediction models model or remote sensing platforms, without considering their coordinated action in the context of comprehensive livestock management and adaptive environmental governance [3].

There are some constraints in the current farm management practices to achieve climate-smart livestock management. When evaluating environmental performance, greenhouse gas emissions are often the only metrics considered, while other sustainability metrics of equal importance, like soil health, water-use efficiency, nutrient recycling, biodiversity conservation, ecosystem restoration and waste valorization are ignored. Similarly, the economic feasibility, farmer adoption, policy implementation, and social sustainability are often studied separately from each other and not linked in a comprehensive decision-support tool [2], [4], [5]. The current system of livestock management is also largely reactive and reactive in nature, leading to inappropriate use of resources, late detection of disease, greater water and energy usage and deterioration of the environment. Furthermore, the fragmented implementation initiatives often do not lead to a successful collaboration between farmers, technology providers, environmental agencies and policy makers, which may limit the scale of the implementation of climate smart livestock systems [6, 7].

One important constraint of the current approaches is that they lack integrated intelligent decision-support systems, which are able to simultaneously process climatic information, the environmental parameters, livestock health indicators, and resource utilisation, and give recommendations for adaptive management. Although some precision agriculture technologies have proven to be effective in enhancing productivity and improving operational

efficiency, their use in combination with ecological restoration, principles of circular bioeconomy and sustainability evaluation has been little studied [3, 4]. With the increasing intensity of climate variability, there is more need for full-scale approaches that can consider the trade-offs between productivity and environmental protection and long-term ecosystem resilience.

In this paper, a holistic Climate-Smart Agriculture (CSA) framework is presented that could be used to guide research for sustainable animal production and environmental protection. The framework that is proposed combines ecological sustainability, precision livestock farming, AI based analytics, environmental monitoring via IoT, resource optimization, renewable energy integration, circular waste management, conservation of biodiversity and adaptive decision support into a multi-layer architecture. The proposed framework differs from traditional methods that focus on optimizing single farming stages, thereby allowing to integrate continuous interaction between environmental monitoring, intelligent livestock management, optimizing resources, performance evaluation for sustainability and predictive analytics for informed and adaptive management all along the livestock production process.

The main aims of this paper are to analyse the fundamental principles and recent advancements in Climate-Smart Agriculture (CSA) for sustainable livestock production; to assess the potential of emerging livestock-specific technologies such as AI, IoT, remote sensing and precision livestock farming in climate-smart agriculture and environmental sustainability; to identify key challenges of the current livestock production systems and existing climate-smart approaches; to develop an integrated approach of climate-smart agriculture that incorporates technological innovations with ecological restoration and circular resource management; and to examine the proposed framework by employing comparative sustainability indicators including environmental performance, resource efficiency, productivity, economic feasibility and climate resilience [2], [5], [7].

The highlights of the paper are four-fold. First, it offers a thorough overview of recent climate smart agriculture approaches and digital innovations that could be used in sustainable animal production from the most recent literature [1]–[7]. Second, it offers an integrated multi-layer approach, integrating environmental monitoring, smart livestock management, artificial intelligence (AI) based predictive analysis, principles of circular bioeconomy and sustainability assessment in a single decision support architecture. Third, it integrates an evaluation framework that goes beyond the traditional environmental metrics to account for a multi-dimensional evaluation that combines greenhouse gas mitigation, water conservation, soil health, biodiversity protection, resource efficiency, economic performance and social sustainability. Lastly, the paper provides a range of practical suggestions for researchers, policy makers and livestock producers on the use of climate-smart technologies to support resilient, efficient, low carbon and environmentally responsible livestock production systems to improve global food security, environment protection and to help realize the Sustainable Development Goals (SDGs).

II. Climate-Smart Agriculture in Sustainable Animal Production

Climate-Smart Agriculture (CSA) is a holistic agriculture strategy that tackles the increasing problem of food security, climate change and environmental sustainability. The three objectives are mutually reinforcing: to boost agricultural productivity, to build resilience to climate variability, and to lower GHGs and to use natural resources in sustainable ways. CSA is a holistic approach to the efficient use of land, water, feed, energy and biodiversity to enhance production efficiency while maintaining the health of the ecosystem in livestock production. The CSA has been made more robust with recent technological breakthroughs including Artificial Intelligence (AI), Internet of Things (IoT), remote sensing, precision livestock farming and other innovations which allow continuous monitoring, data-driven decision making and optimization of resources. The synergy of these technologies and sustainable agriculture contributes to environmentally sustainable as well as economically sound livestock production systems.

Climate change is one of the significant factors impacting productivity and sustainability of livestock around the globe. The high temperatures, erratic rainfall, extended periods of dryness, floods and more frequent happenings of animal diseases have adversely affected animal health, feed availability, water availability, and farm profitability. Feed intake, milk production, reproductive efficiency and growth rates are all reduced by heat stress and pasture productivity and availability of feed is reduced by drought conditions. In addition, extreme weather events result in damage to livestock facilities which leads to an increased spread of diseases and substantial loss to farmers. The challenges underline the need for developing climate resilient livestock production systems that are able to adapt to the changing environmental conditions.

Climate Factor	Major Impact

Heat stress	Reduced productivity
Drought	Feed and water scarcity
Floods	Disease outbreaks
Rainfall variability	Decline in pasture growth
Extreme weather	Economic losses

Table 1. Climate Impacts on Livestock Production

Climate change has significant impacts on livestock production, which are summarized in Table 1. It also demonstrates how increased temperatures, droughts, flooding and altered rainfall create challenges for animal productivity, feed and water availability, pasture growth and farm profit, highlighting a need to build adaptation strategies to climate change that are smart in their approach.

In sustainable livestock production, the focus is on increasing the productivity of the animal and on maintaining and conserving natural resources and reducing the environmental impacts. Climate-smart livestock management involves rotating the livestock between different fields, using integrated crop-livestock farming systems, precision feeding and climate-smart livestock breeds, and ensuring suitable livestock housing. Rotational grazing helps to improve the growth of the pasture, increase soil fertility, and crop residues are fed to livestock and the manure used for organic fertilization; integrated farming systems can recycle crop residues as feed for livestock and manure as organic fertilizer. The effectiveness of the use of feed and the reduction of methane emissions improve the cost of production and environmental performance thanks to Precision nutrition. Together, these practices help to boost productivity on farms, boost the welfare of animals and drive ecologically sustainable farming.

Feed, water and energy use must be efficient in order to ensure a sustainable livestock production. Precision feeding technologies maximize nutrient intake based on animal needs, minimize feed losses and emissions of greenhouse gases. Smart irrigation systems, automation of drinking water, rainwater harvesting and wastewater recycling are measures of water conservation that enhance the efficiency of water use under the new climate conditions. In the same way, renewable sources of energy like solar, biogas plants etc. cut down on the need for the conventional fossil fuels and utilize the waste of livestock as a beneficial source of energy and organic fertilizers. Such sustainable methods boost efficiency, minimize pollution, and foster sustainable livestock production practices, making them eco-friendly and optimizing resource usage.

Resource	**Technology**	**Sustainability Benefit**
Feed	Precision feeding	Reduced emissions and feed waste
Water	Smart irrigation	Water conservation
Energy	Solar power and biogas	Lower carbon footprint
Waste	Anaerobic digestion	Renewable energy and organic fertilizer

Table 2. Resource-Efficient Technologies in Climate-Smart Livestock Farming

Table 2 shows the technologies used in Climate-Smart Agriculture which are considered to be key for resource efficient production. It clearly outlines the benefits of precision feeding, smart irrigation, renewable energy and anaerobic digestion for efficiency of feed and water use, greenhouse gas reduction, clean energy production and sustainable livestock production in the context of good resource use.

Adapting and becoming resilient to climate change are essential in sustaining the productivity of livestock in a climate that is becoming more uncertain. Adapting livestock to climate change by using climate-proof livestock breeds, better livestock housing systems, sustainable grazing systems, diversified fodder sources, and techniques for managing heat stress are effective adaptation measures. In addition, AI-powered disease forecasting, IoT for livestock management and weather prediction systems offer real-time data which allows farmers to make informed and timely decisions. These smart technologies enable early detection of disease, better utilization of farm resources, and better farm management, which increases the resilience of livestock production systems.

III. Existing Literature Review

The issue of climate change, food security, and environmental sustainability is a complex one and climate-smart agriculture (CSA) has come to the fore as a holistic approach to solving it. Recent research shows that CSA can boost agricultural productivity and at the same time increase the resilience of farms to climate variability and decrease greenhouse gas emissions. Good practice in livestock management has been highlighted as a way to ensure sustainable production over the long term within an environmental and economic framework, such as use of climate-smart animal production, precision feeding, better pasture management, using renewable energies and mixed

farming systems [7, 9, 16]. All these studies underscore the shift of the traditional livestock system to an integrated and resource-conserving farming system.

The significance of digital transformation in agriculture has been highlighted in recent research studies as well. The use of Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), cloud computing and remote sensing has contributed a lot to farm management by providing real-time monitoring and prediction. The intelligent systems continuously monitor the animal health, environmental conditions, feed consumption, and production performance, allowing intervention at the right time, and decision-making based on data. AI algorithms can also enhance production predictions, behavior analysis, and resource management, as well as disease forecasting, further boosting productivity and operational efficiency [8], [10], [12]. These technological advances have helped to increase the uptake of precision livestock farming and smart agriculture systems.

Sustainability of the environment is another big research area for climate smart livestock production. Many studies have been conducted on the strategies for emission reduction, nutrient recycling, water resources conservation, degraded ecosystems restoration and principles of a circular bioeconomy. There is a significant potential for reducing the environmental impact of livestock production by sustainable manure management, renewable energy generation (biogas production), carbon sequestration and ecosystem restoration [9], [14], [16]. Scientists have also pointed to the critical role biodiversity can play in ensuring long-term agricultural resilience in the face of a changing climate, as well as effective natural resource management.

Climate adaptation measures have become more significant over the last years, as droughts and floods have become more frequent, heatwaves are becoming more intense and new diseases of livestock are appearing. Various studies have investigated the characteristics of drought-resistant breeds of livestock, drought-resistant fodder species, adaptive grazing systems, and water-efficient irrigation technologies for improving the resilience of agriculture. Other innovations such as indigenous knowledge, integration of tree-livestock and agroforestry based livestock systems have also proved to be promising ways to create ecosystem stability while promoting farmer resilience to climate variability [11, 15]. These adaptive management practices play a big part in minimising production risk and enhancing environmental sustainability.

The use of digital livestock farming has also contributed to the change in climate-smart farming. Recent studies have shown the effectiveness of AI-powered monitoring systems, as well as animal sensors, automated feeding systems, drones, and cloud-based analytics in real-time tracking of animal behavior, health, and environments. Such intelligent systems not only enhance disease monitoring, reproductive control, precision nutrition, and overall farm efficiency, but also decrease the workload and expenses associated with farm operations [8], [12]. Likewise, the application of IOT in the management of the supply chain has enhanced traceability, transparency and quality assurance in the livestock production and agricultural value chain [13].

While considerable work has been done, the literature to date mainly focuses on the individual aspects of climate-smart agriculture, and not on integrated livestock management systems. The majority of studies focus on particular challenges like precision livestock management, machine learning, irrigation, GHGs reduction or climate adaptation, with no particular consideration of the complexity of the interaction between technological innovation, environmental conservation and socio-economic sustainability [8],[10],[11]. Thus, a wide range of frameworks that can incorporate environmental monitoring, smart livestock management, resource optimization, and ecosystem restoration are still relatively rare.

The lack of comprehensive decision-support systems which consider climate change, animal health, environmental quality, use of resources and production performance were also pointed out as a key limitation of previous studies. The current methods are mostly focused on optimizing individual farming businesses, and often lack holistic considerations for predictive analytics, circular resource management, biodiversity conservation, renewable energy use, and sustainability assessment [9, 12, 16]. Additionally, some of the studies that focus on technology have neglected to consider farmer adoption, implementation of policy, availability of infrastructure and economic viability – especially in agricultural economies in developing countries.

There are also reports of sustainability assessment being limited to a few performance indicators in the literature. While most studies focus on either greenhouse gas emission assessment, productivity or water-use efficiency, there are comparatively few investigations which report on both soil health and biodiversity conservation, as well as renewable energy use, waste recycling, animal welfare, economic viability and social sustainability [14, 15]. This disjointed assessment can prevent a full assessment of the environmental impacts of climate-

smart livestock systems along with their cumulative benefits in the long-term.

IV. Climate-Smart Technologies and Environmental Protection

In the age of Climate-Smart Agriculture (CSA), innovation is becoming essential in the fields of livestock production and sustainable resource use, through the use of advanced digital technologies. Precision SLF, Artificial Intelligence (AI), Internet of Things (IoT), remote sensing, GHG mitigation methods, circular bioeconomy and biodiversity conservation represent an integrated approach to build resilient and environmentally friendly animal production systems.

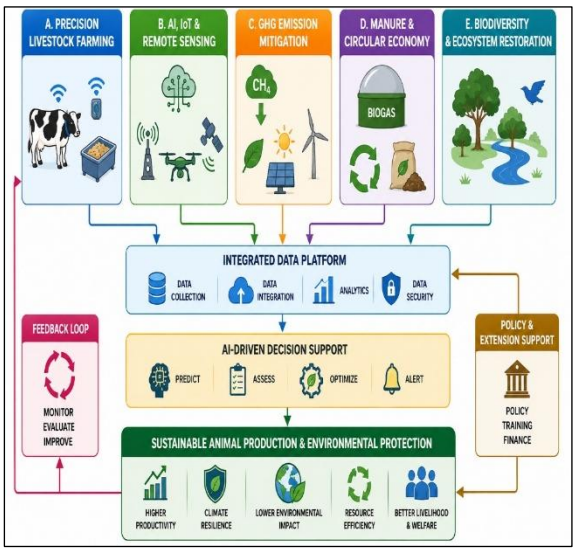


Figure 1. Architecture of Climate-Smart Technologies for Sustainable Animal Production

The framework of Climate-Smart Technologies for sustainable animal production and environment protection is presented in Figure 1. It is based on a centralised data platform and AI-based decision support system that incorporates precision livestock farming systems, AI, IoT, remote sensing, greenhouse gas reduction, circular bioeconomy and biodiversity conservation. This results in informed management decisions for the farm, increased productivity, increased climate resilience, decreased environmental footprint, efficient use of resources and improved farmer livelihoods.

These technologies offer the ability to monitor the land and livestock continuously, help with predictive decisions, maximise use of resources, and restore ecosystems, which means they contribute to low carbon and climate-resilient livestock farming. Precision Livestock Farming (PLF) has revolutionized agriculture and animal husbandry by implementing continuous monitoring and recording of animal health, behavior, feeding habits, reproduction and welfare through use of wearable sensors, RFID tags, smart cameras and automated feeding systems. Early detection of diseases, heat stress, nutritional deficits, abnormal behavior patterns and other issues, will be possible through real-time monitoring, therefore benefitting animal welfare and production losses. Precision feeding systems enhance nutrient utilisation by providing feed to meet the individual animal's physiological needs, which yield greater productivity and reduced methane emissions.

The recent progress of the technologies such as Artificial Intelligence (AI), Internet of Things (IoT), and remote sensing has revolutionized management of livestock for climate-smartness. A lot of environmental and livestock data is fed into AI algorithms that can forecast disease outbreaks, feed management, milk production and suggest adaptive management strategies. The temperature, water availability, humidity and animal health are monitored continuously with the help of IoT-sensors; while remote sensing and drone technologies are used for assessing the pasture conditions, health of the vegetation and changes in land use. These are "wrapped up" digital technologies, that enable evidence-based decision-making, operational efficiency and climate resilience. Minimizing greenhouse gas (GHG) emissions is now a key concern of sustainable livestock production. Utilizing precision nutrition, better manure management, growing climate-resistant fodder, rotation grazing and renewable energy are all climate-smart practices that substantially decrease gas emissions of methane and nitrous oxide. Better managing pasture and agroforestry also helps to sequester carbon to help mitigate climate change and enhance soil fertility and stability.

Sustainable manure management and circular bioeconomy solutions turn manure into valuable resources instead of environmental pollutant. By processing the manure in an anaerobic digester, the gas is converted to renewable energy supplies and the manure is converted to well-balanced, organic fertilizer for crop production. Nutrient recycling decreases the need for synthetic fertilizers and helps to solve the waste disposal issues while promoting an efficient use of resources and less environmental impacts, thereby fostering a circular agriculture economy. Last, but not least, the conservation of biodiversity and the restoration of ecosystems are vital in being a part of climate-smart livestock systems. Good grazing management practices, cropping-livestock enterprises, agroforestry, rehabilitation of degraded areas and soil management practices favour biodiversity, sequestration of carbon, decrease of land degradation and increase of the resilience of the ecosystem. All these climate smart technologies and ecological management practices form an integrated

approach which boosts livestock productivity, conserves natural resources, limits environmental pollution and ensures sustainable animal production in the long run.

V. Proposed Integrated Climate-Smart Framework for Sustainable Animal Production

The proposed Integrated Climate-Smart Agriculture (CSA) framework aims to create a comprehensive and intelligent system for sustainable animal production in a way that reduces the environmental impacts. The methodology departs from the traditional livestock management approaches aimed at ensuring maximum production, and extends to a range of novel technologies that are key to the resolution of environmental issues, including precision livestock farming, artificial intelligence (AI), Internet of Things (IoT), renewable energy and circular resource management. This framework will seek to continuously monitor and adaptively manage livestock production to enhance productivity, increase climate resilience, maximize resource use, and minimize GHG production.The framework is based on five principles of design. Efficient use of feed, water, energy and land resources, with the reduction of waste and degradation of the environment, is the first step toward achieving sustainability. Second, climate resilience supports livestock systems to adapt to changing climatic conditions through predictive analytics and adaptive management strategies. Third, digital intelligence is based on artificial intelligence, the Internet of Things, cloud computing and remote sensing technologies, all of which are used for real-time monitoring and automated decision-making. Circular resource management also encourages the recycling of livestock manure, biomass re-use and generation of renewable energy, as outlined below. Lastly, continuity of sustainability evaluation means that the environmental, economic, and social performance is evaluated continuously, based on sustainability indicators outlined in advance. The overall structure is composed of 6 layers that are mutually connected and functional layers. Each layer carries out special functions and shares information with the rest of the layers via a central decision-making platform. This is a holistic structure that supports synchronized control of livestock farming, environment protection and climate adaptation.

Figure 2 shows the proposed Climate Smart Livestock Farming Model where environmental data is gathered using smart monitoring technologies and combined with AI based decision support for smart livestock farming. This framework optimises the use of available resources, encourages the use of renewable energy and methods from the circular bioeconomy and continually assesses sustainability performance, leading to increased productivity, resilience to climate change, reduced GHG emissions, efficient use of resources and environmental-friendly animal production.

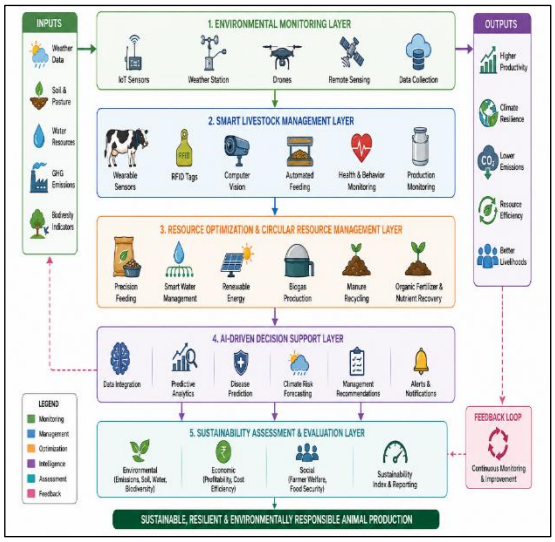


Figure 2. Proposed Model for Climate-Smart Framework for Sustainable Animal Production

The EML is the layer that is constantly gathering data on climatic conditions and availability of natural resources. Temperature, humidity, rainfall, soil moisture, pastures quality, water availability, greenhouse gas emissions, air quality are monitored by various IoT sensors, weather stations, satellite imagery, drone, and remote sensing platforms. Adaptive livestock management and early recognition of climate related risks are based on these environmental observations. Farmers can use continuous environmental monitoring to detect drought, too much heat, flooding, pasture damage and water shortage before it has a significant impact on livestock productivity. The historical environmental data can also be used with real-time observations to develop trend analysis and sustainable land management planning for long-term climate change.

Main products of this layer are Climate observations, Soil health indicators, Water resource status, Pasture condition, Greenhouse gas measurements and Biodiversity indicators. These data sets are then passed on to the intelligent livestock management system for further analysis.

Sustainable Livestock Management Layer is the focus on ongoing tracking of animal health, behavior, feeding, reproduction and welfare. Information is captured on a real-time basis with wearable sensors, RFID (radio-frequency identification) tags, smart collars, computer vision systems, automated feeding stations, body temperature, activity levels, heart rate, feed intake, milk production, movement patterns and

physiological conditions. AI algorithms are used to identify signs of unusual animal activity, disease outbreaks, production performance, and other recommendations for preventive measures, all from their analysis of these datasets. They send an automatic alert to farmers when there are any irregular health symptoms or environmental stress, allowing farmers to take prompt action and reduce production losses. This smart monitoring system will enhance Animal health management, Disease surveillance, Reproductive efficiency, Precision feeding, Animal welfare, Production forecasting. The ability to continually monitor livestock parameters with digital sensors instead of manual checks improves the accuracy, efficiency and responsiveness of livestock management.

One of the key goals of Climate-Smart Agriculture (CSA) is to achieve efficient use of agricultural resources. The Resource Optimization Layer optimizes the utilization of feed, water, energy, recycling of nutrients and waste, to maximize production efficiency and minimize environmental impacts. The precise feeding algorithms are designed to ensure absorption of the optimum nutritional input for the age, weight, physiological state and production level of the animal. Smart irrigation systems control water distribution according to weather forecasts and the soil moisture. The use of renewable energy sources such as solar power and biogas digesters helps minimize the use of fossil fuels and extracts energy from animal waste. The circular resource management element encourages Organic manure recycling, Nutrient recovery, Biogas production, Using renewable energy, Minimizing waste, Improving soil fertility. The integrated processes create a circular agricultural economy, in which agricultural waste is transformed into valuable resources instead of pollutants in the environment.

The Decision Support Layer is the “brains” of the proposed framework. It brings together data on the environment, livestock health, production, climatic forecasts, and resource utilization statistics, all in one central AI platform. These algorithms can use multi-dimensional data to continuously learn and find patterns that were previously unknown, forecast future risks, allocate resources optimally, and suggest appropriate management strategies. Before adverse conditions, predictive models estimate the probability of disease, feed demand, milk yield, water demands, heat stress, and GHGs. The DSS provides recommendations for Disease prevention, Precision feeding, Climate adaptation, Water management, Grazing optimization, Emission reduction, Energy utilization. This smart suggestion supports farmers to make informed decisions for management and minimises uncertainties in their operations.

The last layer assesses overall the sustainability performance of the livestock production system. This module does not only take an effort to measure productivity, but also measures environmental, economic and social sustainability with multiple performance indicators. Main assessment criteria are GHG emission, carbon-footprint, water-use efficiency, soil health, conservation of biodiversity, renewable energy use, efficiency of waste recycling, livestock productivity, operational cost and profitability of the farmer. The assessment module is an ongoing process that continuously compares how well a product, service or system is performing against sustainability targets, and suggests areas for improvement.

Category	**Performance Indicators**
Environmental	GHG emissions, carbon footprint, biodiversity, soil health
Resource	Feed efficiency, water use, renewable energy, waste recycling
Production	Milk yield, growth rate, animal health, mortality
Economic	Production cost, profitability, resource savings
Social	Farmer welfare, food security, technology adoption

Table 3. Sustainability Evaluation Indicators

Table 3 shows the sustainability evaluation indicators which were used to measure the performance of the Climate-Smart Agriculture framework proposed. It comprises environmental, resource, production, economic and social measures, offering an holistic picture of the productivity of livestock, efficiency of the use of their resources, environmental protection and sustainability.

The sustainability assessment allows continuous improvement through adaptive farm management, in the form of quantitative feedback. The proposed approach will include the incorporation of environmental monitoring, smart farming practices, resource management, intelligent decision making, and sustainability evaluation into a single Climate-Smart Agriculture platform. When they work together, the coordinated interaction between these functional layers allows intelligent decision-making, efficient resource use and environmentally responsible livestock production. The proposed framework will be anticipated to yield a number of long-term benefits. It has environmental benefits such as greenhouse gas reduction, soil health enhancement, water conservation, biodiversity and renewable energy use. Precision resource

management and predictive analytics can lead to savings in production costs, better feed efficiency, more productive livestock, and more profitable farms economically. Socially the framework helps to promote better livelihoods for farmers, increased climate resilience, improved food security and promote better use of sustainable livestock management practices.

VI. Performance Evaluation and Comparative Analysis

A Climate-Smart Agriculture (CSA) framework is evaluated based on the multidimensional performance assessment, which includes environmental, economic and production-related indicators. The key difference with the proposed evaluation methodology is that, rather than just looking at livestock productivity, it incorporates the overall sustainability of livestock production by looking at resource efficiency, climate resilience, environmental protection and economic viability. The framework is evaluated by comparing the conventional livestock production with the sustainable livestock production based on a climate-smart system as proposed, using some representative sustainability indicators indicated in the recent literature.

Five performance dimensions are taken into account: environmental sustainability, efficiency of resource use, livestock productivity, economic performance and social sustainability. Environmental indicators are GHGs, carbon footprint, water-use efficiency, soil health, and biodiversity conservation. Resource indicators measure feed conversion ratio, renewable energy, recycling of nutrients and waste management. Production performance is evaluated based on a livestock productivity, incidence of disease, a mortality rate and animal welfare. Economic indicators are: operational cost, profitability, resource saving; and social indicators are: farmer adoption, resilience to climate change, food security.

Performance Category	Evaluation Metrics
Environmental	GHG emissions, carbon footprint, biodiversity, soil quality
Resource	Feed efficiency, water efficiency, renewable energy use
Production	Milk yield, growth rate, animal health, mortality
Economic	Production cost, profitability, return on investment
Social	Farmer adoption, climate resilience, food security

Table 4. Performance Evaluation Indicators

Table 4 shows main performance indicators to assess the proposed framework of Climate-Smart Agriculture. The indicators are organised into five categories: environmental, resource, production, economic and social, which give a comprehensive overview of sustainability, operational efficiency, livestock productivity, profitability and climate resilience.

The proposed framework offers several benefits, including the optimization of resources. Precision feeding reduces the amount of feed wasted and AI-powered resource planning ensures better use of water, energy and nutrients. Biogas and solar power further significantly decrease reliance on fossil fuels, leading to more efficient operation and lower production costs.

Indicator	Conventional (%)	Proposed CSA (%)
GHG Emission Reduction	40	82
Water Conservation	48	86
Waste Recycling	45	91
Biodiversity Protection	52	88
Carbon Footprint Reduction	43	84

Table 6. Environmental Performance Comparison

Livestock production under the proposed Climate-Smart Agriculture (CSA) framework in Table 6 has a lower environmental impact, as precision feeding, using renewable energy, recycling manure, and sustainable grazing. The proposed system reduces GHG emissions, water use efficiency, biological diversity and waste recycling as compared to the conventional system.

The environmental performance of conventional livestock rearing and the proposed CSA are illustrated in figure 3. The proposed framework achieves the highest performance for all environmental indicators, such as reduction in greenhouse gas emissions, water saving, waste recycling, protection of biodiversity and reduction of carbon footprint, showing its effectiveness to

encourage sustainable livestock production in the environment.

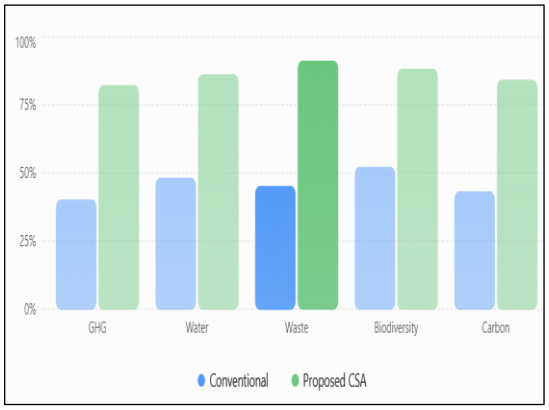


Figure 3. Environmental Performance Comparison

Feed, water, energy and nutrients are resources that can be used efficiently leading to better farm profitability and sustainability. By using AI to manage production, precision management reduces resource waste and optimizes production.

Resource Indicator	Conventional (%)	Proposed CSA (%)
Feed Efficiency	68	92
Water Efficiency	65	90
Renewable Energy Utilization	30	82
Nutrient Recycling	42	88
Energy Efficiency	60	89

Table 7. Resource Utilization Efficiency

Table 7 shows a comparison of the efficiency of the use of resources in conventional livestock systems and the proposed Climate-Smart Agriculture framework. The findings reveal that the proposed system is more feed efficient, water efficient, utilises more renewable energy and recycles nutrients, thereby increasing overall energy efficiency and the sustainability of livestock production.

As shown in Figure 4, the proposed Climate-Smart Agriculture framework not only meets but continually surpasses the conventional livestock farming in terms of various sustainability metrics. Environmental effects are significantly reduced, enhanced waste management, and reduced greenhouse gas emissions, more productive due to precision livestock monitoring and AI assisted decision making. Optimized feed, water and energy use makes the utilization of resources much more efficient.

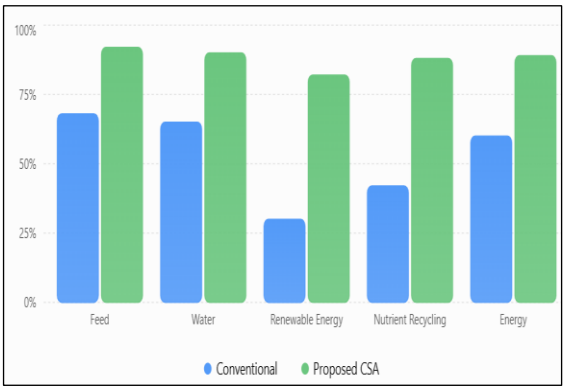


Figure 4. Resource Utilization Efficiency Analysis

The proposed framework increases the profits by optimizing the use of resources, intelligent forecasting of diseases, and minimizing operational expenses. Better livestock productivity and farm management also help to enhance climate resilience and food security.

Sustainability Indicator	Conventional (%)	Proposed CSA (%)
Productivity	72	95
Profitability	70	92
Climate Resilience	60	91
Farmer Adoption	68	89
Overall Sustainability	66	93

Table 8. Overall Sustainability Assessment

The overall sustainability assessment of the proposed Climate-Smart Agriculture framework is shown in Table 8. The proposed framework is found to be better than the traditional livestock systems in terms of productivity, profitability, climate resilience, farmer's adoption and overall sustainability, which indicates the potential of the proposed framework in ensuring economically viable and environmentally sustainable animal production.

The comparative analyses in figure 5 suggest that the proposed Climate-Smart Agriculture framework is always superior to the traditional livestock systems in terms of environmental, resource, economic and social aspects. The combination of AI-supported decision making, precision livestock farming, renewable energy and circular bioeconomy

solutions results in significant environmental benefits, increased sustainability, productivity and climate resilience.

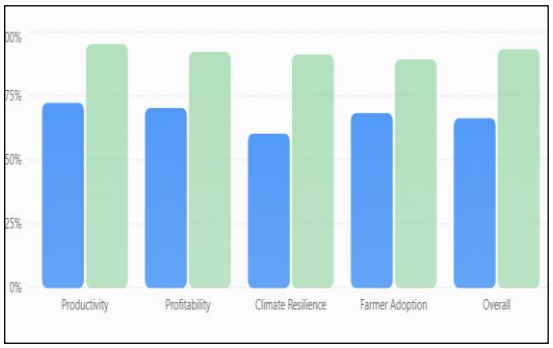


Figure 5. Overall Sustainability Analysis

There are some issues in implementation of it. Initial investment costs, insufficient digital infrastructure, a lack of technical knowledge and competency, data privacy issues, and reduced technology acceptance by smallholder farmers may be limiting the possible scale of implementation. Other research issues are integration of heterogeneous sensor platforms and the establishment of reliable real-time communication between the sensors. The future research challenges include creating cost-effective AI models, machine learning algorithms to explain AI results, Blockchain-based livestock traceability, Digital twins, Farm management systems with autonomy and Edge computing architectures. Enhancing policy support, farmer training and public-private cooperation will further drive the transition towards and uptake of CS-Ag and support the transition towards sustainable, low carbon and resilient animal production systems.

VII. Conclusion and Future Research Directions

The impact of climate change on sustainable animal production has proven to be a major challenge through the impacts on livestock health, productivity, resource availability and environmental quality. Traditional livestock farming systems can involve high resource use, and can lead to greenhouse gas emissions, loss of biodiversity, water scarcity and soil degradation. Hence, there is an emergency need to develop integrated agriculture approaches which will boost productivity, increase climate resilience and preserve natural ecosystems. Climate-Smart Agriculture (CSA) has become a promising approach that integrates sustainable agricultural practices and the use of digital technologies to ensure sustainable and environmentally responsible livestock production with economic viability. The present paper summarized the principles, technologies and applications of Climate-Smart Agriculture with regards to sustainable animal production and environmental protection. It explored recent advances in precision livestock farming, Artificial Intelligence (AI), Internet of Things (IoT), remote sensing, greenhouse gas mitigation measures, circular bioeconomy and biodiversity protection measures. The study also revealed key strengths of current livestock management practices, such as the lack of adoption of technologies, insufficient incorporation of sustainability elements and weak multidimensional assessment of environmental and economic performance.

Addressing these constraints, a comprehensive Climate-Smart Agriculture framework was proposed that would bring together the monitoring of the climate, the management of the livestock, the optimization of resources, the use of artificial intelligence for decision-making, renewable energy utilization and the assessment of the sustainability of the farming system in a common framework. Comparative performance assessment showed that the proposed framework significantly enhances environmental sustainability, efficiency of the utilization of resources, productivity of livestock, profitability and climate resilience, in comparison with conventional livestock production systems. The combination of precision farming technologies with a circular approach to resource management can help to reduce GHG emissions by using water and feed more efficiently, optimize nutrient cycling and promote the conservation of biodiversity. Although there are numerous benefits, several issues need to be addressed to make the proposed framework a success, such as infrastructure availability, high initial investment costs, digital literacy, interoperability of technologies for smart farming, and policy support. Agreements between governments, researchers, industry and farming communities, capacity building and training programs, and economic incentives are also vital for the uptake of climate-smart technologies by smallholders.

Future studies should explore the creation of explainable AI models, the use of digital twins in livestock management, traceability systems based on blockchain, a new breed of-edge computing for real-time farm analytics, robotic farming without human participation, and complex accounting methods for carbon. The integrated sustainability assessment models covering environmental, economic and social impacts under various climatic and geographical conditions should also be explored in further research. Furthermore, extensive field testing of climate-smart farming systems for livestock will be crucial to ensure their effectiveness and scalability in the long run. To summarise, Climate-Smart Agriculture offers a viable and adaptable solution for the intelligent and sustainable management of livestock production via adaptation and mitigation strategies, while also being resource-

efficient and scalable. The proposed framework plays a role in progress towards sustainable animal production by combining the modern use of digital technologies with ecological conservation, which will support global food security, environmental protection and fulfillment of the United Nations Sustainable Development Goals (SDGs).

References

[1] S. Getahun, H. Kefale, and Y. Gelaye, "Application of precision agriculture technologies for sustainable crop production and environmental sustainability: A systematic review," *Scientific World Journal*, vol. 2024, Art. no. 2126734, 2024.

[2] T. R. C. Konfo, A. B. P. Chabi, A. Amoussouga Gero, C. Lagnika, F. Avlessi, G. Biaou, and C. K. D. Sohounhloue, "Recent climate-smart innovations in agrifood to enhance producer incomes through sustainable solutions," *Journal of Agriculture and Food Research*, vol. 15, Art. no. 100985, 2024.

[3] R. Abiri, N. Rizan, S. K. Balasundram, A. B. Shahbazi, and H. Abdul-Hamid, "Application of digital technologies for ensuring agricultural productivity," *Heliyon*, vol. 9, Art. no. e22601, 2023.

[4] M. Keshavarz and H. Sharafi, "Scaling up climate-smart regenerative agriculture for the restoration of degraded agroecosystems in developing countries," *Sustainable Production and Consumption*, vol. 38, pp. 159–173, 2023.

[5] Ajani, S. N., and Atique, M., "Efficient Classification of Animal Health Conditions Using Gradient Boosting Machine-Based Models," in *Proceedings of the 2024 International Conference on Artificial Intelligence and Quantum Computing-Based Sensor Applications (ICAIQSA 2024)*, 2024, doi: 10.1109/ICAIQSA64000.2024.10882389.

[6] G. Tilahun, A. Bantider, and D. Yayeh, "Impact of adoption of climate-smart agriculture on food security in the tropical moist montane ecosystem: The case of Geshy watershed, Southwest Ethiopia," *Heliyon*, vol. 9, Art. no. e22620, 2023.

[7] B. Singh, A. Singh, Y. S. Jadoun, P. Bhadauria, and G. Kour, "Strategies for sustainable climate smart livestock farming," in *Adapting to Climate Change in Agriculture—Theories and Practices*, S. S. Mahdi, R. Singh, and B. Dhekale, Eds. Cham, Switzerland: Springer, 2024, ch. 16.

[8] S. Reddy and A. Walker, "Machine learning in agriculture: Applications and challenges," *International Journal on Advanced Electrical and Computer Engineering*, vol. 12, no. 1, pp. 15–20, 2025.

[9] M. Awais, X. Wang, and M. U. Ashraf, "Mitigation and adaptation strategies in climate-smart agriculture: A review for sustainable production," *Climate Smart Agriculture*, vol. 3, no. 1, Art. no. 100097, 2026.

[10] S. Ndung'u, M. Thiga, P. Wandahwa, and V. Ogema, "A data-driven model for sustainable deployment of climate smart agriculture practices among smallholder farmers in Kakamega," *Kabarak Journal of Research & Innovation*, vol. 13, no. 1, 2023.

[11] B. Serote, S. Mokgehle, C. Du Plooy, S. Mpandeli, L. Nhamo, and G. Senyolo, "Factors influencing the adoption of climate-smart irrigation technologies for sustainable crop productivity by smallholder farmers in arid areas of South Africa," *Agriculture*, vol. 11, no. 12, Art. no. 1222, 2021.

[12] B. Horváthné Kovács and Z. Zörög, "Digital livestock farming in climate-smart agriculture: An overview to advance the SDGs," *Discover Sustainability*, vol. 6, Art. no. 940, 2025.

[13] J. V. Vaibhav, D. N. Vitthal, K. S. Mangesh, O. B. Prashant, and C. Amruta, "Easy supply chain management for Indian agriculture business using IoT and big data approach," *Multidisciplinary Journal of Research in Engineering and Technology*, vol. 4, no. 2, pp. 1197–1205, 2017.

[14] S. Bhatnagar, R. Chaudhary, S. Sharma, Y. Janjhua, P. Thakur, P. Sharma, and A. Keprate, "Exploring the dynamics of climate-smart agricultural practices for sustainable resilience in a changing climate," *Environmental and Sustainability Indicators*, vol. 24, Art. no. 100535, 2024.

[15] A. S. Assani, A. K. Yarou, N. V. F. G. Dedehou, et al., "Towards indigenous community-based adaptation to climate change: A typological analysis of tree-livestock integration in smallholding systems in dryland areas of Benin (West-Africa)," *Agroforestry Systems*, vol. 98, pp. 197–211, 2024.

[16] H. Azadi, N. Siamian, S. Burkart, S. Moghaddam, I. Goli, T. Dogot, P. Lebailly, D. Teklemariam, A. Miceikienė, and S. Van Passel, "Climate smart agriculture: Mitigation and adaptation strategies at the global scale," in *Climate Smart Agriculture*. Cham, Switzerland: Springer, 2022, ch. 4