SUSTAINABLE DAIRYING
IN THE ERA OF CLIMATE CHANGE

Editors
Shahaji Phand and
Sushrirekha Das

Sustainable Dairying in the Era of Climate Change

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Edition: 2025

ISBN: 978-81-19663-06-4

Citation: Shahaji Phand, and Sushirekha Das [book] Hyderabad: National Institute of Agricultural Extension Management, Hyderabad, India.
Designed By: Archana Gogikar (Multimedia Designer)

Published for Dr. S. H Singh, IPoS, Director General, National Institute of Agricultural Extension Management (MANAGE), Hyderabad, India by Dr. G. Bhaskar, Assistant Director (IT), MANAGE and printed at MANAGE, Hyderabad as publication.

डॉ. सागर हनुमान सिंह, भा.डा.से.
महानिदेशक

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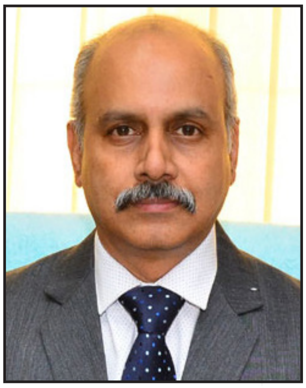
Director General

Foreword



It is my pleasure to convey my warm felicitations on the publication of "Sustainable Dairying in the Era of Climate Change". At a time when the dual challenges of ensuring nutritional security and mitigating environmental degradation are becoming increasingly intertwined, this book addresses one of the most critical sectors at the nexus of livelihood, food systems, and ecological balance.

Dairying has long been an integral part of India's rural economy, not only as a source of income and nourishment for millions of households but also as a vehicle for inclusive development. However, the impacts of climate change ranging from altered precipitation patterns and heat stress to shifts in feed and fodder availability pose novel risks to the resilience and sustainability of dairy systems. The imperative, therefore, is to transition from conventional practices to those that are ecologically smart, economically viable, and socially inclusive.

This volume brings together evidence-based insights, practical innovations, and strategic pathways that can help reorient dairy development towards sustainability. Its thematic focus on climate-aware interventions, resource-efficient production, and adaptive management resonates deeply with MANAGE's mission of strengthening agricultural and rural extension systems in service of farmers. The knowledge synthesized here can empower extension professionals, policy-makers, researchers, and dairy value chain stakeholders to design and disseminate climate-resilient dairy practices be it through improved breed-management, sustainable feed strategies, low-emission milk production technologies, or community-based adaptation frameworks.

I am particularly encouraged by the emphasis on capacity building and knowledge dissemination, as lasting transformation in dairying must be rooted in informed and empowered communities. MANAGE remains committed to facilitating multidimensional learning, promoting participatory extension approaches, and fostering partnerships that scale up sustainable innovations across regions.

As we collectively strive to meet our national goals of doubling farmers' income, ensuring rural livelihoods, and contributing to climate commitments, sustainable dairying can and should be a pillar of that journey. I congratulate all the editors, and authors who have contributed to this important work. I am confident that the ideas and recommendations contained within will stimulate dialogue, inform policy, and inspire on-ground action.

I extend my best wishes for the wide circulation of this book and for its impactful role in shaping the future of climate-smart dairy development in India and beyond.

Director General, MANAGE

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कृषि-संबन्धित क्षेत्रों में विस्तार केंद्र तथा
प्रधान समन्वयक - एसी एवं एबीसी योजना

Dr. Shahaji Phand
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MESSAGE

Dairying is not only a source of nutrition and livelihood for millions of rural households, but also an integral part of India's agricultural economy and socio-cultural fabric. It plays a crucial role in ensuring food and nutritional security, especially for small and marginal farmers, landless labourers, and women. However, the sustainability of this sector is increasingly being challenged by the multifaceted impacts of climate change. Rising temperatures, erratic rainfall, heat stress, fodder and water scarcity, and the resurgence of climate-sensitive animal diseases are already affecting livestock productivity, animal health, and overall farm incomes.

In this context, there is an urgent need to transition towards climate-resilient and environmentally sustainable dairying systems. This calls for a paradigm shift that combines traditional knowledge with modern scientific and technological innovations. Emphasis must be placed on adaptive breeding strategies, improved housing and shelter management, stress-mitigating feeding practices, climate-informed animal health management, and renewable energy-based dairy operations. Strengthening farmer-centric extension services, financial support mechanisms, and climate-resilient infrastructure is also vital.

The present book, ***"Sustainable Dairying in the Era of Climate Change"***, is a timely and commendable initiative. The book offers an in-depth exploration of the challenges and opportunities that lie at the intersection of dairying and climate resilience. It captures practical field experiences, policy frameworks, institutional interventions, and research-based insights that together form the foundation of climate-smart dairy development. The inclusion of region-specific case studies, climate forecasting services, and mitigation-financing instruments adds significant value to the content.

I appreciate the authors' and editors efforts in compiling this comprehensive and well-researched volume. The editorial team deserves special recognition for curating diverse perspectives that reflect both ground realities and future directions. I am confident that this publication will serve as an important resource for researchers, academic institutions, extension professionals, policymakers, development practitioners, and dairy entrepreneurs alike.

I extend my heartfelt congratulations to the editorial board, contributing authors for their valuable contribution. I sincerely hope that this publication receives wide readership, stimulates policy dialogue, and contributes meaningfully to building a sustainable and climate-resilient dairy sector in India and beyond.

Shahaji Phand

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Preface

Dairy farming has been the backbone of rural livelihoods and a vital source of nutrition for millions of people worldwide. However, in the 21st century, the sector is facing unprecedented challenges due to climate change, resource constraints, and evolving market demands. Rising temperatures, erratic rainfall, increased frequency of extreme weather events, and shifting disease patterns are affecting dairy productivity, animal health, and the socio-economic well-being of farming communities. These challenges demand a paradigm shift from conventional practices to climate-resilient, sustainable, and innovative dairy systems.

The book ***Sustainable Dairying in the Era of Climate Change*** is an earnest attempt to bring together contemporary knowledge, scientific research, and field-based best practices to address these pressing issues. Drawing from the expertise of researchers, practitioners, policymakers, and progressive farmers, this volume explores practical strategies for climate-smart nutrition, efficient resource management, renewable energy integration, animal welfare, and policy interventions. It also emphasizes the importance of technology adoption, community participation, and financial planning for building resilient dairy value chains.

We believe this book will serve as a valuable resource for students, academicians, extension professionals, and dairy entrepreneurs. It aims to foster informed decision-making, encourage innovation, and inspire a collective effort towards transforming the dairy sector into a model of sustainability.

We express our sincere gratitude to all contributors, reviewers, and institutions whose commitment and insights have enriched this work. We also acknowledge the dairy farming communities whose resilience and adaptability continue to inspire sustainable solutions.

It is our hope that this book will not only inform but also ignite action ensuring that dairying remains economically viable, environmentally responsible, and socially inclusive in the face of climate change.

Editors

Shahaji Phand
Sushrirekha Das

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Chapter-1

AN OVERVIEW OF MANAGEMENT OF DAIRY SUPPLY CHAIN IN INDIA

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Abstract

The dairy sector plays a vital role in India's agricultural economy, serving as a primary source of livelihood for millions of rural households and contributing significantly to nutritional security. Despite emerging as the world's largest milk producer, the Indian dairy industry continues to face systemic challenges related to quality assurance, cold chain infrastructure, transportation, price volatility, and supply chain visibility. This paper explores the evolution of dairy farming in India, from subsistence-based operations to an organized cooperative movement catalyzed by Operation Flood. It analyzes the structure and functioning of both organized and unorganized dairy supply chains, highlighting operational inefficiencies and sustainability concerns. The role of co-operatives, particularly Amul, in transforming rural livelihoods through integrated supply chain models is emphasized. Furthermore, the study addresses modern-day challenges including logistics coordination, environmental impact, and food safety, and evaluates how Artificial Intelligence (AI) can address inefficiencies through predictive analytics, quality control, inventory optimization, and real-time visibility. The findings underscore the need for robust infrastructure, technological adoption, and inclusive policies to ensure a resilient, competitive, and sustainable dairy supply chain in India.

Key Words: dairy, supply chain, cold chain, milk production, distribution

1. Introduction

The dairy sector is an integral part of India's agriculture and rural economy. Milk has been an important source of protein for Indians since the ancient period. However, India has not always been able to produce enough milk to satisfy consumer demand. In the 1950s and 1960s, India faced severe shortages and relied heavily on imports. Millions of Indian farmers, most with just a few cows, produced milk, but they could not deliver their highly perishable products to the fast-growing cities where milk demand was rising. Operation Flood (also known as the White Revolution), a national-scale, federally sponsored intervention that began in 1970 and lasted until 1996, has noticeably contributed to India's present status as the largest milk producer in the world. India has been ranked 1st in milk production since 1998, contributing 25 per cent of global milk output. Milk production has increased by 63.56% over the past 10 years from 146.3 million tonnes during 2014-15 to 239.2 million tonnes during 2023-24,(Figure 1) (National Dairy Development Board 2024, Food and Agriculture Organization 2025) with an annual growth rate of 5.7 % during the past 10 years and whereas, world milk

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production is growing at 2% per annum. The country's per capita availability of milk has increased by 48% in the last decade, with more than 471g/person/day during the year 2023-24, as against the per capita availability of 322 g/ person/ day worldwide. (Press Information Bureau 2025)

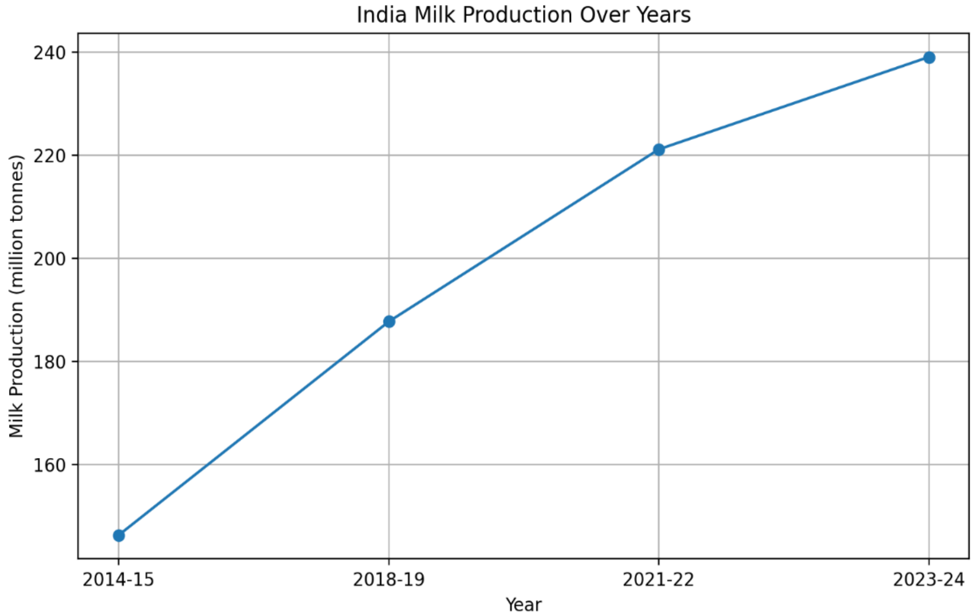

Fig. 1. India's Total Milk Production Trajectory (2014-15 to 2023-24)

The Indian dairy market size stood at Rs.18, 975 billion in 2024. The market is set to grow at a CAGR of 12.35% between 2025 and 2033. The Indian dairy market is likely to reach Rs.57, 001.8 billion in 2033. The dairy sector is crucial to India's economy, employing over 80 million rural households, predominantly small and marginal farmers. It has also empowered women significantly within rural communities. Indigenous buffaloes contribute approximately 31.94% of total milk production, followed by crossbred cattle at 29.81%, while goat milk accounts for 3.30%, and exotic cows contribute 1.86% (Department of Animal Husbandry and Dairying (DAHD) 2024). Despite being the largest producer of milk globally (accounting for 24% of world production), India's share in global dairy exports is only about 0.25%. This low percentage highlights a disparity between production capacity and export activity.

The first Co-operative Act was enforced in India in the year 1904. Since then, the co-operative movement has rapidly changed all socio-economic activity fields. The contribution of co-operatives to India's dairy industry is enormous. The co-operatives have ushered in a white revolution in the country, which has made India the leading producer of milk in the world. The milk revolution started in India in 1946 in Anand (Gujarat), and has contributed considerably to the socio-economic development of rural milk producers. It has also established an effective partnership between farmers and professionals in the dairy industry. Dairy development helps the rural poor have additional regular income. Today, in India, there are about 141221(rural-137507, urban-3714) primary dairy co-operatives (India stat). However, most state federation brands are regional, except for Amul. These include 'Verka' in Punjab,

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'Nandini' in Karnataka, 'Vijaya' in Andhra Pradesh, 'Saras' in Rajasthan, 'Anchal' in Uttarakhand, Sanchi in Madhya Pradesh, 'Mother Dairy' in Delhi and Kolkata. Dairy co-operatives account for a significant share of processed liquid milk marketed in the country.

2. Importance of Supply Chain in the Dairy Sector

Dairy serves multiple roles: a source of daily nutrition, an avenue for rural income, and a catalyst for women empowerment. Approximately 48% of milk produced in India is utilised by milk producers, while 52% is sold in urban areas (Nanda Kumar *et al., 2022*). Among the milk available for commercial sale, 38–40% is managed by dairy co-operatives and private dairies, whereas the remaining 60–62% is distributed through the unorganised dairy sector. Various programmes such as White Revolution 2.0, National Dairy Plan (NDP), and Animal Husbandry Infrastructure Development Fund (AHIDF) have been implemented to enhance the market supply chain of dairy products and distribution within the dairy industry.

The term' dairy supply chain' (DSC) encompasses the management of milk supply from farms, its subsequent processing, and transportation of the final product to end consumers. Milk is collected from rural production sites, transported to processing plants, including chilling centres, and finally to distribution points in various locations (Nanda Kumar *et al*., 2022). Procurement of raw milk and transportation of processed milk are the vital components of supply chain management (SCM). On this front, Indian co-operatives are less susceptible and lag behind the MNCs and other private firms. Non-observance of deadlines, inefficient distribution of milk, frequent breakdowns of milk vans, delays in loading and unloading at depots, lead to a disturbed supply of milk and its products. The fundamental difference between the food supply chain (FSC) and others is the continuous and significant variation in product quality over time. SCM activities like service, delivery, and information flow are still key challenges in the food sector. Strategically, rather than competing within the low-cost market segment, many food producers are working on different marketing strategies to target the rural market. This has led the industries to implement various sustainable practices like local sourcing, reuse, recycling, and green purchasing.

The highly perishable dairy products entail special treatment, a cooling mechanism, handling, and quick actions from milk procurement to distribution or retailing. The sector has seen growth in value-added products like cheese, yogurt, and butter due to rising demand driven by changing consumer preferences and increasing disposable incomes. DSC entails four main elements: the raw milk supplier/farmer, the milk processing plant, the retailer, and the end consumer. The dairy industry has observed vast changes in its business structure, such as globalisation, technological development, the enhanced shelf life of products, and seasonal demand fluctuation. India operates on an entirely different production, processing, and marketing model than the rest of the world. Since only a small fraction of milk reaches the processing plants, a significant proportion of the total production is sold raw to small-scale retailers or directly to customers. In 2018, the Food Safety Standards Authority of India (FSSAI) conducted a National Milk Safety and Quality Survey (FSSAI, 2018), in which 7% of the milk samples had contaminants or adulterants that rendered such milk unsafe. The agency's additional surveys on milk products also revealed specific quality issues and hygiene concerns. Thus, it launched an action plan to produce safer and higher-quality milk products (FSSAI, 2019a). According to the 2021-2022 report of India's National Dairy Development Board (NDDB), Amul, a co-operative society located in Anand, Gujarat, procured 27.1 million litres per day (LLPD), which is 46% of co-operative milk procurement in India. In addition, the following regions/states contribute with significant percentages to the total milk procurement in India: Dairy co-operatives of Karnataka at 8.2 LLPD (14%), Rajasthan at 4.0 LLPD (7%), Maharashtra co-operatives at 3.9 LLPD (7%), and Tamil Nadu at 3.6 LLPD (6%) (NDDB, 2022).

In the early stages, dairy farming in India was primarily a subsistence activity, where farmers maintained a small number of cows or buffaloes mainly to meet their household milk requirements. These operations were rooted in traditional practices, with minimal technological intervention and virtually no value addition or processing involved. However, this scenario began to evolve significantly with the rise of the co-operative movement, led by the National Dairy Development Board (NDDB). The introduction of co-operatives brought about far-reaching changes in the sector, providing farmers with an organized platform for collective bargaining, thereby enabling them to secure fair prices and gain access to essential services such as veterinary care, feed, and technical support.

One of the key advantages of the co-operative system was the elimination of middlemen, which fostered direct linkages between producers and consumers, resulting in higher returns for farmers and improved product quality for end-users. The creation of widespread co-operative networks further facilitated the establishment of streamlined milk procurement systems supported by robust refrigeration and cold chain infrastructure. A pivotal milestone in this transformation was the launch of Operation Flood in the 1970s, which aimed to unite small-scale dairy farmers under co-operative structures and strengthen the rural dairy supply chain. Through this initiative, farmers benefited from better procurement practices, organized marketing systems, and the establishment of thousands of village-level milk societies and modern processing units.

The co-operative model enabled farmers to pool milk resources, negotiate better terms, access modern technology, and receive veterinary and extension services, all of which contributed to increased production and income. By promoting collective marketing, training, and financial assistance, Operation Flood helped uplift the socio-economic status of millions of rural households. A standout example of success within this framework is the Gujarat Co-operative Milk Marketing Federation (GCMMF), popularly known as Amul, which became a symbol of the Indian dairy co-operative movement and set a precedent for similar initiatives nationwide.

The creation of milk collection centers at the village or district level was crucial for streamlining milk procurement. These centers served as middlemen, collecting milk from farmers and ensuring its prompt and effective delivery to processing facilities. They acted as centers for gathering milk from various sources, streamlining the collection procedure and easing logistical difficulties. By offering a centralized location for milk collection, quality assurance inspections, and storage prior to transportation to processing units, milk collection centers contribute to the overall efficiency and dependability of the dairy supply chain. Larger-scale milk collection was made much simpler due to this action, and as the industry expanded, it was essential to create a reliable cold chain infrastructure. Refrigerated storage and transportation facilities were set up to maintain the quality and freshness of milk throughout the supply chain.

These investments increased product safety standards, reduced spoilage, and extended shelf life. Cutting-edge processing facilities were needed to satisfy the rising demand for processed dairy products. Forward-thinking facilities have implemented the latest equipment and technology to heighten the efficiency and output of dairy processing operations. The efficient pasteurization, homogenization and packaging of milk made possible by these cutting-edge tools ensure the superior quality and safety of dairy products. Additionally, in order to meet the constantly shifting demands of the market, these facilities are able to produce a wide variety of high-value goods like butter, cheese, ghee, milk powder, yoghurt and ice cream. Modern processing facilities also enhanced product standardization and quality assurance procedures.These facilities adhere to strict quality standards and implement advanced testing procedures to ensure that dairy products meet regulatory requirements and consumer expectations. This fostered consumer trust and confidence in Indian dairy products, contributing to their domestic and international market competitiveness. Recognizing changing consumer preferences, processors and co-operatives shifted their focus to value addition and product diversification.

Through research and development initiatives, new dairy products were introduced to cater to evolving tastes and demands. This strategic shift allowed the industry to tap into new market segments and enhance revenue streams. The growth of organized retail chains, including supermarkets and hypermarkets, played a significant role in reshaping the distribution of dairy products. These modern retail formats established direct links between processors and consumers, offering increased product visibility, wider market reach, and more efficient supply. Mishra and Shukla (2022) discussed the innovative approach of a dairy retail firm that used an app-based application to enable self-orders and brought digital transformation to the dairy business. Kumar and Nambirajan(2014) observed that supply chain competency, like the ability to fill orders with accuracy, forecasting sales with accuracy *etc*., has positive impact on supply chain performances

However, the dairy industry in India has been grappled with many problems due to the dominance of unorganized players (individual milkmen) contributing approximately60% of the total milk procurement and the remaining 40% by the organized players such as dairy co-operatives and private companies (IBEF, 2021). It has traditionally been dominated by unorganized small-scale producers supplying milk directly to consumers or local aggregators . The supply chain of organized players in the dairy industry is highly structured whereas the supplychain of the unorganized players is unstructured.

With an increased demand for hygienic and quality products, India saw the emergence of organized supply chains offering cold chain infrastructure, traceability systems and efficient distribution networks. At present, producers are using both structured and unstructured supply chains for selling their products to consumers. The structured system refers to organized milk co-operative societies or private dairies that collect raw milk directly from registered members who have taken up the membership provided by them. These co-operatives operate mostly on village level collecting milk during the morning time each day which subsequently goes through stringent quality testing processes before being processed and sold throughout various parts of the country. This chain relies on intermediaries such as distributors or wholesalers to facilitate transactions between farmers/producers and retailers. Product quality control, timely delivery and other important aspects related to production consumption linkages also depend upon such intermediaries .The structured supply chain of the Indian dairy industry is managed by large, organized players and co-operatives like Amul, Mother Dairy and Nandini, which have a significant presence in the market. These players leverage a co-operative network, robust processes and strong distribution channels to ensure efficient and reliable delivery of dairy products.

3. Organized Supply Chain Steps

i. Milk Production at Farm Level:

- Smallholder-dominated, with 70%+ of production from farmers owning less than five animals.
- Focus on indigenous cow and buffalo breeds, with ongoing crossbreeding programs for higher yields.

ii. Collection and Chilling:

- Village Dairy Cooperative Societies (VDCS): Act as primary milk pooling points.
- Quality Testing: Fat and SNF (Solids Not Fat) testing using lactometers and digital analyzers.
- Rapid Chilling: Milk must be chilled to below 4°C within 2 hours to prevent bacterial growth, per NDDB protocols.

iii. Procurement Logistics:

- Chilled milk is transported via insulated tankers to processing plants—distance and time are managed carefully to maintain quality integrity.

iv. Processing & Packaging:

- Pasteurization: Mandatory for eliminating pathogens; value-added processing for products like ghee, curd, cheese, paneer, UHT milk, etc.
- Quality Assurance: Central laboratories ensure FSSAI standards. Batch sampling and traceability are increasingly digitized.

v. Cold Chain & Storage:

- Large dairies invest in cold rooms, automation, and tracking; cold chain coverage is a critical determinant of end-product quality.
- Data: Only 20–30% of all milk moves via refrigerated/insulated transport.

vi. Distribution & Retail:

- Use of both traditional distribution networks and modern retail (supermarkets, e-commerce, direct-to-home).
- Increasing focus on last-mile cold delivery in urban areas.

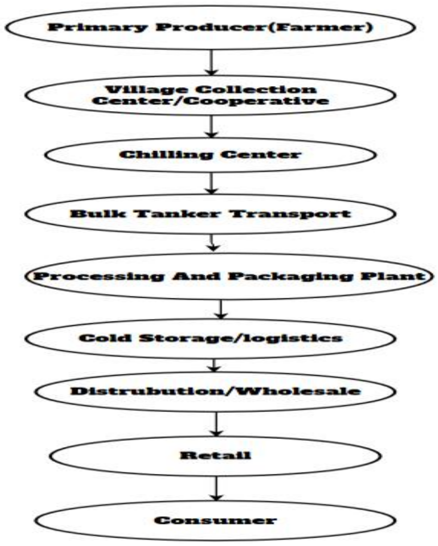

Fig. 2. Organised Supply Chain Model in India

Unlike its counterpart, the unstructured supply chain of the Indian dairy industry is characterized by a lack of organization and formalization. Itis dominated by small-scale dairy farmers, traders and local vendors who operate in a decentralized manner. This model has no formal organization associated with it; instead, independent agents (marginal milk vendors) establish individual links between buyers and sellers locally outlining informal systems operating mainly on a cash basis rather than enabled operations. Further, it lacks dependable storage facilities hampering proper warehouse management leads in keeping expiry dates intact eventually forcing them into adopting alternative distribution strategies including doorstep deliveres with high variable costs involved making difficult processes inaccessible sustainably .The unstructured supply chain followed by unorganized players, often relies on local networks and informal relationships but may face limitations in terms of scalability and consistency.

4. Supply chain management of Amul

The leading dairy co-operative in India is called "Amul," standing for Anand Milk Federation Union Limited. The structure is three-tiered, starting with a dairy co-operativesociety at the local or village level which will be federated within milk unions at various district level, It also falls under the State milk federation, which operates at the provincial level. Milk is collected at the village level by milk collection facilities; milk is procured and processed at the district level by milk unions; and milk and milk products are marketed bythe relevant state milk federation. Amul has a network of over 18,000 village-level milk collection centers, known as Village Dairy Co-operatives (VDCs). These VDCs collect milk from local farmers, who are also members of the co-operative.

- **Milk processing**
  The collected milk is transported to processing plants, where it is pasteurized, homogenized and packaged into various products such as milk, butter, cheese and ice cream.
- **Distribution.**
  The packaged products are then distributed to various retail outlets and distributors across India. Amul has a strong distribution network, with over 3,500 distributors and 1 million retail outlets.
- **Sale and marketing**
  All efforts are made towards promotions and market development including retail promotional schemes supported by continuous engagement among a wide spectrum of customers.

5. Challenges in the Indian Dairy Supply Chain

With rising consumer awareness and increasingly stringent government regulations, dairy corporations are under growing pressure to integrate sustainability into every aspect of their operations-ranging from technical systems to animal welfare and logistics (Fredriksson & Liljestrand, 2014). In an effort to minimize transportation costs and improve efficiency, dairy enterprises have increasingly started sourcing and processing milk closer to production zones (Douphrate et al., 2006). However, despite these shifts, sustainability in the Indian dairy sector remains under threat, primarily due to the continued use of non-eco-friendly refrigerants in cold chain infrastructure, including trucks and storage units (Khan et al., 2021). One of the most critical operational bottlenecks in the industry is the lack of integration and coordination between logistics, warehousing, and cold storage systems. This disconnect frequently leads to inefficient transportation routes and higher carbon emissions across the supply chain. To mitigate these impacts, experts recommend the use of multimodal transport systems—such as combining rail, road, and air routes—to improve logistical efficiency (Mangla et al., 2019). The environmental footprint of dairy waste is also significant. According to recent estimates, milk waste alone constitutes over 50% of dairy food loss across the value chain, followed by cheese (23%), yoghurt (20%), and cream (8%). Food waste accounts for the largest share of carbon emissions in the dairy sector—over 50%—while processing contributes 20%, consumption 10%, and retail 5% (Al-Obadi, 2021). These statistics underscore the challenges that stem from outdated and traditional supply chain management practices, which continue to be followed by several Indian dairy enterprises.

6. Key Operational Challenges

i. Quality Management

The Indian dairy industry is predominantly driven by small-scale farmers, many of whom lack access to adequate infrastructure and resources. As a result, ensuring consistent quality across supply sources becomes a major concern. It is the responsibility of dairy co-operatives and private processors to regularly test and monitor milk quality to meet established safety and hygiene standards. Failure to do so affects both product safety and brand credibility.

ii. Transport Constraints

Transportation remains a significant challenge due to the remote locations of milk producers. The lack of adequate processing and chilling infrastructure often results in milk spoilage before it reaches factories. Given that milk is highly perishable, the need for timely and temperature-controlled logistics is paramount to maintaining quality.

iii. Storage Limitations

Proper storage of milk requires consistent cooling to preserve freshness and safety. However, in many parts of India, access to refrigeration facilities remains limited or unreliable. The absence of appropriate storage solutions leads to quality degradation, waste, and ultimately, economic losses for both producers and processors.

iv. Supply Chain Visibility

The Indian dairy supply chain is highly fragmented, involving numerous stakeholders including small farmers, village-level aggregators, dairy processors, transporters, distributors, and retailers. This complexity makes it difficult to track the flow of milk through the system, especially when using traditional, manual methods. A lack of real-time visibility contributes to inefficiencies, delays, and quality lapses.

v. Price Volatility

Milk prices in India are largely dictated by market demand and supply fluctuations, exposing small farmers to considerable income instability. These farmers often have no choice but to sell their produce to intermediaries at low prices, resulting in poor profit margins and limited reinvestment capacity in production or infrastructure.

7. Role of Artificial Intelligence (AI) in Strengthening the Dairy Supply Chain

While Enterprise Resource Planning (ERP) systems have long been used for managing logistics, more than 75% of ERP implementations fail in post-deployment stages, often due to poor planning, unreliable demand forecasting, and logistical mismatches. Excess milk production by farmers, combined with weak market forecasting, leads to surplus and wastage, even as food shortages persist in some regions (Banaeian et al., 2018).

To address these structural inefficiencies, Artificial Intelligence (AI) offers a powerful solution for transforming supply chain operations in the dairy sector. AI can drive improvements in quality, efficiency, and competitiveness, especially when integrated with real-time data and smart analytics.

8. Key Benefits of AI Integration:

- Predictive Analytics: AI-driven models can forecast milk production volumes, consumer demand, and seasonal fluctuations, helping firms optimize production schedules, minimize wastage, and ensure product availability.
- Quality Monitoring: Advanced sensors and AI-enabled monitoring systems can detect quality issues early in the processing cycle. This allows for timely interventions, reducing losses and ensuring product consistency.
- Route Optimization: AI tools can analyze data on traffic, road conditions, and weather to plan cost-effective and faster delivery routes, preserving the freshness of milk and lowering emissions.
- Inventory Management: AI systems can determine optimal stock levels by analyzing demand trends, production capabilities, and storage constraints, thereby reducing holding costs and spoilage.
- Enhanced Supply Chain Visibility: With real-time tracking capabilities, AI can provide end-to-end visibility across the supply chain—from farm to retail shelf—helping companies identify bottlenecks and streamline operations

Conclusion

India's dairy sector has undergone a profound transformation, from fragmented, subsistence-level production to becoming the largest milk producer globally. This growth was driven largely by cooperative models, infrastructural development, and policy support through initiatives like Operation Flood. However, the current supply chain remains bifurcated between organized and unorganized sectors, with persistent challenges related to quality control, transport and storage, inefficient logistics, and price volatility. These issues are exacerbated by outdated practices, inadequate infrastructure, and environmental concerns. To bridge the gap between production capacity and global competitiveness, strategic investments in cold chain logistics, technological upgradation, and process automation are critical. Artificial Intelligence offers a forward-looking solution by enabling predictive analytics, real-time monitoring, and smarter resource management. Integrating AI with traditional systems, improving coordination among stakeholders, and promoting value addition will not only reduce waste but also enhance profitability and sustainability. A restructured, tech-driven, and farmer-centric supply chain can ensure equitable growth, food safety, and global positioning of India's dairy sector.

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Chapter-2

CLIMATE SMART DAIRY FARMING: CLIMATE CHANGE IMPACTS AND MITIGATION MEASURES

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Abstract

Climate-smart dairy farming seeks to sustain milk production and farmer livelihoods while reducing the sector's environmental footprint under increasing climate variability. Climate change impact such as heat stress, altered feed and water availability, heightened disease risks, and disrupted supply chains pose significant threats to dairy productivity and animal welfare. At the same time, the dairy sector contributes notably to greenhouse gas emissions, mainly methane from enteric fermentation and nitrous oxide from manure. Mitigation measures include improved nutritional strategies with methane-reducing feed additives, genetic selection for heat-tolerant and low-emission breeds, sustainable manure management with biogas recovery, and enhanced energy and water use efficiency through renewable technologies. Adaptation strategies focus on climate-resilient housing, efficient water management, disease monitoring, and use of climate advisory services for farm-level decision-making. Digital innovations, value-chain integration, and enabling policies are essential to scale these interventions. Adopting an integrated, systems-based approach will enable dairy farming to become more resilient, sustainable, and aligned with both climate and development goals.

Key Words: dairy, climate, mitigation and adaptation

1. Introduction

Climate change complicates global challenges including hunger, malnutrition, illness, and poverty. Due to its dependence on regional climatic elements like precipitation, temperature, and others, the agricultural industry is especially vulnerable to climate change. Agriculture must develop a "climate smart" strategy to handle climate change. This includes sustainable agriculture production and revenue growth and climate change adaptation and fortification. Greenhouse gas emissions should be reduced wherever possible. Climate-Smart Animal Agriculture (CSAA) is important, but adopting climate-smart technology, methods, and practices in dairy production is difficult. Adapting climate-related knowledge, technology, and behaviours to local circumstances is crucial. This method facilitates collaborative learning among farmers, academics, and extension workers and widely disseminates Climate Resilient Dairying practices. To select the right dairy technology and techniques for rural development, site-specific studies are needed. The extension service can help farmers cope with climate change's myriad impacts. Raising awareness and educating farmers about the many climate change adaptation and mitigation options for the dairy business may accomplish this.

Climate change impacts dairy farming too which include milk quantity and quality productivity. Changes in feed and fodder amount and quality may also impact dairy management. Changes in rainfall, temperature, crop variety, sickness, and mortality may also occur. As dairy farming system organisms grow more or less competitive, adaptive measures may be needed. Adaptations might include growing drought-tolerant fodder or tillering maize. Agriculture, including forests and fisheries, must adopt a "climate smart" strategy to manage climate change's complex challenges. This includes sustainable agriculture output and incomes, climate change adaptation and fortification, and greenhouse gas (GHG) emission reduction or removal wherever possible. Community-Driven Development (CRD) programs help achieve sustainable development objectives.

By addressing food security and climate change, sustainable development integrates economic, social, and environmental factors. The framework focusses on sustainable agricultural production and income growth, climate change adaptation and fortification, and greenhouse gas (GHG) emission reduction. Extension providers may help Community-Based Rural Development (CRD) in several ways. These include technology and information creation, farmer empowerment, and relationship brokering, advocacy, and policy assistance. Rural Advisory Services (RAS) help accomplish Climate Resilient Development (CRD) by conveying climate knowledge and technology relevant to climate-adaptive agricultural methods. Innovative solutions like paravets, clinics, and interactive video approaches (Digital Green's India case study) achieve this. RAS also promotes climate-smart towns, climate training, and workshops. The 2007 IPCC research found that 13.5% of global greenhouse gas (GHG) emissions come from agriculture. The agricultural animal business accounts for 18% of human-caused greenhouse gas emissions, according to a 2006 FAO assessment. Due to climate change, farming's sustainability is under question. Agriculture emits 5100-6100 megatonnes (Mt) of carbon dioxide equivalents annually, according to statistics. This emission level is comparable to worldwide transportation. Agriculture also produces a lot of N2O and CH4, two powerful greenhouse gases. Various "climate resilient dairy (CRD)" methods may improve milk production, strengthen the dairy industry's climate change resistance, and reduce greenhouse gas (GHG) emissions. Climate-smart dairy farming helps fulfil global milk demand without increasing emissions. In climate change, adaptability is key. This may require using dairy breeds that can endure high temperatures, drought, and other problems. Several efforts are needed to reduce the cattle industry's climate change effect. Improving production and feed systems, breeding ruminant breeds with lower methane output, managing manure emissions, and integrating livestock and crop systems to reduce waste and increase soil fertility are some ways to reduce greenhouse gas emissions in the livestock sector. Improved grazing management may boost animal nutrition and reduce greenhouse gas emissions. Also, feed regimes and pasture management must be changed. Adapting to short-term climatic unpredictability and long-term climate change requires insurance plans and better weather predictions for farmers. There are several ways to meet livelihood and agro-ecological system needs while improving the dairy sector's greenhouse gas balance. The biggest challenge to climate-friendly dairy production is implementation, especially among smallholders. Insufficient land management techniques, expertise and information, dairy farming training, and access to key inputs, tools, equipment, and financial facilities all plague the area. Due to several contextual constraints, climate-smart dairy farming techniques vary by area. However, climate-smart dairy farming practices must be carefully implemented to provide food security and sustainability in a changing environment.

2. Impact of climate change on livestock productivity

In developing countries, livestock contributes up to 40% to the agricultural GDP. The cattle business will need to expand as worldwide demand for animal-based commodities rises (FAO, 2009). Harsh weather harms cattle. Sejian (2013) noted that climate extremes and seasonal herbage quantity and quality affect cattle welfare, productivity, and reproduction. Climate change threatens global cattle systems. Thus, responding to and lowering the negative effects of hard climates has helped address the climatic impact on cattle (Sejian et al., 2015a). Climate change is expected to negatively affect cattle performance in several areas, according to prediction models. Climate change may occur abruptly over a few years or gradually over decades. Climate change usually causes a global temperature increase. Multiple climate model estimates suggest the average global temperature might rise by 1.1-6.4 °C by 2100 compared to 2010. Cattle face harsh weather including heat waves, floods, and droughts. Extreme events can reduce production and impact morbidity of animals (Gaughan and Cawsell-Smith, 2015). Animals can adapt to extreme temperatures, but their survival adaptations may impair their function. This article examines how climate change reduces cattle production.

Heat stress may appear in the high 20s Celsius (80s Fahrenheit). Lethargy, sweating, and decreased breathing depth and frequency are first seen in cattle. When ambient temperatures reach 30 degrees Celsius, cows may pant and produce less milk. Bovines may die from high temperatures without relief. Due to their higher feed intakes, greater body proportions, and faster growth rates, modern dairy cows produce more metabolic heat and are more susceptible to heat stress. Heat stress may weaken the immune system and spread mastitis. It was previously thought that only tropical cows were affected by hot heat. However, rising temperatures at higher latitudes, like the US, Canda and Europe have made cattle more vulnerable.

Numerous studies have shown that increased temperature negatively affects feed intake, reproductive processes, and performance in various cattle species. For example, cattle, sheep, goats, pigs, and poultry operate best around 10-30°C. When the temperature climbs 1°C above baseline, all species reduce their feed consumption by 3-5%. This will have a major influence on cattle quality and quantity. Temperature increases will degrade pasture quality, reducing cow output. Waterlogging may reduce pasture productivity and make it more susceptible to grazing. Farmers must hold their animals inside longer after heavy rains, increasing their demand on supplemental cow feed. Forage and feed availability and quality may be impacted by extreme precipitation, increasing costs and decreasing milk output. Due to climate change and a carbon dioxide-rich atmosphere, many places may see major forage quality losses.

3. Direct effects of climate change on cattle

The primary and noteworthy consequence of climate change on livestock output is the direct influence of heat stress. Heat stress imposes a substantial economic cost on milk producers due to its negative impact on milk component and milk production, reproductive efficiency, and animal health. Hence, the anticipated rise in atmospheric temperature, as projected by several climate change models, may have a direct impact on animal function.

4. Indirect effects of climate change on cattle

Climate change's indirect effects, namely feed and water shortages, cause most productivity losses. Climate change may affect forage production quantity and dependability. Climate change may also influence fodder quality, water needs, and plant patterns on broad rangelands. In the future decades, crops and forage plants will face greater temperatures, more carbon dioxide, and variable water supply due to precipitation patterns. Climate change may harm grassland production, species composition, and quality. These consequences alter grassland ecological services beyond fodder production (Giridhar & Samireddypalle, 2015). Variable rainfall distribution throughout the growing season will affect fodder output worldwide. Due to climate change, cattle production techniques are expected to suffer more than benefit.

Climate change affects water demand, availability, and quality. Temperature and weather patterns affect precipitation quality, amount, geographical distribution, snowmelt, river flow, and groundwater availability. High precipitation due to climate change may increase peak run-off and decrease groundwater replenishment. Low precipitation may reduce groundwater replenishment, river water flow, and water resources, agricultural operations, and drinking water supplies. Naqvi et al. (2015) found that water restriction reduces animal body weight, reproductive rates, and immune systems. Water resources' climate change sensitivity must be assessed to help agricultural adaptation strategies be developed and implemented. Climate change might also cause vector-borne illnesses, which would have serious economic consequences.

5. Impact of climate change on cattle production

Gaughan and Cawsell-Smith (2015) found that heat-stressed cows consume less grain and more water. Their endocrine state also increases maintenance needs, resulting in lower performance. Environmental stresses reduce cattle body weight, average daily increase, and condition. Significant milk production drops affect milk quality. These effects include reduced fat, lower-chain fatty acid, solid-non-fat, and lactose levels. Additionally, palmitic and stearic acid levels have risen. Animals with higher productivity are usually more affected. Extended stresses may reduce productivity.

6. Impact of climate change on cattle reproduction

Thermal stress influences reproductive systems. Research indicates that the conception rates of dairy cows decline by approximately 20-27% during the summer season. The reduction in fertility is linked to heat stress, which adversely impacts the expression of oestrus in cows. Heat-stressed cows demonstrate diminished oestrus behaviour, largely attributable to reduced oestradiol secretion from the dominant follicle. The reduction in oestradiol secretion results from the low luteinizing hormone levels observed in heat-stressed cows. Heat stress results in reduced reproductive efficiency, primarily due to changes in ovarian function and embryonic development. These changes result in a decreased capacity for oocytes to achieve successful fertilisation and develop into viable embryos (Naqvi et al., 2012). Heat stress adversely affects oocyte development in cows, resulting in changes to the secretion of progesterone, luteinizing hormone, follicle-stimulating hormone, and ovarian dynamics throughout the oestrous cycle. Heat stress correlates with impaired embryo development and increased embryonic mortality in cattle. Heat stress during pregnancy has been shown to hinder foetal growth and may increase the risk of foetal loss. Heat stress may induce alterations in the secretion of hormones and enzymes essential for the regulation of reproductive tract function. Heat stress adversely affects spermatogenesis in males, likely due to its inhibitory effects on spermatocyte proliferation.

7. Adaptation and mitigation strategies to climate change/variability

The above ideas aim to make dairy operations more climate-resilient and reduce greenhouse gas emissions. Dairy farming adaptation strategies include heat stress management, water management, selective breeding for climate resilience, feed diversification, pasture management, disease surveillance and control, weather forecasts, and risk assessment. Environmental mitigation solutions in dairy production include numerous approaches. Reduce methane emissions, manage manure, improve energy efficiency, reduce water and feed waste, use conservation tillage, use alternative feed sources, and implement afforestation and agro-forestry techniques. Dairy farms may reduce greenhouse gas emissions and improve climate resilience by using adaptation and mitigation measures. For the dairy industry to survive in a changing environment and to successfully mitigate climate change, these efforts must be implemented. Climate-smart dairy farming strategies including feeding and manure management may reduce methane emissions.

These techniques may help dairy producers adapt to climate change while maintaining a sustainable and efficient business. Climate-resilient dairy production may reduce greenhouse gas emissions and promote environmental sustainability. Overall, dairy cow welfare reduces greenhouse gas emissions. Given climate change's possible impacts, such as increased heat stress, it's important to study ways to help animals manage heat stress. These approaches may reduce climate change's effects on animal behaviour and performance. Thermal stress may be mitigated by management strategies.

8. Genetic Approach

Engaging in the selective breeding of cows mostly or exclusively from Holstein ancestry is a rational approach to augment milk output. A possible disadvantage is that augmented milk production may entail a compromise in other advantageous traits, such as enhanced fecundity. Holstein cows, distinguished by their large physique and high metabolic rate, has a natural inclination for elevated milk output. This physiological characteristic also makes individuals more prone to heat stress, increasing their risk of overheating. Many indigenous breeds exhibit valuable adaptive traits that have evolved significantly over time, including tolerance to extreme temperatures and humidity, resistance to diseases, and the ability to thrive and reproduce under suboptimal management and feeding conditions.

Therefore, a genetic strategy to address climate change should include actions such as

1. Identifying and enhancing robust local genetic populations.

2. Genetic selection for thermotolerance

3. Identification of genes associated with disease resistance, heat tolerance, and survival in low-input settings, using this information as a foundation for the selection of future breeding stock.

4. Strategies for Breeding Management: Local climate-resilient breeds of intermediate production should be favoured over vulnerable crossbreeds. The introduction of supplementary methods for the selection and integration of genetic traits, such heat tolerance, enhanced yields, or disease resistance, has the potential to provide climate-smart milk. The main challenge is determining the ideal mixture that best fits the specific geographical regions and distinctive characteristics of different dairy farms in a rapidly changing environment. In the realm of cattle husbandry in India, many variables diminish the precision of selection and therefore result in decreased rates of genetic advancement. Factors encompass limited flock sizes, considerable discrepancies in rearing conditions and management practices both inter- and intra-flock, lack of systematic livestock identification, inadequate documentation of livestock performance and pedigrees, and constraints related to the subsistence nature of livestock rearing, where financial gain is not the primary aim. It is essential to recognize that locally suited breeds have great variety, with the most outstanding individuals exhibiting substantial productive potential. Consequently, analyzing livestock populations that have not undergone systematic selection is anticipated to provide rapid results for establishing a foundation stock with significant genetic merit for nucleus flocks. Successful genetic improvement often necessitates simultaneous advancements in nutrition, health, and management approaches. Nonetheless, while improvements in these alternative facets of livestock production provide immediate benefits and incur ongoing expenses, genetic enhancement is permanent and is transmitted from one generation to the next automatically, provided that the enhanced animals are used for breeding and their progeny are retained for future breeding.

9. Nutritional Adjustments

The desired outcome can be attained by implementing the following measures:

- Incorporation of dietary fat at level of 2 to 6% will increase dietary energy density in summer to compensate for lower feed intake.
- High-fiber diets generate more heat during digestion than lower fiber diets.
- Using more synthetic amino acids to reduce dietary crude protein levels.
- Feeding of antioxidant (Vitamin A, C & E, selenium, Zinc)
- Addition of feed additives/vitamins and mineral supplementations
- Allow for grazing early in the morning or later in the evening to minimize stress.
- Concentrate mixture (18% DCP and 70% TDN) prepared with locally available feed ingredients should be supplemented to all categories of animals. When no green fodder is available, addition of vitamin supplement in concentrate mixture helps in mitigating heat stress.

Further, in extreme conditions, energy intake becomes less compared to expenditure as the animal has to walk more distance in search of grazing resources which are poor in available nutrients. Hence, all the animals should be maintained under intensive system with cut and carry of available fodder. The concept of complete feed using crop residues (60%) and concentrate ingredients should be promoted for efficient utilization of crop residues like red gram stalk, etc. Further, productivity and profitability from ruminants can be increased by strengthening feed and fodder base both at village and household level with the following possible fodder production options.

10. Managemental interventions:

- **Water supply**: Animals must have access to large quantities of water during periods of high environmental temperatures. Much of the water is needed for evaporative heat loss via respiration to help them cool off. Hence, provision has to be made for supply of continuous clean, fresh and cool water to the animals. Cleaning the feeding trough frequently and providing fresh feed will encourage the animals to take more feed. Splashing the cool water over the animals at regular intervals during the hot period will reduce the heat stress.
- **Feeding time**: Providing feed to the animals during cool period i.e. evening or night will improve the feed intake by the animals. Likewise, providing additional drinking water supplies and shifting feeding times, so that cows are not all feeding during the hottest parts of the day, will cut heat stress risks.
- **Stocking density**: Reducing the stocking density during hot weather will help the animals in dissipating the body heat more efficiently through manifestation of behavioural adaptation.
- **Shade**: The use of shades is an effective method in helping to cool animals.
- **Provision of vegetative cover** over the surrounding area will reduce the radiative heat from the ground.
- **Provision of elongated eaves** or overhang will provide shade as well as prevent rain water from entering the sheds during rainy season.

- **Ventilation**: increasing the ventilation or air circulation in the animal sheds will aid the animals in effective dissipation the heat.

Many introduced shading in feeding, drinking and corral areas to give cows plenty of opportunities to seek respite from the sun when they need it.

11. Manure management

Cow dung is a major worldwide methane source, and cow urine and manure have high nitrogen levels, which generate nitrous oxide, a greenhouse gas. Dairy producers may benefit from animal waste by improving manure and urine management. Faeces may be collected in livestock barns and outside milking parlours. This reduces the risk of runoff during strong rains or ammonia release during hot temperatures. Anaerobic digestion, which produces and captures methane for energy, uses waste as an input. Many agricultural facilities use biogas for heating, producing electricity, or injecting it into the gas distribution network. In agricultural settings, anaerobic digester residuals may replace synthetic fertilisers as soil amendments. Segregating manure and urine into enclosed storage facilities reduces air and water pollution when anaerobic digestion is not possible. Despite climate mitigation measures, methane generation is predicted. Aerating manure, reducing storage duration, and flaring methane are among solutions. These strategies limit methane emissions' environmental impact. The diets of cows may also affect waste emissions. Nitrate supplements that inhibit gut methanogens in cows may increase nitrous oxide in their dung and urine. This might change milk production's environmental effect from methane to nitrous oxide emissions. Manures, fertilisers, and cow grazing patterns are the best opportunities for climate-smart milk production on farms. The timing and amount of manure and fertiliser applied must be optimised to maximise grass or crop nitrogen utilisation while minimising atmospheric and aquatic losses. Implementing some actions may reduce cow behavior's environmental effect. Avoiding waterlogged regions and streams, moving feeders and drinkers periodically, and strategically placing field gates at hill summits, where it's drier, are examples. These methods reduce soil compaction and disturbance, lowering pollutants and greenhouse gas emissions.

12. Other interventions

A. Revival of common property resources (CPRs): CPRs need to be reseeded with high producing legume and non-legume fodder varieties at every 2-3 years intervals as a community activity. Further, grazing restriction till the fodder grows to a proper stage and rotational grazing as community decision would improve the carrying capacity of CPRs.

B. Intensive fodder production systems: Growing of two or more annual fodder crops as sole crops in mixed strands of legume (Stylo or cowpea or hedge Lucerne, etc) and cereal fodder crops like sorghum, ragi in rainy season followed by berseem or Lucerne etc., in rabi season in order to increase nutritious forage production round the year.

C. Short duration fodder production from tank beds: Due to silt deposition, tank beds are highly fertile and retain adequate moisture in the soil profile for cultivation of short season fodder crops like sorghum and maize during winter and or summer.

D. Year-round forage production systems: Cultivation of a combination of suitable perennial and annual forages for year round nutritious fodder supply using limited water resources. It consists of growing annual leguminous fodders like cowpea or horse gram, etc. inter-planted with perennial fodders like Co-3, CO-4, APBN-1 varieties of Hybrid Napier in monsoon and inter-cropping of the grasses with berseem, lucerne, etc. during post-monsoon season.

E. Use of unconventional resources as feed: The available waste products form food industries like palm press fibre, fruit pulp waste, vegetable waste, brewers' grain waste and all the cakes after expelling oil etc., and thorn-less cactus should be used as feed to meet the nutritional requirements of animals.

F. **Agro-forestry**: Out in the fields there is often an opportunity to use the natural shading and shelter provided by trees to increase hot weather resilience dairy cows given such shaded areas have shown reduced panting and heat stress symptoms. Tree shelterbelts around fields can reduce the impacts of extreme weather events, including storms, intense rainfall, and extremes of heat and cold. Some farmers have extended the benefits of livestock agroforestry to include extra forage for the animals, a source of biofuel for energy generation, and even as a natural filter for pollutants - the trees can help reduce nitrate leaching to drainage streams and capture ammonia emissions to the atmosphere.

13. Specific mitigation measures

Methane overproduction in dairy cows' rumens harms the environment, especially climate change, and the dairy farming sector. Methanogens use carbon dioxide and hydrogen from feed fermentation and digestion to create methane. The breakdown of resistant dietary items like straw increases hydrogen generation and methane emissions. Superior feeds and forages may reduce methane generation and boost milk output in dairy cows. Many feed and forage kinds have been assessed for methane emissions. Improving feed quality is a key technique for increasing livestock productivity and reducing carbon emissions. However, many farmers cannot afford better feed alternatives, and others struggle to manage their cattle's diets owing to excessive grazing, making feeding patterns difficult to regulate. Dairy producers with strict food management and modern feed blends have more methane reduction options. Higher-quality meals reduce methanogens' hydrogen generation, changing digestion. Various feed additives may divert hydrogen or target methane-producing microbes. Tea, garlic, seaweed extracts, cinnamon, curry spice, and oregano directly block methanogens. Nitrate and sulphate compete with methanogens for hydrogen in cows' rumens. These chemicals may reduce methane emissions by almost 75%. These entities may also be short-lived. However, methane-producing microbes often acquire resistance to the additives after prolonged exposure. Nitrate overuse may affect cattle. Methane emissions and digestion thermal output may be reduced by lipids, especially sunflower oil. Dietary fats come from algae and other sources. They also avoid several synthetic methanogen inhibitor health risks, such as antibiotics. Monensin, an antibiotic used in cattle feed to boost growth and minimise methane emissions, is banned in Europe owing to antibiotic resistance concerns. The use of antibiotics to fight illnesses is less controversial in climate-smart milk production. Livestock medications, together with improved veterinary care and animal health extension services, may help cattle resist diseases and parasites. Healthy, happy cows are more resilient to climate change and release less greenhouse emissions.

Published by National Institute of Agricultural Extension Management (MANAGE), Hyderabad

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DAIRY ANIMAL MANURE, WASTE, AND EMISSION MANAGEMENT

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Abstract
India's vast livestock population generates approximately 3 million tonnes of waste annually. Comprising dung, urine, feed residues, and bedding, livestock waste is often underutilized and improperly managed, leading to environmental degradation and health hazards. Despite these challenges, livestock waste is rich in beneficial constituents that, if effectively recycled, can serve as valuable fertilizers for crops and even as fodder for animals. Efficient waste management yields considerable economic savings through improved human health and environmental quality, leading to higher productivity, reduced medical costs, and ultimately, increased farmer income. Livestock dung plays a pivotal role in the rural economy. Beyond its direct economic contribution through milk production, the efficient utilization of livestock resources in biogas systems can provide localized, clean cooking energy for rural communities. This article reviews the environmental implications of livestock waste, evaluates traditional and innovative management strategies, and explores the transformative potential of converting livestock waste into valuable resources.

Key Words: livestock waste, biogas, bio slurry, emission reduction, organic fertilizer, circular bio-economy, one health

1. Introduction

The 'Livestock Revolution', driven by rising global demand for milk, meat, and eggs, has intensified waste generation, especially in high-density systems. In India alone, over 3 million tonnes of animal waste are produced annually, presenting both environmental threats and resource opportunities. Traditional disposal methods such as open dumping and burning pose risks, including greenhouse gas (GHG) emissions, groundwater contamination, and disease spread. Modern science and technology offer sustainable solutions by integrating livestock waste into renewable energy systems and organic farming models.

2. Livestock Waste Generation: Global & Indian Context

Globally, animal product consumption has doubled in developing nations since the 1980s. This growth, particularly in confined systems near urban markets, escalates waste concentration. India's livestock sector, a pillar of rural livelihoods, faces challenges in waste management, with only 60% of dung utilized for biogas. Given the average dung output of 15 kg/animal/day the potential for bioslurry production and nutrient recycling is significant, warranting structured waste handling systems.

3. Characteristics of Livestock Waste

Livestock waste varies by species, age, diet, and management. Up to 90% of dietary nitrogen and phosphorus is excreted. Biogas slurry (bioslurry) contains 20–30% organic matter and macro- (NPK) and micronutrients (Zn, Fe, Mn, and Cu). (Gagandeep 2017)

4. Types of Livestock Waste

Solid Waste: Includes:

Dung: Specifically referring to bovine waste (cow pats or cow manure). It's the undigested plant matter that passes through the animal's gut and is rich in minerals.

5. Cow dung composition:

Moisture:

77%; Organic matter: 20%; Nitrogen: 0.32%; Phosphorus: 0.14%; Potassium: 0.30%; Calcium: 0.40% Wasted feeding material: Food that is discarded, lost, or uneaten. Soiled bedding material: Materials like straw, sawdust, wood shavings, and paper-based bedding that have been contaminated. Liquid Waste: Includes: Urine andWashed water

Table 1: Dung and Urine production by different species

Animals	Quantity of dung (kg/day/animal)	Urine² (ml/kg bwt/day)
	Range	Average
Horse	9-18	13.5
Cattle	18-30	24
Buffalo	25-40	32.5
Sheep and goat	1-2.5	1.25
Pigs	03-May	4
Poultry (100 birds)	2.5-3.5	3

Table 2: Water requirement for washing

Species	Water requirement for washing (liters)/Animal/Day
Cattle and Buffalo	45-70
Horse	36
Pigs	25-28

Collection of Livestock Waste:

The method of collection often depends on the management system. For animals grazing during the day and kraaling at night, a significant portion of feces is deposited directly on crop fields and grazing land, which is not usually collected but fertilizes the soil. Waste deposited within enclosed structures (animal houses, poultry buildings) must be removed to prevent health hazards.

6. Waste collection methods:

Separate Collection:

Solid and liquid manure are separated. A special pit should be constructed for solid waste decomposition, located away from water sources, and human/animal habitations to prevent flies and disease spread. Planning for the pit should consider labor and transport modes.

Collection of solid waste:

Typically done using a wheelbarrow and shovel, then disposed into a pit for decomposition. This method can return 75% of the fertilizing value to the soil. Manure pits should be about 200 meters away from buildings to avoid odors. A dairy cow produces about 24 kg of manure per day, with a fresh manure volumetric capacity of 700 to 900 kg/cubic meter. Collection frequency should be twice daily.

Collection of liquid waste:

Can be flushed through a drain channel to a storage tank or directly into the main drain channel of the area. Flushing of both waste: Manure and other waste are flushed together. This method is suitable where plenty of water is available or in buffalo farms where dung is watery. A U-shaped gutter or drain should be located longitudinally along the shed's long axis. Outside the shed, liquid manure from each shed can connect to a main, preferably closed, drain.The main drain leads the liquid waste to a storage tank, from which it can be pumped for agricultural use.

7. Environmental & Health Implications

a. Water Pollution

Excess manure application leads to nitrate leaching and eutrophication. Nitrates above 50 mg/L in drinking water cause infant methemoglobinemia and other illnesses.

b. Soil Degradation

Repeated manure use can lead to heavy metal accumulation (Cu, Zn, Pb, Cd), altering soil health. Ammonia volatilization and phosphorus accumulation affect soil pH and runoff quality.

c. Air Pollution

Manure decomposition emits NH_3, CH_4, H_2S, and N_2O. Ammonia causes odor and acidification; methane and nitrous oxide are potent GHGs, contributing to global warming and ozone formation.

d. Climate Change

Livestock contributes 9–12% of global GHGs. CH_4 from enteric fermentation and manure handling is dominant. A study on Indian dairy farms highlighted that total GHG emissions in baseline production were 735,379 kg CO_2-eq/year (Vijayakumar et al., 2022). Methane from enteric fermentation was the main source of GHG emission (60.64%), followed by CO_2 emissions from feed production (14.37%) and N_2O from fertilizer and crop residues (8.82%) (Vijayakumar et al., 2022). Specifically, methane from manure management in a liquid/slurry system was a major contributor, releasing 6,471.53 kg CH_4/year (Vijayakumar et al., 2022).

e. Health Hazards

Pathogens in manure (E. coli, Salmonella, and Listeria) contaminate water and food. Zoonotic disease outbreaks (e.g., Avian Influenza, Nipah virus) have been linked to poor waste management in high-density animal systems.

8. Sustainable Management and Mitigation Strategies

Effective mitigation of nutrient losses and emissions from livestock farms requires clear public objectives for environmental quality. Balancing the urgent need to increase livestock production and farmer income with the imperative to protect natural resources and biodiversity presents a complex political challenge (Ogbuewu et al., 2012). Protecting soils is vital for future food security, and reducing atmospheric pollution is crucial for human and animal health and mitigating climate change. Biodiversity holds both economic value (genes for the future) and ecological function (healthy ecosystems). Therefore, sustainable environmental management must be integrated early into the intensification of crop and livestock production and should be a core consideration in environmental policy development. Various livestock waste handling techniques are employed to ensure timely application of manure, improve its nutritive value, and reduce pathogen viability. These methods also aim to minimize environmental pollution and health risks associated with improper disposal.

9. Traditional Animal Waste Handling Methods

- Pit Disposal: This has been a low-cost and convenient method for animal waste, particularly for deceased animals, involving burial in deep, covered pits or trenches. It requires at least two feet of earth cover to control odors, flies, and scavengers. Traditional methods of livestock waste management, widely practiced, include the creation of dung cakes where cow manure is hand-collected, sun-dried on racks, and subsequently used as fuel for cooking and heating, particularly prevalent in North Indian states.

- **Composting:** An aerobic decomposition process for solid manure that generates heat (typically 60-70°C), effectively killing pathogens and weed seeds, and producing a hygienic solid manure for land application. It involves layering straw, carcasses, and manure with specific ratios and maintaining 50-60% moisture.
- **Rendering:** This option allows for the removal of carcasses from the farm, eliminating environmental pollution potential while recycling waste material into valuable by- product meals. It involves heating, hydrolyzing, and pressing processing plant wastes
- **Lactic Acid Fermentation:** A preservation method for carcasses, allowing them to be held for up to three months before rendering. It involves grinding carcasses, mixing them with a fermentable carbohydrate, and adjusting moisture content to 60-70%. Lactic acid bacteria then anaerobically convert the energy source to lactic acid, lowering the pH to 3.0-4.5, which prevents spoilage (Ogbuewu et al., 2012).

10. Modern and Innovative Approaches: "Waste to Wealth"

The concept of a waste to wealth focuses on producing animal-based commodities with minimal external inputs, closing nutrient loops, and reducing negative environmental impacts in the form of wastes and emissions. This approach is gaining significant traction globally as a solution to current challenges, especially given projections of global population growth to 10.4 billion by 2100 (UN, 2022). India's Bio-Economy registered 14.1% growth in 2021, with the livestock sector poised to contribute to India's "Energy Independent" vision by 2047. The following innovative approaches exemplify the 'waste to wealth' paradigm:

11. Biogas Production (Anaerobic Digestion):

This is a cornerstone of sustainable manure management. Anaerobic digestion of animal waste produces biogas (methane-rich gas) and a nutrient-rich digestate (bioslurry). Biogas serves as an alternative fuel source, reducing reliance on fossil fuels and mitigating methane emissions. In India, the efficient use of livestock resources in biogas systems can generate localized clean cooking energy for rural masses.

12. Organic Fertilizer from Bioslurry:

The biogas spent slurry (BSS) is a potent source of macro (N, P, K) and micronutrients (Zn, Fe, Mn, Cu, B, etc.) besides organic matter. Its proper utilization after processing has vast potential in meeting the nutrient requirement of crops, thereby reducing the use of chemical fertilizers and providing sustenance to soil health.

13. Bio-oil Production:

Thermal processes can convert manure into liquid bio-oil fuels, including biodiesel, and useful by products like biochar. These bio-oils can be used for heating or generating electricity, with biodiesel directly replacing petroleum diesel. Special Fiber Products: Manure fiber can be processed to produce specialty consumer products such as plant growth media (e.g., as a peat moss substitute), seed starter pots, fertilizer garden sculptures, paper, and building materials, effectively turning an environmental liability into a commodity.

14. Animal House Bedding

A practical and cost-saving method where separated manure solids are reused as bedding in animal houses.

Organic fertilizers: include *Jeevamritha and pancha gaavya.* This traditional mixture, prepared by fermenting cow dung, urine, milk, curd, and ghee, has demonstrated beneficial uses in soil physical chemical properties and soil microbial count.

Algal Cultivation: The carbon dioxide (CO_2) produced from anaerobic digestion and thermochemical conversion processes of livestock waste can be utilized for cultivating algal biomass, which can then be used for various valuable products.

Livestock-Fish Integration: This integrated farming system effectively recycles organic wastes. Cattle manure, for instance, has been extensively used in India as a source of manure in carp polyculture.

Biodegradable Plastic: Poultry feathers, rich in keratin protein, can be pulverized into fine dust and converted into biodegradable plastic through polymerization.

Electricity Generation: Poultry litter has high energetic potential. Technologies like anaerobic digestion and biomethanation can produce methane (biogas) from litter, which is then used to run turbines for power generation.

Technical Textiles: Low-cost chicken feathers can be used to prepare versatile nonwoven textile materials for various technical textile applications.

Alternative Animal Feed: When properly handled and dried, animal wastes can contribute to reducing feed costs, especially in areas where conventional feedstuffs are scarce and expensive. This practice can increase profit margins and reduce competition between humans and livestock for food (Parihar 2019). Poultry and swine manure have been recovered for re-feeding to beef cattle, dairy cattle, and sheep, proving to be effective sources of energy, protein, and mineral nutrients.

15. Vermicompost Production:

Vermiculture, the non-thermophilic biodegradation and stabilization of organic materials by earthworms and microorganisms, converts animal droppings into vermicast and vermi-meal. Vermicast is a high-quality organic fertilizer with a fine texture, pleasant odor, and superior plant growth benefits compared to conventional inorganic fertilizers. Liquid livestock waste management, specifically for ammonia recycling, involves using gas-permeable membranes. These membranes are waterproof but allow only gases, such as ammonia, to pass through. Gaseous ammonia then travels through a microporous hydrophobic membrane, where it is captured and concentrated in a stripping solution, typically an organic or mineral acid of 1 normality. Common membrane materials include polypropylene and polyurethane. This process can achieve an average ammonia removal rate of 45-153 mg per liter per day (Vanotti, 2012). Ammonia recovery is significantly influenced by the manure's pH, increasing by 1.2% per hour at pH 8.3 and accelerating to 13% per hour when the pH reaches 10.

16. Improved Animal Husbandry Practices

Optimizing animal health and productivity can significantly reduce overall emissions per unit of product.

Enhanced Reproductive Performance and Animal Health: Interventions that improve animal reproductive performance (e.g., reducing age at first parturition, increasing fertility rate) and animal health (e.g., reducing mortality rates) can substantially reduce GHG emissions by increasing herd productivity and enhancing animal longevity (Vijayakumar et al., 2022). Healthier and more productive animals lead to more efficient resource utilization and lower emissions per unit of milk or meat produced. Poor fertility, for example, increases GHG emissions by requiring more animals per unit of production (Crosson et al., 2011; Vijayakumar et al., 2022).

Nutrient Management in Feed: Adjusting animal diets to precisely match nutrient requirements can reduce the excretion of excess nitrogen and phosphorus, thereby minimizing nutrient losses and related emissions from manure.

17. Specific Emission Mitigation in Dairy Farms

A study on Indian dairy farms demonstrated the effectiveness of a package of interventions in reducing GHG emissions. By improving animal reproductive performance, animal health, and manure management, a 28.58% reduction in total GHG emissions annually was observed (Vijayakumar et al., 2022). Manure Storage Modification: A significant finding was the impact of shifting manure storage methods. Transitioning from a liquid/slurry system (which contributed 6,471.53 kg CH4/year) to a solid storage system resulted in an 87.42% reduction in CH4 emissions and a 16.97% reduction in N2O emissions from manure management (Vijayakumar et al., 2022). Solid storage, commonly practiced in Indian dairy farming, involves collecting fresh manure in unconfined piles, where aeration can potentially reduce methane production compared to anaerobic conditions in liquid systems (Vijayakumar et al., 2022).

18. Benefits of Integrated Manure Management

Effective livestock waste management yields several crucial benefits: Utilization of dung in biogas digesters provides affordable, clean energy for cooking and simultaneously produces bioslurry, a high-quality organic fertilizer for crops. This generates economic savings on fuel costs and offers additional income from selling bioslurry. The use of bioslurry-based bio-fertilizers can reduce farmers' expenditure on chemical fertilizers and boost their income through improved yields. Organic fertilizers derived from manure enhance crop growth, quality, and yields, while also improving soil health and the overall ecosystem. Effective manure management is environmentally friendly, improving sanitation and decreasing environmental pollution by controlling the emission of greenhouse gases (GHGs), thereby preventing hazardous impacts on air, water, soil, wildlife, and marine environments. This approach provides a sustainable solution for manure management, contributing to increased farmer income and aligning with broader sustainable development goals. It also creates new business and employment opportunities across various skill levels, leading to more attractive and pleasant human settlements and better social amenity, and encouraging positive shifts in community attitudes and behaviors towards waste, fostering a culture of resourcefulness and sustainability (Ghatoura 2015).

Conclusion

The synthesis of traditional and modern waste management strategies, particularly within a 'circular bio-economy' framework, offers promising pathways. Innovations such as anaerobic digestion for biogas and nutrient-rich bioslurry, alongside the development of specialized products like bio-oils, manure fibers, and vermicast, demonstrate the immense potential of converting "waste to wealth." Furthermore, integrating improved animal husbandry practices that enhance productivity and health directly contributes to reducing overall emissions per unit of product. The tangible economic and environmental benefits of such integrated approaches include reduced reliance on chemical fertilizers, increased crop yields, clean energy generation, and significant mitigation of greenhouse gas emissions.

Achieving sustainable development goals necessitates a holistic approach to waste management, recognizing its direct and indirect links to every objective. The 'circular bio-economy' provides a robust framework for producing animal-based commodities with minimal external inputs, closing nutrient loops, and minimizing negative environmental impacts. Moving forward, a "One Health Initiative" that integrates science-based information across human, animal, and environmental health domains is essential. By embracing smart livestock farming practices, digital monitoring, efficient waste-to-wealth techniques, and fostering increased awareness among all stakeholders, the livestock sector can significantly reduce its environmental footprint, contribute to a low-carbon economy, and play a vital role in ensuring global food and nutrition security for future generations.

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Published by National Institute of Agricultural Extension Management (MANAGE), Hyderabad

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Chapter-4

STRENGTHENING CLIMATE-RESILIENT AGRICULTURE THROUGH LIVESTOCK INTEGRATION

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Abstract

As climate change continues to impact agriculture worldwide, farmers face growing challenges such as unpredictable weather, declining soil health, and reduced crop yields. These impacts are especially severe for smallholder farmers who depend on agriculture for their livelihoods. Integrating livestock into crop-based farming systems offers a practical pathway to strengthen resilience against climate shocks. Livestock not only provides food and income but also plays a crucial role in nutrient recycling, soil improvement, and risk buffering. Integrated Crop-Livestock Systems (ICLS) promote sustainable use of land, reduce input costs, and increase overall farm productivity. This chapter explores how livestock integration supports climate adaptation and mitigation goals. It also highlights innovations, policy frameworks, and grassroots models that make climate-smart livestock systems more adaptable. By combining traditional knowledge with modern science and ensuring inclusive participation, livestock integration emerges as a key strategy in building a more resilient and sustainable future for agriculture.

Keywords: Climate resilience, livestock integration, sustainable agriculture, Integrated Crop-Livestock Systems, smallholder farming, soil health, climate-smart farming, adaptation strategies

1. Introduction:

Climate change is no longer a distant threat it is already changing agriculture around the world. From unpredictable rainfall patterns and recurring droughts to rising temperatures and declining soil fertility, farmers are increasingly struggling with challenges that affect both crop productivity and livelihood security. Smallholder farmers in vulnerable regions, where farming is not just a profession but a way of life, are most affected. As traditional farming practices struggle to keep pace with these changes, there is an increasing need to rethink agriculture — an agriculture that has resilience, diversity, and sustainability at its core.

2. The role of livestock farming in building climate resilience

In the search for climate-resilient farming systems, integrating livestock into crop-based agriculture is a practical and proven solution. In many parts of India and the world, mixed farming, where crops and livestock are farmed together, has been practised for generations.

This model is not just about maximising yield, but also about creating a balanced system where each component supports the other. Livestock, for example, is more than just a source of milk, meat, or income - it fulfils multiple functions, such as providing organic manure, converting crop residues into valuable protein, and acting as a financial cushion in difficult times.

By recycling nutrients through manure, improving soil fertility, and efficiently utilising available resources such as forage crops and agricultural by-products, integrated systems reduce input costs and increase farm stability. If the harvest fails due to adverse weather conditions, the animal products can secure the household income. This kind of in-built buffer is essential in today's climate of unpredictability.

3. Why is integration more important than ever?

In the face of increasing climate pressures, the case for integrating arable and livestock farming is stronger than ever. Livestock farming can restore degraded soils, improve soil structure, and increase water retention — key elements for maintaining productivity in arid or marginal areas. Well-managed pasture and forage systems also contribute to carbon sequestration and biodiversity conservation. This approach not only supports farmers but also contributes positively to wider environmental objectives.

However, in order to effectively integrate livestock farming, certain issues need to be addressed, such as limited access to quality veterinary services, insufficient availability of feed, poor animal breeds, and the risk of overgrazing. In addition, livestock farming itself is affected by climate change and is exposed to stress from heat, water scarcity, and disease outbreaks.

Despite these challenges, the integration of livestock farming is a promising way forward. It strengthens the resilience of farming households, reduces dependence on chemical inputs, and leads to a regenerative agricultural model. As the world strives for sustainable food systems, the combination of arable and livestock farming is not just a return to traditional wisdom, but a smart, future-proof strategy for climate-resilient agriculture.

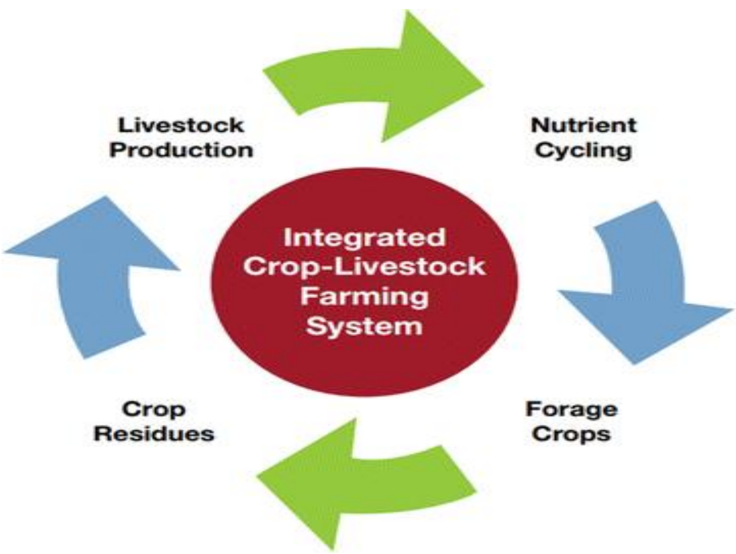

Fig. 1. Conceptual diagram of Integrated Crop-Livestock Farming System (FAO, 2018)

4. Integrated Crop-Livestock Systems (ICLS)

What is ICLS?

Integrated crop-livestock systems involve the strategic combination of crop and livestock production within the same agricultural system. These models include mixed farming, agro-pastoral systems, and silvo-pastoral systems that are customised to local agro-climatic conditions.

Main advantages:

Nutrient recycling: Fertiliser enriches soil fertility and reduces dependence on chemical fertilisers.

Lower input costs: On-farm resources such as feed reduce expenditure on external inputs.

Efficient land utilisation: The same area is used for two purposes - crops and livestock, improving productivity per unit area.

Traditional wisdom:

Many indigenous communities in India and other parts of the world have been practising ICLS for a long time. Their proven knowledge ensures sustainability, resilience, and adaptability to local climatic challenges.

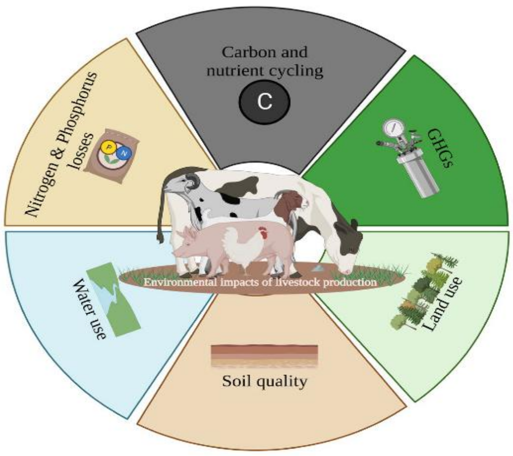

Fig.2 Adapted from environmental impact models of livestock production (ILRI, 2020)

5. Livestock's Role in Soil Health and Carbon Sequestration

Enhancing Soil Organic Matter:
Livestock manure is a valuable source of organic matter and nutrients. When used correctly, it improves soil structure, promotes microbial activity, and increases water holding capacity.

Reducing dependence on chemicals:

By using manure as a natural fertiliser, farmers can reduce the need for synthetic substances. This not only lowers production costs but also supports more sustainable nutrient management.

Cowdung and cow urine based concoctions such as Jeevamruth and Ganajeevamruth are used by farmers in India under National Mission on Natural Farming for nutrient supplement and to become self-reliant.

Carbon Sequestration through Grazing:

Managed grazing systems promote healthy root growth and continuous ground cover. These practices help to store more carbon in the soil while preventing erosion and degradation.

6. Climate Mitigation Potential of Livestock Management

Tackling Methane Emissions:

Livestock, especially ruminants, are major methane emitters. Strategies such as improving feed quality, the use of feed additives / probiotics in the feed (e.g. fats, tannins) and the promotion of biogas plants can significantly reduce methane release from enteric fermentation and manure. Promotion of succulent fodder like legumes, Azolla in the cropping system and concentrated feed considerably reduce the emission.

Adopting Low-Emission Breeds & Practices:

Switching to genetically efficient, low-emission breeds and promoting better husbandry, health and waste management practises can increase productivity while minimising the environmental footprint.

Leveraging Carbon Credits & Finance:

Sustainable livestock systems can gain access to carbon markets by adopting climate-friendly practices. This can incentivise farmers while contributing to national and global climate goals.

7. Climate Adaptation Strategies for Livestock Systems

Climate-resistant breeds:

Promoting breeds that are naturally tolerant to heat, drought, and disease helps to maintain livestock productivity under changing climatic conditions. Native breeds often have better adaptability.

Efficient water management:

Water conservation techniques such as watering systems, water catchment systems and efficient scheduling are critical to maintaining livestock during dry spells and erratic rainfall.

Heat stress and shelter solutions:

Providing shaded areas, improved ventilation, and cooling mechanisms in shelters reduces heat stress and improves animal welfare, reproduction, and milk yield.

Feed security measures:

Feed banks, silage making, and the cultivation of drought-resistant forage crops (such as sorghum, bajra, and cowpea) ensure the availability of forage in lean and dry seasons.

8. Challenges in Livestock-Based Resilience Building

Overgrazing and land degradation:

In many regions, increasing livestock pressure is leading to overgrazing, resulting in soil erosion, reduced productivity, and rangeland degradation, undermining long-term resilience.

Livestock diseases exacerbated by climate:

Higher temperatures and humidity have increased the range and intensity of livestock diseases, impacting animal health, productivity, and farmers' incomes.

9. Barriers to access:

Many smallholder farmers have limited access to veterinary care, credit, and insurance. This weakens their ability to avoid losses and recover from climate shocks. The village level young men or women or Community Resource persons may be trained on basic basic animal health and extension services in rural areas. They will act as a bridge between farmers and veterinary services. Ex; Pashu Sakhis model in India.

10. Gender and equity gaps:

While women are heavily involved in livestock production, they often lack ownership rights, decision-making power, and access to services, making resilience efforts less comprehensive and effective. One promising solution is the Pashu Sakhi model implemented under the Mahila Kisan Sashaktikaran Pariyojana (MKSP), where trained rural women act as community-based livestock service providers. These women provide doorstep veterinary services, first aid, awareness on improved animal management, and also promote best practices like clean milk production, deworming, mineral mixture use, and fodder management. This model not only bridges the last-mile service delivery gap but also economically empowers women by integrating them into the livestock value chain.

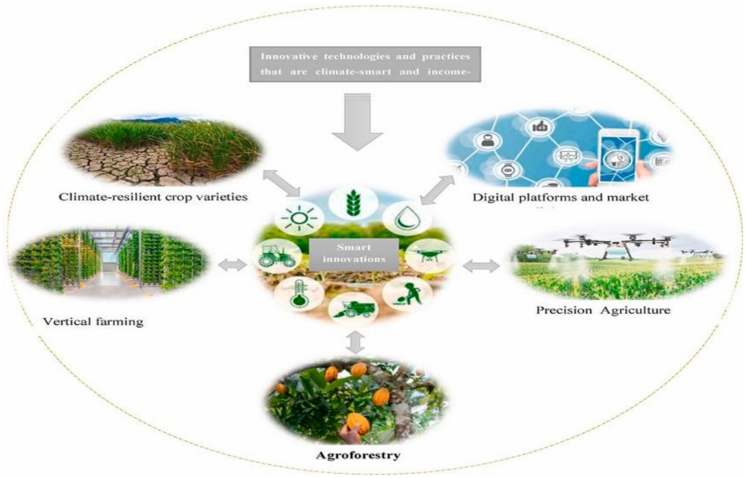

Fig. 3 Adapted from climate-smart agriculture and innovation frameworks (CGIAR, 2021)

11. Technologies and Innovations for Climate-Smart Livestock

Biogas, improved housing, and low-carbon production:

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Utilising livestock waste to produce biogas not only reduces methane emissions but also provides clean energy for rural households. Improved animal housing reduces heat stress, increases productivity, and supports low-emission agriculture.

Mobile veterinary units & e-extension services:

Mobile veterinary clinics and digital platforms are transforming access to animal health, especially in remote and pastoral regions. Real-time support improves disease control, breeding, and animal welfare.

Weather-based advisory services for animal husbandry:

Customised advice based on local climate forecasts helps farmer's plan feeding, housing, and health measures. These services reduce the risks of heatwaves, floods, and droughts and improve preparedness and productivity.

Under the Technology Demonstration Component (TDC) of NICRA, ICAR-NDRI implemented a range of on-farm climate-resilient dairy interventions across selected villages in Haryana. These included:

- Use of area-specific mineral mixtures, vitamin E, and mustard oil to mitigate heat stress and improve milk productivity.
- Promotion of silage making, improved fodder varieties, and safe dung disposal for enhanced fodder and waste management.
- Seasonal dairy product preparation to support women farmers.
  This field-level evidence shows that strategic nutritional and management interventions can significantly boost resilience of dairy systems during climatic stress

Restoring Degraded Lands through Fodder-Based Livestock Systems

Degraded lands—especially in dry and semi-arid zones—pose a major challenge to livestock-dependent communities. However, recent experiences across India suggest that restoring such lands for fodder production can offer tangible ecological and livelihood benefits. In Barwani district of Madhya Pradesh, tribal communities took the lead in reclaiming degraded patches through grassroots restoration, which enabled fodder collection and revived livestock-based income. Similarly, in Andhra Pradesh, fodder grasses were successfully introduced on common lands and wastelands under semi-arid conditions, as part of integrated silvo-pastoral systems supported by ICRISAT and partners. In Gujarat's Bhal region, the Vankar community transformed saline lands through Prosopis juliflora plantations and bunding practices, improving survival rates and fodder availability. These field-level efforts underline the potential of fodder-based land restoration as a pathway to strengthen climate resilience, support livestock, and improve soil and water health in degraded landscapes.

12. Policy Support and Institutional Framework

National missions and climate plans:

India's flagship programmes, such as the National Livestock Mission (NLM), Rashtriya Gokul Mission (RGM), and climate initiatives such as the National Action Plan on Climate Change (NAPCC) also emphasise sustainable livestock development as part of broader climate resilience.

Integration into national and state climate action plans (NAPAs/SAPs):

Livestock are increasingly recognised in policy planning frameworks that guide adaptation strategies and climate investments, and ensure that livestock keepers are part of long-term resilience goals.

Institutional support through FPOs, SHGs and cooperatives:

Producer organisations, self-help groups and dairy cooperatives play an important role in bringing together livestock farmers, improving market access, knowledge dissemination and strengthening resilience at the grassroots level.

The success of models like Pashu Sakhi in Rajasthan-where over 150 trained women served 13,000+ livestock-owning households—demonstrates the value of integrating gender-responsive, community-led livestock extension into formal policy and program frameworks. These models promote sustainability through social capital, improve adoption of climate-resilient livestock practices, and foster entrepreneurship among rural women. They should be considered for scaling under the National Livestock Mission and State Livestock Development Policies.

Livestock insurance and risk financing:

Climate-resilient livestock systems are supported by insurance schemes that compensate for losses during droughts, disease outbreaks, and extreme weather events. These financial instruments help to secure livelihoods.

13. Case Studies / Best Practices in Climate-Smart Livestock Systems

India – Pashu Sakhi Model under MKSP

Implemented in Rajasthan under the MKSP initiative, the **Pashu Sakhi model** is a decentralized livestock extension system where selected rural women (Pashu Sakhis) are trained in animal health care, feed management, and best dairy practices. Each Pashu Sakhi supports 25–30 households with advisory and first aid services, often supported by livestock assistants and coordinators. This model has resulted in:

- Increased adoption of improved animal management practices
- Higher milk yield and reduced calving intervals
- Income generation for women (₹800–₹2,000/month)
- Improved social recognition for women in rural communities

The model bridges critical extension gaps and offers a scalable pathway for climate-resilient and inclusive livestock development.

Kenya – Climate-Smart Dairy Hubs

In Kenya, the establishment of climate-smart dairy hubs has proven effective in enhancing resilience among smallholder dairy farmers. These centralized hubs offer integrated services such as milk refrigeration, balanced feed, veterinary care, and assured market linkages. By reducing post-harvest losses, increasing milk productivity, and improving access to inputs and services, these hubs not only enhance farmer income but also reduce greenhouse gas emissions per litre of milk produced, making dairy farming more sustainable.

Ethiopia – Integrated Livestock Resilience Programmes

Ethiopia's livestock sector has adopted multi-pronged climate adaptation strategies, focusing on the promotion of drought-tolerant indigenous breeds, improved early warning systems, and better veterinary service delivery. These interventions have led to a measurable reduction in livestock mortality during droughts and enhanced food security in vulnerable regions. By combining technology, local knowledge, and institutional support, Ethiopia has strengthened the adaptive capacity of its livestock-dependent communities against climate shocks.

14. Key lessons learnt:

- Successful programmes rely on local knowledge, institutional support, gender inclusiveness, and a systemic approach that combines adaptation, mitigation, and livelihoods in one framework. Livestock, Digital Innovation & Community-Led Climate Action
- Livestock plays a key role in achieving several Sustainable Development Goals - in particular SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 15 (Life on Land). It supports food security, helps reduce climate risks, and promotes sustainable land use when managed wisely.
- New digital technologies such as AI, remote sensing, and IoT are changing the way we manage our livestock in the face of climate change. These tools are helping to predict disease outbreaks, monitor grazing patterns, and track weather risks, making livestock management more responsive and efficient.
- Equally important is the role of local communities. Community-led adaptation models— such as pastoral co-operatives, women-led producer groups, and knowledge-sharing networks are proving effective in building resilience. When local experience is combined with modern tools, livestock becomes a powerful ally in responding to climate change.

Conclusion

To build climate-resilient and sustainable livestock systems, a holistic approach is essential. Scaling up integrated livestock-crop systems with strong policy backing and region-specific research will ensure ecological and economic sustainability. Strengthening extension services and grassroots capacity especially among smallholders can improve adoption of climate-smart practices. Women and youth must be actively included in livestock value chains through targeted training, credit access, and leadership roles. Community-led extension models such as Pashu Sakhi must be mainstreamed into national programs to ensure last-mile delivery of climate-smart livestock services, especially in resource-poor and women-centric farming systems. Models like NICRA's TDC demonstrate that integrated livestock adaptation packages, when delivered through community-based systems, can ensure both productivity and resilience in climate-vulnerable regions. Finally, meaningful collaboration among farmers, government bodies, the private sector, civil society, and research institutions is key to designing responsive solutions and unlocking climate finance for long-term resilience.

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CLIMATE CHANGE ADAPTATION MEASURES FOR SUSTAINABLE DAIRY FARMING

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Abstract

Livestock sector plays a pivotal role in the upliftment of poorer sections of society. Climate change poses a substantial threat to sustainable dairy farming systems globally, particularly in regions where dairy production is a critical component of rural livelihoods and food security. Rising temperatures, increasingly frequent heat waves, altered precipitation patterns, and extreme weather events exert direct and indirect impacts on dairy cattle, leading to physiological stress, diminished productivity, reduced reproductive efficiency, and heightened vulnerability to diseases. These environmental stressors are especially detrimental to resource-constrained farmers, who face greater challenges in adapting to rapidly changing conditions. Addressing these challenges requires an integrated approach, combining scientific innovation with traditional management practices to enhance animal resilience, optimize productivity, and ensure the continued sustainability of dairy farming in the face of climate uncertainty.

Key Words: Climate change, dairy farming, heat stress, milk yield, integrated approach

1. Introduction

Livestock sector plays a key role in global food security. According to Food and Agricultural Organization more than 12 % of people, approximately 1.3 billion people, depend on livestock for their livelihoods. This sector is crucial for food security, income generation, and overall economic well-being, particularly in developing countries. This dependency is particularly high in developing countries, where livestock contributes an average of 40% of the total agricultural GDP, varying from 15 to 80 % in case of individual countries. Demand for animal source foods is growing rapidly, fueled by population growth, urbanization and rising incomes. However, this sector is not without its challenges and climate change is the first challenge.

Climate change is defined by changes in long-term temperature and precipitation patterns as well as an increase in seasonal variation (Chakraborty et al. 2018)., has been happening worldwide and is becoming a major concern among various production systems. Temperature, rainfall, and sunlight are fundamental to plant growth and yield. Changes in these factors, due to climate change, can lead to reduced harvests, crop failures, and disruptions to food supply, and negatively impact livestock production systems. The fluctuations in temperature and weather events are predicted to be more frequent in the future due to the natural and ever continuing human activities. The Intergovernmental Panel on Climate Change (IPCC)

Fifth Assessment Report projected a "likely range" for the increase in global average surface temperature of 0.3 °C to 4.8 °C by the year 2100 (IPCC, 2014). Studies show that most global warming over the past 50 years is caused largely by human activity, resulting in a clear rise in global temperatures. Since pre-industrial times, the atmospheric concentration of CO_2 has increased by over 40%, methane has increased by more than 150%, and nitrous oxide has increased by 20%. More than half of the increase in CO_2 has occurred since 1970 (The RoyalSociety, 2020). Extensive scientific research has made it clear that climate change poses a serious risk to the world's food security. The interaction between ongoing climate change and demands for more nutritious food products makes it challenging to increase production while lowering climate impacts. With the ongoing shifts in climate patterns and the rising frequency of extreme weather events, livestock production systems—particularly those centred on dairy animals—are facing heightened vulnerability to diverse environmental stresses. Climate change, through droughts, higher temperatures, and erratic rainfall, reduces dairy livestock productivity, limits feed and water availability, and increases disease risk. These challenges threaten the livelihoods of farmers and the sustainability of the dairy industry as a whole. Tackling these issues needs a combined approach, blending new adaptation methods with traditional knowledge to keep dairy farming viable and sustainable amid climate uncertainty.

Implementing effective climate change adaptation strategies are essential to maintain a balance between global food demand and impacts of climate change. The nutritional value of milk and dairy products is well recognized, providing essential protein and micronutrients to a large portion of the world's population. However, in recent years, livestock farming has been associated with a series of negative environmental impacts, such as deforestation (Austin, 2010), soil degradation, water pollution and the reduction of biodiversity (Pezo, 2017). Those effects are due to poor management efficiency of livestock farms, which makes them less resilient to climate change and more prone to produce higher greenhouse gas emissions. This necessitates a concerted effort to develop and adopt sustainable dairy farming practices that not only build resilience to climate change impacts but also minimize the sector's environmental footprint. There is a correlation between greenhouse gas emission intensities and animal efficiency. Animals with lower production efficiency tend to emit higher amounts of greenhouse gases. A single cow is capable of emitting between 220 and 500 liters of methane per day. Although methane has a shorter atmospheric lifetime than carbon dioxide, it possesses a substantially higher global warming potential. Keeping quality animals with proper management will lower the environmental impact (Ames, 1980)). Improving management and realizing genetic potential are both essential for boosting production efficiency and mitigating livestock's impact on climate change.

2. Impact of climate change on livestock production

Animals exposed to impacts of climate change and consequent heat stress show reduced feed intake and increased water intake, with changes in the endocrine status which in turn increase the maintenance requirements leading to reduced performance (Sejian et al, 2012). Environmental stressors reduce body weight, average daily gain and body condition of livestock. Declines in the milk yield are pronounced and milk quality is affected: reduced fat content, lower-chain fatty acids, solid-non-fat, and lactose contents; and increased palmitic and stearic acid contents are observed. Generally, the higher production animals are the most affected (Das et al., 2016). Adaptation to prolonged stressors may be accompanied by production losses. It is better to keep locally adapted animals rather maintain high producers (Gaughan, 2015).

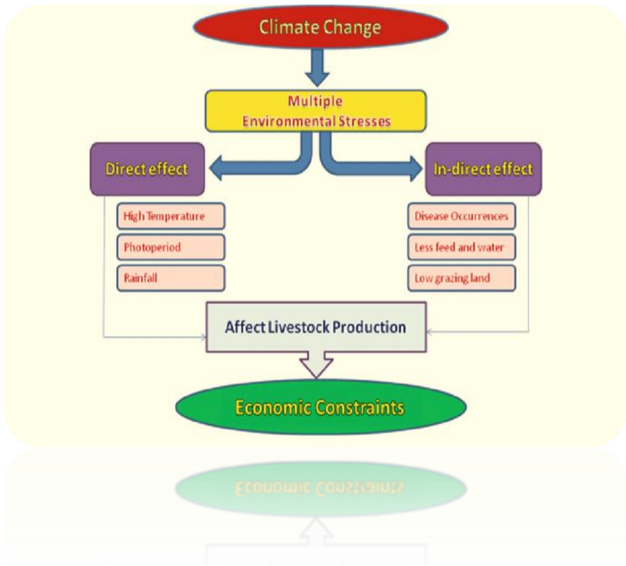

Fig. 1 Impact of climate change on livestock production, Sejian et al 2012

Thermal stress also affects the reproductive potential of animals. Fertility rates also are dropped in summer, and heat stressed cows often have poor expression of estrus due to reduced estradiol secretion. Reproductive efficiency is also affected due to altered progesterone secretion, poor embryonic development and increased embryonic mortality in cattle. In males, heat stress adversely affects spermatogenesis. Changes in the production and reproduction capabilities of dairy animals may result in reduced productivity and present challenges to global food security.

The world faces the challenge of sustaining economic growth while tackling climate change, largely caused by excessive GHG emissions from long-term industrial, agricultural, and other systems (Polymeni et al. 2024)

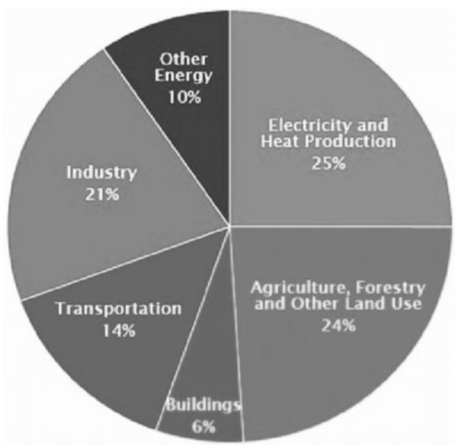

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Fig.2 Sector wise percentage of global CO 2 emissions. Source: IPCC, 2014

This write-up explores the critical climate change adaptation measures for sustainable dairy farming, focusing on key areas such as improved animal management, feed and fodder resource enhancement, water conservation, and manure management. It aims to highlight the diverse strategies that can enable dairy farmers to tide over the challenges posed by a changing climate and contribute to a more sustainable and resilient dairy industry.

3. **Adaptation measures for sustainable dairy farming**:

Adaptation strategies can enhance the resilience of livestock productivity to climate change (Collier et al 2019). Implementing adaptation strategies aims to maintain development despite the unavoidable effects of climate change by gradually reversing its negative effects.

4. **Different mitigation measures:**

Heat stress mitigation:

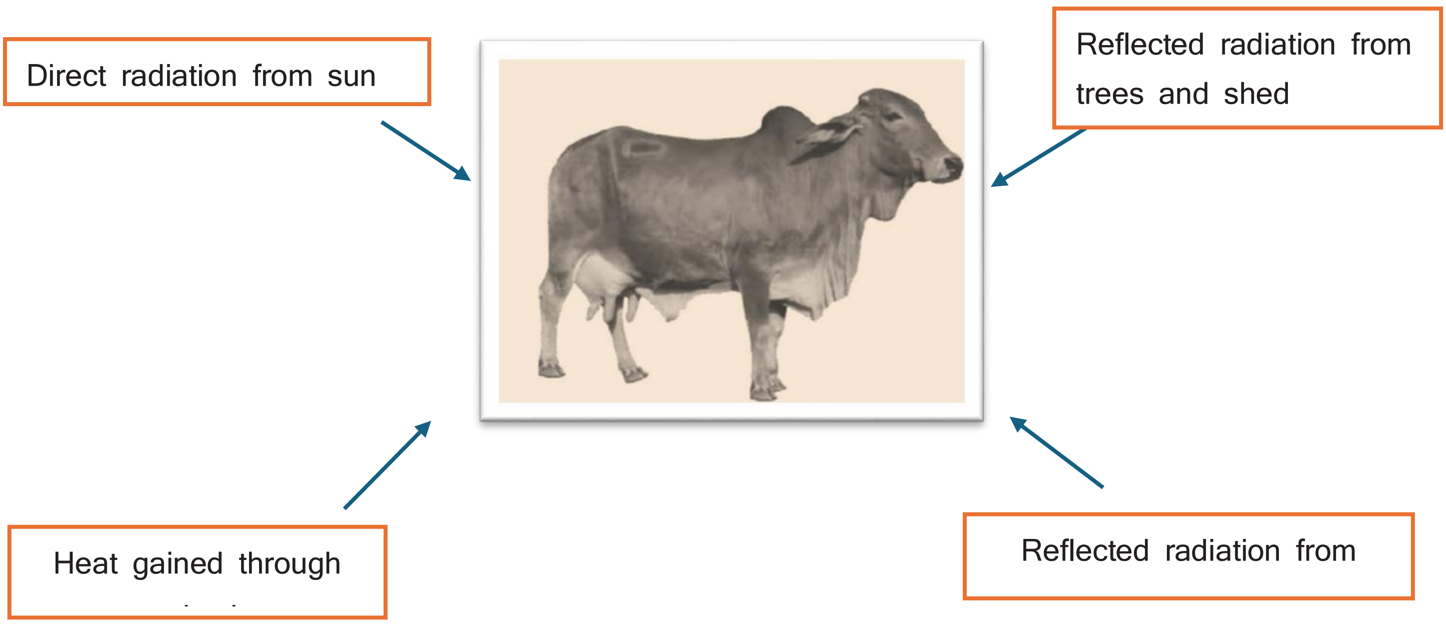
Rising temperatures are a major concern for livestock, significantly impacting performance and survival. Prolonged thermal stress from climate change leads to substantial economic losses in the dairy industry. Assessing heat stress and applying mitigation strategies are important for maintaining dairy cattle welfare, productivity, and the long-term viability of dairy farming. The thermal environment is a primary climatic factor affecting animal production. Animals adjust by activating mechanisms to decrease heat production and enhance heat dissipation, such as increased respiration rate, sweating, elevated core body and skin temperatures, reduced dry matter intake and metabolism, vasodilation leading to increased blood flow to the skin surface, and changes in feed utilization and water metabolism efficiency. These adjustments alter physiological and biochemical processes, including immunity and microbiota composition, which can influence overall productivity.

Heat stress mitigation measures involve a combination of controlling air temperature, humidity, and air movement. A warmer atmosphere contains more water vapor. Water vapor is a strong greenhouse gas, and its short atmospheric lifetime means it rises mainly with warming. Thus, water vapor is treated as an amplifier, and not a driver, of climate change. The ideal conditions are commonly known as the thermal comfort zone or thermo neutral zone. In this zone, animal's exhibit optimum performance and minimal energy expenditure (Nardone et al 2006) as are not forced to alter the metabolic activities to counter the impacts.

Multiple factors, in addition to increased temperatures will influence the degree of heat stress and its impact on animals, such as the duration of high temperatures, the rate of temperature change, and the relative humidity of the air. Many methods and models have been constructed to assess the heat stress impact on animals. Among the methods to measure livestock heat stress levels, bioclimatic thermal indices appeared to be least intrusive (Gaughan et al., 2008) and helps to take corrective steps. Temperature humidity index (THI) is the simplest, effective, and most commonly used technique, which can be utilized as a means of measuring the combined impact of both temperature and humidity to estimate the level of heat stress cows will experience based on environmental conditions (Dixit et al 2025). When determining the intensity of the thermal environment on livestock, the THI has historically been regarded as the gold standard (Hahn et al., 2009).In addition to these indices, the following expressions also will give a clue about heat stress:

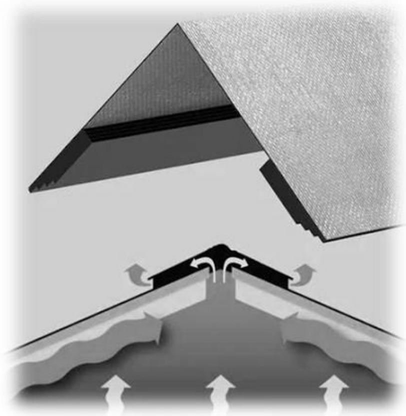
1. Increased respiration rate
2. Anorexia
3. Increased water consumption and increased visits to water troughs
4. Lethargic movements
5. Spending more time standing
6. Reduced milk yield etc.,

Providing adequate shade through strategically planted trees or constructing shelters is crucial for reducing direct exposure to sunlight and consequent rise in animal's body temperature, especially during the day. The shade and shelter provided by trees in paddocks and surrounding areas can reduce the radiant heat load by 50% or more. Ensuring a constant supply of clean and cool drinking water is also essential. Implementing cooling systems, such as fans, sprinklers, misters, and foggers, within animal housing can further enhance heat dissipation in addition to proper ventilation. Air quality inside the sheds can be improved through efficient ventilation systems. Ridge vents and sidewall openings promote cross-ventilation in the dairy sheds which is absolutely essential for keeping the air quality at its optimum levels. This setup also ensures the removal of excess heat and moisture, maintaining a comfortable environment for the cattle.



Ridge ventilation

Exhaust fans and tube cooling systems will help reduce the heat generated inside the cattle sheds and also play a role in removal of humidity which acts like an amplifier of heat stress (Ali Pakari &Saud Ghani, 2021).



Genetic improvement:

Breeding animals for natural heat tolerance and disease resistance is a key long-term adaptation strategy. This process entails identifying and promoting locally adapted breeds or developing new breeds with greater resilience, as indigenous breeds frequently exhibit inherent adaptations to local climates. These traits make them an important foundation for breeding programs. Adjustments in breeding strategies can affect animal reproduction and growth by influencing their tolerance to climate change and diseases. The primary focus of breeding programs needs to shift from simply increasing yield to developing crops and livestock with greater climate resilience,

Adopting strategies such as using locally adapted breeds suited to the climate and improving them through crossbreeding with climate- and disease-tolerant breeds will help in reducing the impact of climate change. Maintaining genetic diversity within and across livestock species is crucial for long-term adaptation to climate change. Use of molecular genetic markers for heat tolerance in selection programs may also be an option in identifying resilient breeds. Methane produced in the rumen can be effectively reduced by adopting Genomic selection, which targets the methane heritability traits such as changing the microbiome profile, which play a role in the synthesis of VFAs and also methane in the rumen (Bilton et al, 2025), which in turn helps to target methane production in tropical countries, where low quality feeds are usually fed to the animals.

5. **Disease prevention and control**:

Climate change directly and indirectly impacts animal health, leading to reduced immunity and higher disease risk. Rising temperatures increase illness and death rates in livestock, causing metabolic issues, oxidative stress, immune suppression, and lower reproductive performance. Strengthening herd health management, including vaccination programs, parasite control, and timely treatment of illnesses, is crucial, especially as warmer temperatures can increase the prevalence of diseases and parasites.

Night grazing:

Altering grazing times to allow cooler hour grazing can offer relief from heat stress, particularly in hot and humid environments and reduce the impact of heat related issues.

Nutritional interventions:

Adjusting feeding practices can contribute to climate resilience. This involves offering high-quality feed, supplementing minerals and vitamins, and using feed additives that support animal health and productivity during periods of stress. Incorporating drought-tolerant fodder crops and tree fodders (like *Moringa olifera*) can enhance feed availability during dry seasons and reduce reliance on traditional rain-fed pastures. Silage and hay production can also ensure year-round feed reserves.

Optimizing feeding strategies:

Adjusting feed composition and timing to account for seasonal variations and heat stress can improve nutrient utilization and minimize negative impacts on milk production. Supplementation with concentrate feed, fats, and minerals can ensure a balanced diet and enhance feed efficiency.

6. **Integrated crop-livestock systems**:

Combining crop and livestock farming can increase farm resilience by providing diverse income streams, utilizing agricultural byproducts as feed, and improving soil fertility through manure management.

7. **Feed quality and conservation**:

Maintaining the quality of fodder and feed through proper harvesting, storage, and processing is crucial, particularly during periods of heat stress when nutrient degradation can occur.

Water resource management:

1. Use water-saving irrigation like drip systems for fodder and practice water harvesting to secure water for livestock.
2. Prevent runoff and contamination to maintain clean, available water sources.
3. Build storage infrastructure to collect rainwater as a reserve during dry spells.

8. **Manure management and emission reduction**:

Methane in dairy barns mainly comes from rumen fermentation (enteric methane), with cows producing 100–700 g (150–1,050 L) per day. A secondary source is anaerobic breakdown of organic material during manure storage (Kuipers et al, 2025). Implementing low-emission manure management techniques, such as using compost-bedded pack barns, and advanced indoor treatment systems, can reduce greenhouse gas (GHG) and ammonia emissions from dairy farms. Air treatment technologies such as using air scrubbers and methane oxidation systems within barns can improve air quality and further reduce GHG emissions from enteric fermentation. To create a quality environment in the dairy sheds removal of contaminants and gases from inside air is an essential aspect and it also helps to maintain the health and reduce the stress on animals.

Conclusion

The dairy industry encounters considerable challenges as a result of climate change, affecting animal productivity, health, and the economic viability of farms. Nevertheless, several adaptation strategies can be adopted to bolster the resilience and sustainability of dairy production systems. These approaches include optimizing animal management practices, enhancing the efficiency of feed and water resource use, and implementing responsible manure management techniques. The successful implementation of these adaptation measures requires a multi-faceted approach, integrating scientific knowledge, technological innovations, and policy support. Empowering farmers with access to timely climate information, training, and financial assistance is critical for enabling them to make informed decisions and implement necessary changes. Furthermore, fostering partnerships among researchers, farmers, industry stakeholders, and governments is essential for developing and implementing effective climate-resilient dairy production strategies.

The dairy sector can become resilient and safeguard animal welfare by positively adapting to the challenges that are going to occur by a changing climate and can sustain the contribution to the global food sector.

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Chapter-6

HOUSING AND SHELTER DESIGN FOR CLIMATE RESILIENCE DAIRY FARMING

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Abstract

Effective housing and shelter design is a cornerstone of climate-resilient dairy farming, directly influencing animal welfare, productivity, and the sector's adaptive capacity to increasing climatic variability. This paper presents an overview of design principles and technologies that enhance the resilience of dairy housing systems to heat stress, extreme rainfall, and seasonal variability, with particular attention to resource-constrained and tropical/subtropical environments. Key elements include passive cooling (orientation, ventilation, reflective/insulating roofing, and shaded zones), advanced microclimate control (evaporative cooling, misting, and controlled airflow), and structural adaptations for flood and rainfall management. Integration of renewable energy for lighting, ventilation, and water pumping reduces dependence on fossil fuels and contributes to both mitigation and reliability under climate-induced grid instability. The design framework also emphasizes water-efficient waste handling, hygienic flooring, and flexible space allocation to allow for changes in herd size or grazing patterns. Animal-centric considerations—such as comfortable resting surfaces, disease-preventive layout, and thermal comfort thresholds—are linked to productivity gains and reduced emissions intensity. Socioeconomic and participatory design aspects ensure that interventions are locally appropriate, affordable, and maintainable by smallholder farmers. Through a systems approach, the chapter argues that resilient dairy housing not only buffers climate shocks but also creates co-benefits in sustainability, animal health, and farmer livelihoods, forming a critical component of broader climate-smart dairy development strategies.

Key Word: dairy, housing, climate, resilience

1. Introduction

Shelter plays an important role in combating climatic change and adverse effect of climate on livestock. Dairy animals are sensitive to climatic change which requires modification of microclimate for their better productivity. The defaulted housing and shelter causes lot of stress and cumulative production loss in Dairy sector. Hence considering the climate change trend, dairy housing system needed scientific design considerations to improve comfort level for optimising production. Heat stress is one of the major concerns for the global livestock sectors under changing climatic conditions the major concerns for the global livestock sectors in terms of increased environmental factors and stressors (high ambient temperature and relative humidity) which hinders animal production during climatic extreme conditions resulting in disastrous economic implications

Discomfort of dairy animals due to heat stress lead to production losses such as milk yield, milk quality, milk composition, etc. Further milk yield can be decreased by 40-50% during extreme heat stress in dairy animals. However, this reduction in milk yield is due to a decrease in dry matter intake by the animal. To enhance the comfort of the dairy cow and minimize loss of production under extreme heat stress conditions, proper shelter design is of paramount importance in tropical parts of the world

The basic principle to provide housing and shelter to the animals is for proper provision of comfort and to satisfy their basic needs along with the emphasis on five freedom, and also to protect them from extreme climatic condition by modifying all factors for production and welfare reason. The impact of climate change on dairy animal is most influenced factor, climate change in given place contribute stressors on the animals, change in physiological values which hamper production, reproduction, health of the animal and disease outbreak under their production system. In Indian scenario most of the livestock is owned by small and marginal farmers and landless labourers, with poor livestock resources. The owners with poor resources are more vulnerable to climate change and are at greater risk. Stress factors are inevitable problem related to dairy production in tropical and sub-tropical countries. Such conditions decreases feed intake, growth, milk quality, and quantity as well as reproduction, thereby affecting animals' health and welfare.

Hence to address this issue of impact of climate change on dairy animal production various strategies and actions were worked out to move towards climate resilient pathways for sustainable dairy development. The key method for minimizing the negative impact of climate is considered to be the physical alteration of the surroundings within the animal shed. Various modifications include the installation of a shade structure within farm premises, roofing designs and materials used, proper dimension of a shed, roof height, and adequate ventilation system, therefore housing and shelter design is an important under dairy production management.

Animal housing and management is the high priority adaptation measure to minimize the effects of climate and climate change on livestock production. Principles of animal housing like, orientation, height, shape of roof and roofing material, open space in walls for ventilation and floor space. Scientifically designed animal housing with proper ventilation for protection of animals from heat in sub-tropical arid and semiarid and from heat and high humidity in tropical and subtropical wet zones and production system based provisions are very important.

Covertness and provision of shelter to the dairy animals can increase dry matter intake by 5-15% and also reduce the stress on dairy animals. There will be better metabolic conversion of feed leading to faster body weight gain. The number of cows standing, lying down or eating may be counted for the comfort of dairy animal. Comfort of the floor is judged by the resting time of the animal in hours on that particular floor. Misters or sprinklers may be installed to provide more comfort in dry summer by increasing evaporative cooling.

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2. Housing and shelter design

Shed construction

The most simplest and effective method of reducing climatic stress on dairy animal is provision of proper shed. Shed plays a pivotal role in reduction of heat accumulation, altering air temperature and relative humidity around the animal (micro environment). The provision of shaded structure was found to minimize total heat load by 30-70 percent. During hot summers, provisions of shaded shelters for dairy cows have been found improve reproductive and production performances. In a comparative study between shaded and un-shaded dairy cows, the shaded cows have improved milk yield and reproduction, as well as lower respiration rate and rectal temperature when compared with un-shaded cows. Subsequently, dairy cows provided with well-designed shade tend to show increases in milk yield (about 3%) when compared with cows of non-shaded areas.

The provision of shade must be either natural (tree shade) or artificial (roof shade) for each and every animal. During planning of animal housing a care must be taken to alter or modify the animal housing system based up on extreme climatic conditions. Single row system with open walls always reduce stress and climatic burden on the dairy animal. With the higher number of animals double row system preferably tail to tail system of housing is better. Shed roof measuring 10.0 feet x 4.0 feet will provide adequate shade for each animals. To reduce the radiation from the shade roof to the cows, a mature dairy cow requires minimum 3.5 to 4.5 Sq.mt of shaded area, and the height of the shade should be 3.5–4.5 mt. Reports indicating, that the cooling efficiency of the animal increased by 30% when the shed height was increased from 5 m to 8 m high

Free air movement, proper drainage and low human traffic is also a key factor in animal housing plan and lay out, the location and orientation of shed plays important role in reduction of climatic stress, hence the orientation of shed should be in east -west direction for proper ventilation, wind movement and sunlight. The location of shed should be planned on elevated places for drain collection, channelizing the drain for proper drainage to reduce the drainage contamination, disease outbreaks and proper handling of waste.

Roof and Roofing Material

The roof prevents the animal from direct solar radiation, rain and draft air, which is an integral part of the housing. Hence this is another strategy for physically altering the house environment and limiting the negative impacts of high ambient temperature, is effective thermal insulation of the barn roof. The Various types of roofing materials can be used such as dry leaves, asbestos sheet, zinc sheet, aluminum sheet, paddy straw, thatch, clay tiles, reinforced cement concrete, plastic sheet, GI sheet, reinforced cement concrete (RCC),etc. for constructions of livestock shed in the Indian subcontinent. Roofs may be of either single or double type with the same or different materials. The most effective roofing material for minimizing heat load is a reflective roof such as aluminum or white galvanized roof. However, as per rural structure in the tropics, the most common type of roofing material is thatch for animal housing in tropical countries and helps in heat dissipation due to lower thermal conductivity. A shed roofing with 4-6 inches thick hay thatch will absorb minimum heat from solar radiation and will present a cooler micro-environment and subsequently comfort to the

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dairy cows. Roof insulation with paddy straw in dairy housing helps to reduce thermal radiation and presents a thermo-comfortable environment to the dairy cows. Further studies indicated that, the physiological indices, better cardinal signs and milk yield was improved significantly. A gable roof was found to reduce heat load by 30% when compared with multiple shed roofs in the barn. Reports also indicating that the rectal temperature of cows reared under modified roof was lower (39.02°C), similarly the average daily gain of the cattle was higher (0.632 kg/d). Further, the reports shown that, the modified shed reduces the roof surface temperature by about 5-7ºC. and animals reared under-insulated roof to have a favorable microclimatic environment and tend to consume more feed, at the rate of 0.2 kg/day/cow, and consequently, milk yield increases by 0.6kg/day/cow.

Floor

Floor is the frequent utility area of the dairy animals which is required to perform all the activity, whatever the flooring material used must provide comfort, durability, hygienic maintenance, drainage and cow comfort. Floor discomfort leads many abnormalities and induces stress on the animal. Housing structure with loose housing system with combined pucca floor in shaded area with kutcha flooring in open area is always ideal for dairy animal. Concrete is the most common base for floors in milking parlor, cubicles and alleys, and the alleys are either slatted or solid and scraped. Concrete has advantages and disadvantages, such as abrasiveness of new concrete and slipperiness of older worn concrete. Concrete flooring can be covered with materials such as rubber or mastic asphalt which alter the growth and wear of claw horn. Mastic asphalt has very good frictional properties but the wear off rate (abrasion) could be too high. The slipperiness of the rubber matting of floors depends on the rubber quality and softness of rubber. If rubber is hard and smooth, it can be as slippery as smooth concrete. Several studies show that the introduction of softer alleys with rubber surface improves walking comfort of cows and results in less laminitis-related claw diseases. Another study shows that dairy cows had a preference of 80 per cent both for standing and for walking on rubber compared to concrete.

Floors should not be uneven. In case of pucca flooring there should be sufficient slope (1:30) toward drains for drainage so that floors remain free from development of pools of water or urine and dampness. Most of the research findings indicating that the flooring with combination such as concrete and kutcha floor is ideal. The over-crowding should be avoided to keep the environment cool and comfort.

Ventilation

Ventilation inconsideration air movement and sunlight is an important factor in dairy housing to mitigate climatic stress. Two common types of ventilation in dairy housings are natural ventilation and forced or tunnel ventilation. In traditional or loose housing barns, we encountered natural type of ventilation with open sidewalls with continuous ridges. Natural ventilation types include continuous eave openings, large continuous sidewall openings, and continuous ridge openings. Good ventilation keeps the air quality higher and helps to maintain a less stressed environment within the barn. Ventilation is crucial to help dairy calves to reduce their body heat and it also reduces the risk of respiratory illnesses. Heat stress during hot summer is thought to be mitigated by an air exchange of 40 to 60 liters per hour. A well-oriented semi-opened building with a high and well-insulated roof can maximize natural ventilation rates, studies demonstrated that crossbred cows reared under open-ridge ventilated double slope thatch roofs have a comfortable microenvironment and significantly affected cows' comfort index. They also reported that there is a reduction in a heat-stress-oriented drop in milk yield and milk composition as well as improved udder health of dairy cows (Bernabucci et al., 2010). In hot and humid areas, the sidewalls should include a movable curtain to ensure cross-flow ventilation for the animals' comfort. The side walls in the barn should be provided with a height of a minimum of 1 meter and should not be fully covered to allow maximum airflow. This dimension ensures the free flow of air and minimizes the thermal load. Another effective approach to minimizing heat stress is through the construction of a double wall in the shed (Belsare & Pandey, 2008). Consequently, extra wall layers were added at the shed's end, and the outer layers were situated about 10 cm from the inner wall, with vertical openings on both ends. In this, cold air was allowed to enter through the bottom aperture, while heated air was permitted to depart through the higher opening. The ten-centimeter spaces between the two walls act as a thermal barrier and prevent conductive thermal energy from entering the animal shed. Regardless of the barn ventilation system, sufficient airspeed near the cows is critical for controlling heat stress. An air flow of 4 mph over the cow housing area is the ideal one. Additional fans can be installed to increase the air flow. If possible, misters or sprinklers may be installed to provide more comfort in dry summer by increasing evaporative cooling.

Cooling and cooling Systems

In dairy animals, evaporative cooling can be achieved through sweating and panting, where water evaporates from the skin and respiratory tract, respectively which is basis for cooling system. Naturally the animals go under wallowing to cool their body temperature in spite of this, which can be achieved by the use of fans, mists, sprinklers, foggers, and forced ventilation. According to a recent study, milk output losses due to thermal stress will rise at a rate of 174 ± 7 kg/cow/decade in the twenty-first century, however, heat abatement strategies with fans, water or air conditioning reduce milk yield loss and are associated with significant economic return for dairy producers. Consequently, the use of fans and sprinklers effectively reduces cow core body temperature and showed a 4-5% increase in milk yield of lactating dairy cows. The reports also shown that using fans in the barn can reduce the cow's body temperature by 0.3 to 0.4 ºC. A combination of fan and sprinkling is a more effective technique in minimizing heat stress in high yielding animals during warm climate. Water as a cooling agent has been demonstrated to be an effective strategy for minimizing the effects of heat stress on animals, especially in dry and hot humid conditions. Consequently, water is the primary cooling agent that cools the micro environment and allows animals to cool through evaporation. Installation of air-conditioning in the barn reduces air temperature and relative humidity. A net increase of 0.5 kg milk/day/cow with reduction of rectal temperature by 0.4º C.

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Cleanliness and hygiene

Housing management practices including cleaning and hygiene is utmost important factor in reduction of stress in dairy animal, cleanliness and hygiene depends up on the seasonal variation and climatic changes. Design and structure, slope and proper drainage of the animal hose influence the cleanliness and hygiene, which keeps animal healthy and to produce healthy production according to the scientific recommendation.

Conclusion

Stress (heat stress) is a major concern in climatic change and its consequences causes change in physiological values of the animal, which hamper production, reproduction, health of the animal and disease outbreak under their production system. Hence it can be managed by proper housing and shelter management with modifications to reduce the stressors. The scientific management of shelter and housing design as per the need of animal can alter the micro environment for comfort of animal. Various steps to mitigate stress in dairy animals is included to provide proper shed structure, roof design, ventilation, cooling system, cleanliness and hygiene and material used is utmost important.

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Chapter-7

NUTRITIONAL MANAGEMENT OF DAIRY ANIMALS IN VARIOUS CLIMATIC CONDITIONS

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Abstract

Climate change is the invisible driver reshaping the future of livestock farming, with rising temperatures, droughts, and extreme weather events severely disrupting feed quality, animal health, fertility, and productivity. Heat stress lowers feed intake and immunity, while droughts shrink fodder availability and degrade nutrient density. Climate-resilient smart feeding strategies offer a sustainable path forward as balancing productivity, animal welfare, and environmental stewardship. Rooted in Climate-Smart feeding, these approaches integrate precision feeding, drought-tolerant forages, functional additives (e.g., antioxidants, postbiotics, seaweeds), and innovative systems like TMR, silvopasture, hydroponics, and insect-based proteins. These solutions optimize nutrient efficiency, reduce methane and nitrogen waste, and build resilience to climate extremes. Technologies such as ration-balancing tools, hyperspectral monitoring, and emergency feed/fodder banks further strengthen adaptability. Smart feeding isn't just about nutrition it's about securing livestock livelihoods, ensuring food security, and building climate-proof dairy systems. In this changing climate, smart nutrition is no longer optional, it's the new frontier of sustainable livestock production.

Key Words: dairy, nutrition, climate, feeding

1. Introduction:

Climate is the unseen force behind every drop of milk. From scorching heat to freezing cold, shifting weather patterns directly affect the feed consumption, animal health, fertility, and milk production in dairy herds. Heat stress lowers productivity, droughts shrink fodder supplies, and extreme weather invites disease and without climate stability, there will not be any dairy production. Climate change refers to long-term shifts in local, regional, and global weather patterns, primarily driven by human activities such as greenhouse gas emissions, global warming, urbanization, and deforestation (Sahoo et al., 2024). In livestock systems, its consequences particularly heat stress during extreme summers in arid tropics and cold stress in temperate or high-altitude regions are increasingly severe. Rising temperatures, droughts, and declining forage quality are undermining feed efficiency and animal productivity (Sahoo, 2021). Heat stress increases plant lignin content, reducing digestibility and nutrient release in the rumen (NAAS, 2016), which disrupts the rumen microbiome, elevates lactate levels, and triggers metabolic disorders that severely impact milk and meat yields (Kim et al., 2022). Coupled with reduced feed intake and hormonal imbalances, reproductive performance also suffers, highlighting the widespread impact of climate change on livestock health and production.

2. Climate Change and Its Impacts on Livestock Health:

Climate change results in global warming and extreme weather which disrupt ecosystems and shift species distribution (IPCC, 2007; Pankaj et al., 2013). Animal agriculture itself contributes significantly 18% of global greenhouse gas emissions including 9% CO_2, 37% CH_4, and 65% N_2O thereby intensifying climate impacts (Pankaj et al., 2013). Livestock health is affected by both directly, through heat stress, and indirectly, via changes in feed quality and disease patterns (Chauhan et al., 2014). Directly, heat stress impairs thermoregulation, lowers feed intake, fertility, milk yield, and immunity, while increasing disease susceptibility and mortality, particularly in high-yielding crossbreds (Vitali et al., 2015; Hooda et al., 2010). Indirectly, climate change reduces forage quality and water availability, forcing animals onto nutritionally poorer diets, leading to deficiencies and weakened immune systems (Lacetera, 2019; Thornton et al., 2009). Combined, these impacts reduce productivity and livestock resilience under a changing climate (Chauhan et al., 2014).

Nutritional strategies tailored to withstand the extreme weather as it heat, cold, or drought, are essential for sustaining the health, productivity, and welfare of dairy animals. In hot conditions, cooling diets and electrolyte supplements help combat heat stress. Cold weather calls for energy-rich feeds to support thermoregulation and maintain body warmth. During droughts, resilient forages and alternative feed resources ensure nutritional balance despite forage scarcity. As the saying goes, *"Smart feeding in every season isn't just good practice but it's the key to year-round performance and profitability."*

Climate-resilient feeding strategies are essential for sustaining livestock productivity, improving animal health, ensuring food security, and minimizing environmental impact (FAO, 2018). Rooted in the Climate-Smart Agriculture (CSA) framework, these approaches enhance resilience to climate variability and disruptions (Germer et al., 2023). At the heart of CSA, nutrition is the role of diet in thermoregulation and mitigating heat stress, with strategies like precision feeding, drought-resilient forages, and supplementation with electrolytes and bioactive compounds showing promise (Sammad et al., 2020). Functional feeds rich in antioxidants, phytogenics, and essential minerals strengthen immunity, stabilize metabolism, and improve oxidative balance. Additionally, the use of sustainable, low-emission, drought-tolerant feed resources, combined with practices like feeding during cooler hours, low heat increment diets, genotype-specific formulations, and methyl donor supplementation for epigenetic support, enhances thermal tolerance and nutrient efficiency, boosting livestock resilience under climate stress (Sammad et al., 2020).

3. Key Components of Climate-Resilient Smart Feeding

I. **Precision Feeding**

- Delivering the right nutrients to the right animal at the right time, enhancing feed efficiency and minimizing waste.

- Not only boosts productivity but also helps reduce environmental impact by lowering enteric methane emissions and nitrogen excretion.

Climate-smart nutrition holds strong potential for enhancing the performance of high-yielding dairy animals, particularly during early lactation and rapid growth phases. Although these animals utilize dietary protein efficiently, they still excrete 2–3 times more nitrogen in manure than is secreted in milk. This inefficiency can be minimized by formulating diets based on rumen degradable protein (RDP) and undegradable protein (UDP or bypass protein) rather than relying solely on crude protein. Such targeted feeding strategies can sustain or boost productivity while reducing nitrogen waste. Optimizing microbial protein synthesis and providing adequate bypass protein and essential amino acids is key to improving growth, reproduction, and milk yield (Chandrashekharaiah et al., 2024). Additionally, supplementing protected (bypass) fat under field conditions has been shown to enhance milk production and reproductive outcomes. The recommended dose is 20 g/kg of milk yield for cows and 15 g/kg for buffaloes, not exceeding 200 g/day for cows and 150 g/day for buffaloes to prevent adverse effects on rumen fermentation.

II. **Smart feeding** is a climate-resilient strategy ideal for developing countries, aimed at meeting animals' nutritional needs while minimizing costs and environmental impact. A key approach is shifting toward fodder-based diets and reducing dependence on protein-rich concentrates. These rations are both cost-effective and efficient in low- to moderate-yield systems without compromising milk protein output (Makkar, 2016). Utilizing on-farm resources like fodder and crop by-products lowers reliance on external inputs, prevents nutrient excess, and supports manure recycling. In semi-arid areas, integrating local by-products into dairy feed has cut feeding costs and greenhouse gas emissions by up to 14% (Alqaisi et al., 2014). Technologies such as densified straw-based TMR blocks, forage chopping, and harvesting at optimal stages further boost feed efficiency, reduce emissions, and enhance the sustainability and resilience of smallholder livestock systems.

III. **Balanced Ration Formulation**

- It involves creating diets tailored to the specific nutritional requirements of dairy animals, taking into account factors such as their age, breed, and stage of production.
- It enhances animal health, productivity, and fertility, while also lowering greenhouse gas emissions per unit of milk produced.

Feed represents over 70% of operational costs in dairy production, making least-cost ration formulation a major challenge for farmers. Imbalanced diets can result in nutrient deficiencies or oversupply especially of costly nutrients leading to reduced productivity and increased expenses. Maintaining a balanced ration is crucial for optimizing milk yield, reproductive performance, and cost-efficiency. To address this, ration balancing tools have gained popularity, with user-friendly mobile and computer-based platforms now widely available to help farmers fine-tune nutrition and manage costs effectively. Examples: NDDB Ration balancing, ICAR-NIANP Software- 1. Feed Assist 2. TMR Maker 3. Feed Chart on print, web and mobile media 4. Ration balancing tools for small ruminants.

4. Complete Feed System/TMR:

Blending locally available concentrate agro industrial by-products with roughage to form a total mixed ration (TMR) is a proven, cost-effective strategy in livestock nutrition. This complete feed system enhances feed intake, improves nutrient utilization, and boosts animal performance by enabling the efficient use of fibrous crop residues and non-conventional feed resources. TMR prevents selective feeding, allowing inclusion of less palatable but nutrient-rich components make feeding more economical. It also promotes the use of agro-industrial by-products and farm waste like cottonseed hulls, lentil straw, mesquite pods, oilcakes, sugarcane bagasse, poultry droppings, and tree foliage. Incorporating these into livestock diets not only reduces feeding costs but also supports sustainable and resource-efficient animal production.

Table. 1 Inclusion levels of Crop residue (%) in complete ration

Crop residue	**(%)Level in TMR**
Sorghum stover	20-60
Maize stover	20-50
Paddy straw	Up to 50
Wheat straw	Up to 60
Pulse straw	Up to 50
Sweet sorghum stover	Up to 60
Maize cobs	Up to 50
Sunflower straw	30-50
Sunflower heads	33.5-50
Cottonseed hulls	Up to 50
Cotton straw	Up to 45
Sugarcane bagasse	Up to 40
Sweet sorghum bagasse	Up to 60

5. Use of Climate-Resilient Feed Resources

- It includes drought-tolerant and heat-resistant fodder species, like sorghum and millet, which can thrive in challenging climatic conditions.
- It improves feed security and lowers reliance on water-intensive crops.

Climate-resilient feed resources are vital for maintaining sustainable livestock production amid climate change. They are specifically developed to endure environmental stresses like drought, heat, and water scarcity, ensuring consistent nutrition for animals and supporting farmers' livelihoods.

Drought-Resistant Crops: Sorghum and millet are standout examples of climate-resilient feed crops. With origins in Africa, these cereals thrive in dry, arid conditions thanks to their deep root systems and efficient water use. They not only provide nutritious feed for livestock but also offer economic benefits for farmers in regions where traditional crops often fail, making them valuable assets in climate-smart agriculture.

Indigenous Fodder Plants:

In regions like Ethiopia and the Peruvian Andes, farmers are turning to indigenous plants such as *Ficus thonningii* and cactus pears as resilient livestock feed. Rich in nutrients and excellent at retaining moisture, these plants are especially vital during dry periods. In Ethiopia, integrating them into silvopastoral systems has reduced water use by up to 83% while significantly increasing forage biomass highlighting their role in sustainable, climate-smart feeding.

Top feeding:

Tree leaves are a valuable feed resource, especially during forage-scarce periods, offering green biomass with moderate to high digestibility and good protein content. Their dry matter typically ranges from 20–40%, with crude protein levels of 10–15% and calcium content 2–3% higher than common fodder crops. Rich in protein, vitamins, and minerals, tree leaves are the most nutritious part of the tree. They play a crucial role in hilly regions during winter and summer, when both the quality and quantity of green forage are limited, helping sustain livestock nutrition year-round.

Table. 2. Chemical composition of different forage leaves

Forage leaves	**DM**	**OM**	**Ash**	**CP**	**NDF**	**ADF**	**ADL**
Neem leaves leaf meal (*Azadirachta indica*)	92.8	90.5	9.5	28.2	31.8	21.9	4.9
Pigeon pea leaf meal (*Cajanus cajan*)	94.4	92.5	7.5	16.7	54.0	39.7	13.7
Acacia karro leaves	97.1	92.1	7.9	12.7	38.0	32.5	--
Air-dried *Moringa stenopetala* leaf	94.4	88.0	-	29.5	17.8	16.5	-
Khejari leaves	45.09	--	--	17.89	48.11	40.41	--
Leucaena leucochepala leaf	96.2	--	9.92	20.26	50.05	19.98	15.52
Moringa oleifera	22.8	--	9.14	22.8	30.8	22.8	--
Cow-pea leaves (*Vigna unguiculata*)	91.0	--	--	13.0	46.2	19.5	--
Water hycinth leaf protein (*Eichhornia crassipes*)	15.33	86.67	13.43	20.80	--	--	--
Bamboo leaves (*Bambusa vulgaris*)	45.0	--	11.5	14.15	68.8	42.3	--
Berseem leaves (*Trifolium Alexandrium*)	23.8	85.58	15.4	29.80	43.91	27.5	--

Cassia obtusifolia Leaves	97.0	95.26	13.00	27.84	40.32	17.28	--
Sweet potato leaf (*Ipomea batatas*)	91.8	95.3	--	26.5	25.8	15.2	--
Ber leaves (*Ziziphus mauritiana*)	48.9	--	9.8	13.3	35.8	25.5	--

Dual purpose varieties:

Growing dual-purpose (DP) crops and using their residues as livestock feed is a widely adopted strategy in dryland farming systems (Sprague et al., 2021). Around 70% of crop residues come from cereals like maize, sorghum, and pearl millet, as well as legumes such as cowpea and groundnut. Recently developed high-yielding DP varieties of cowpea, millet, and sorghum offer both nutrient-rich grains for humans and quality fodder for livestock. These crops are especially valuable during the dry season when grasses lose nutritional value. DP varieties with "stay-green" traits retain leaf biomass at maturity, providing nutrient-rich feed when it's most needed. For instance, DP cowpea varieties retain over 50% of their leaves, enhancing fodder quality and feed efficiency (Martens et al., 2012).

Insect farming for protein:

Black soldier fly larvae and mealworms are emerging as valuable alternative protein and mineral sources for livestock feed. These insects can be reared on organic waste, promoting a circular economy by converting waste into nutrient-rich biomass (Newton et al., 2005). Other species like grasshoppers, houseflies, beetles, silkworms, earthworms, and crickets are also gaining traction as sustainable feed ingredients, particularly for poultry (Belhadj et al., 2023). Rich in protein and essential amino acids, insect-based feeds are highly digestible, animal-friendly, and boast a low carbon footprint with excellent feed conversion efficiency. By reducing reliance on conventional feed crops, insect protein offers a sustainable solution for future feed demands. Though processing is needed to make insects more suitable for food and feed, they are increasingly recognized as a promising component of sustainable livestock nutrition (Lange, 2021).

Table.3 Protein content of insects

Name	**Scientific name**	**Crude protein %**
Black soldier fly	*Hermetia illucens*	32-61
Grasshoppers	*Orthoptera*	48-65
Silkworm	*Bombyx mori*	46-72
Earthworm	*Eisenia fetida*	41-66
Housefly	*Musca domestica*	40-64

(Ojediran *et al.,* 2024)

Aquatic plants and algae as a supplement to nutrition:

Duckweed and spirulina are excellent examples of protein- and mineral-rich aquatic plants and algae that offer sustainable feed alternatives, especially in areas with limited arable land (Van der Spiegel et al., 2013). Grown in ponds or water bodies, they serve as efficient, nutrient-dense supplements for animal diets. Marine and freshwater algae enhance feed quality due to their high levels of essential nutrients (Wan et al., 2018). As climate-resilient crops, they require minimal land and water, making them ideal for sustainable and low-impact livestock feeding systems.

Table. 4 Proximate composition of aquatic plants

Proximate composition	CP (%)	EE (%)	CF (%)	Ash (%)	Moisture (%)
Hyacinth(*Eicchornia crassipes*)	8.20	2.21	21.42	18.10	89.21
Algae (*Botryococcus braunii*)	25-26	2-22	-	-	--

(Ojediran *et al.,* 2024)

Microalgae:

Microalgae are a diverse group of unicellular or simple multicellular organisms with highly variable nutrient profiles. Their amino acid compositions are generally comparable to those of soybean and rapeseed meals (Becker, 2013), though they tend to be lower in histidine often the first limiting amino acid for milk production in animals on grass silage and cereal-based diets. Supplementing microalgae via drinking water has shown promising results in growing cattle grazing on low-quality grasses, improving rumen microbial protein synthesis and enhancing overall diet digestibility (Panjaitan et al., 2015).

Seaweeds:

Seaweeds are complex multicellular marine organisms that thrive in saltwater and coastal zones (van der Spiegel et al., 2013). They have a high moisture content of 700 to 900 g/kg dry matter necessitating quick use or preservation through drying or ensiling. Though low in cellulose (~40 g/kg DM), seaweeds are rich in unique carbohydrates like alginate, laminarin, and fucoidan. Introducing seaweed gradually into livestock diets allows rumen microbes to adapt and efficiently utilize these complex compounds (Makkar et al., 2016), making seaweed a promising functional feed ingredient.

Single-cell protein:

Single-cell protein (SCP) is composed of microbial cells from yeast, bacteria, fungi, or microalgae. Its protein content varies depending on factors such as culture conditions, species, and strains (Lindberg et al., 2016), but generally falls within a similar range as soybean expeller.

Hydropogenic feed production:

Hydroponically produced fodder offers a sustainable, soil-free method of growing fresh, nutrient-rich feed year-round using minimal water an ideal solution during droughts or when climate change limits traditional forage (Jan et al., 2020). Grown in greenhouses or polyhouses over 6–8 days, this system relies only on seeds, water, sunlight, and nutrients. In India, cereals like barley, oat, wheat, sorghum, maize, and legumes like alfalfa and cowpea are successfully cultivated hydroponically (Raghvendran et al., 2020). The resulting dense green mats, 20–30 cm tall, are highly palatable, digestible, and beneficial for livestock health. Producing 1 kg of hydroponic maize fodder needs just 1.5–3.0 liters of water, with seed cost making up nearly 90% of the total expense. A recommended daily supplement is 5–10 kg per cow (Naik et al., 2015). Hydroponic crops grow up to 50% faster, yielding high-quality fodder with lower environmental impact making it a rising global solution to land, water, and climate challenges (Kide et al., 2015).

Table. 5 Proximate composition of hydroponically produced maize fodder

CP%	EE%	CF%	Ash%	Moisture%
12.42	2.67	9.50	2.77	83.22

(Ojediran *et al.,* 2024)

6. Food-Not-Feed Resources:

Utilizing non-human-edible feed resources such as biofuel co-products, protein isolates, leaf meals, food and slaughterhouse waste, and spineless cactus is a promising strategy for building climate-resilient and sustainable livestock systems. These alternative feeds reduce reliance on arable land and minimize competition with human food sources. This approach aligns with the FAO's Sustainable Animal Diets (StAnD) framework, which emphasizes environmental, economic, and ethical sustainability in livestock feeding practices.

Table. 6 Agro-industrial byproducts:

Table 6 Proximate composition of some agro-industrial byproducts					
Agro-indutrial byproducts	**CP%**	**EE%**	**CF%**	**Ash%**	**Moisture%**
Brewery waste	24.30	5.20	19.66	5.77	79.19
Rice bran	17.50	13.10	23.33	4.92	4.3
Wheat bran	17.10	2.11	11.25	6.11	3.10
Palm kernel cake	15.75	12.23	21.42	1.4	9.42
Biscuit waste dough	19.4	3.87	4.18	7.00	9.91
Cashew kernel waste meal	21.10	35.09	6.83	4.10	9.20
Cassava distillers waste	11.82	2.83	34.86	3.54	10.10
Cassaca vinnase	19.26	3.72	7.96	9.33	5.68

(Ojediran *et al.,* 2024)

- Co-products from the biofuel industry, including DDGS, glycerin, and fatty acid distillates, offer energy- and protein-rich alternatives to maize and soybeans. These substitutes help reduce the use of human-edible feeds and lower greenhouse gas emissions.

- Redirecting food and slaughterhouse wastes into animal feed reduces pollution and lowers feed costs, while supporting circular economy principles and promoting "waste-to-wealth" initiatives.
- Fresh banana foliage can be included in lactating cow diets at up to 15% of dry matter without significantly affecting milk production; however, increasing banana foliage beyond this level may reduce dairy performance and digestibility.
- Additionally, feeding strategies incorporating spineless cactus in arid regions enhance animal productivity with minimal water requirements, promote land restoration, and contribute to carbon sequestration.
- Reviving technologies such as urea-molasses blocks and treating straw with urea or CaO improves nutrient utilization from low-quality forages, which is vital for sustaining productivity in climate-stressed grazing systems (Makkar, 2016).

Together, these food-not-feed innovations minimize feed-food competition, boost nutrient recycling, and contribute to making livestock production more resilient, ethical, and climate-smart.

6. Supplementation with Feed Additives

Incorporates additives such as antioxidants, minerals, and plant-based products to enhance digestion, lower methane emissions, and improve overall animal health. Nutritional compounds such as antioxidants (vitamin E, selenium, polyphenols, flavonoids), amino acids (methionine, glutamine), electrolytes (Na, K, Cl, Mg), carotenoids (beta-carotene, lutein), and trace minerals (Zn, Cu, Mn) play a crucial role in combating oxidative stress and enhancing cellular resilience under heat stress. These nutrients help preserve cellular function and integrity during challenging conditions. Targeted feed additives including growth promoters, antioxidants, probiotics, and plant-based extracts have shown significant potential in improving heat tolerance and production efficiency in ruminants. They aid in maintaining fluid balance, reducing dehydration, and reinforcing antioxidant defenses, while also supporting gut health and nutrient uptake critical for mitigating the effects of reduced feed intake during heat stress.

Additionally, innovative feed additives such as algae, probiotics, prebiotics, postbiotics, phytogenic extracts, and enzymes are gaining attention for their ability to enhance metabolic health and strengthen stress resilience in livestock (Shaik et al., 2020). As climate change intensifies, integrating these advanced nutritional strategies with effective heat stress prevention measures will be key to maintaining profitable, welfare-oriented, and environmentally sustainable ruminant production systems.

Eubiotics:

Eubiotics are feed additives designed to maintain or restore a healthy gut microflora, promoting better digestion, immunity, and overall animal performance. This group includes probiotics, prebiotics, organic acids, and essential oils. By enhancing nutrient digestibility and feed conversion efficiency, eubiotics help reduce methane emissions and support sustainable livestock production especially under heat stress and other environmental challenges.

Examples: Probiotics: Bacillus subtilis, Lactobacillus spp., Organic acids: Formic acid, butyric acid

Postbiotics:

Postbiotics are non-living microbial-derived functional compounds such as enzymes, peptides, short-chain fatty acids, and cell wall fragments that confer health benefits to the host. Postbiotics improve gut immunity and stress resistance, helping animals cope better with heat stress and oxidative damage during climatic extremes. Examples: Heat-killed Lactobacillus plantarum, Short-chain fatty acids (SCFAs) like acetate and butyrate

Precision Biotics:

Precision biotics are specifically designed microbial metabolites or interventions that modulate defined microbial pathways in the gut to achieve targeted health or performance outcomes. They reduce waste nitrogen and methane emissions by precisely enhancing nutrient metabolism and immune response under variable climates. Examples: Microbiome metabolic modulators targeting SCFA production, Customized oligosaccharides influencing microbiota function

Plant Extracts:

Plant extracts are bioactive compounds sourced from herbs or plants, including essential oils, saponins, flavonoids, and tannins, that are used to boost animal health and performance. With their antioxidant and anti-inflammatory properties, these extracts help alleviate heat stress, enhance feed intake and productivity, and reduce the need for synthetic additives. The key advantages of phytogenic additives in livestock production include improved feed digestibility, antimicrobial effects, replacement of feed antibiotics, and stimulation of growth. Additionally, their anti-inflammatory benefits contribute to better feed conversion and increased feed consumption by animals (Ignatovich, 2017). Examples: Thymol (from thyme), carvacrol (from oregano), Curcumin (from turmeric), saponins (from *Yucca schidigera*).

Table. 7 Use of different feed additives in the diet of different animals to reduce the heat stress

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Item	Species	Dose	Duration
Betaine	Dairy cow	15g/d	60d
Polyherbal vitamin C	Dairy cow	20g/d	131d
Organic acid and pure botanical	Dairy cow	75mg/kg	131d
Immunomodulatory feed ingredient	Beef cattle	56g/d	106d
Phytogenic feed additive	Heifers	0.25g/d	7d
Citrus extract	Dairy cow	4g/cow/d	28d
Dihydropyridine	Dairy cow	3g/d	104d
Probiotic compounds	Dairy cow	-	60d

(Shah et al., 2025)

Seaweed Additives for Emission Reduction

Incorporating small amounts of *Asparagopsis taxiformis*, a red seaweed, into cattle feed has been shown to reduce methane emissions by over 98%, offering a powerful tool for climate change mitigation and more sustainable livestock farming (Dubois et al., 2013). In addition to their methane-lowering effects, seaweeds supply vital nutrients that support ruminant health. For monogastric animals, high-quality protein alternatives such as single-cell proteins, protein hydrolysates, and plant-based protein isolates reduce reliance on conventional feed crops, promoting more resilient and resource-efficient feeding systems.

7. Silvipastoral systems:

The term *'silvo'* refers to trees, while *'pasture'* denotes grasses or grass-legume mixtures. Silvopastoral systems (SPS) are agroforestry practices that integrate trees, forage crops, and rotational livestock grazing to create a sustainable, three-dimensional source of nutritious fodder. These systems not only supply feed but also offer fuelwood, timber, and improve land productivity while conserving soil, water, and biodiversity. By providing shade and improving microclimates, trees in SPS reduce heat stress, enhance soil fertility, and support better forage growth. Overall, SPS ensures climate-resilient, nutrient-rich, and consistent feed supplies, promoting both animal health and environmental sustainability.

There are three basic components in SPS viz., Agriculture, Forestry and Livestock where they form two important systems with livestock:

a) Silvipastoral system (Fodder Trees + Fodder Grasses)
b) Agrisilvipastoral system (Agriculture + Fodder Trees + Fodder Grasses)
c) Hortipastoral system (Horticulture+ Fodder Grasses)

Table. 8 Favourable grasses, legumes, shrubs and tree species for development of SPS

Grasses	Legumes	Shrubs	Trees
Lasiurus sindicus, Cenchrus ciliaris,	Clitoria ternatea, Lablab purpureus, Atylosia	Zizyphus numularia,	Prosopis cineraria, Azadirachta indica, Acacia tortilis,

C.setigerus, Heteropogon contortus Sehima nervosum, Cicer, Melilotus, Trifolium spp., Cenchrus spp., Pennisetum pedicellatum Dichanthium annulatum, Brachiaria mutica, Cynodon dactylon Panicum maximum, Pennisetum polystachyon, P. pedicellatum P. clandestinum, Brachiaria mutica,	scarabaeoides, Stylosanthes hamata, Macroptilium lathyroides, Lablab purpureus, Clitoria ternatea, Alysicarpus monilifer, Stizolobium deeringianum, Clitoria ternatea, Mimosa invisa, M. atropurpureum, Centrosema pubescens, Stylosanthes guianensis, Desmodium spp., Sesbania spp.,	Dichrostachys Spp., Zizyphus numularia, Capparia zeylanica, Sesbania, Atriplex, Acacia spp.	Dalbergia sissoo, Leucaena leucocephala, Emblica officinalis,, Acacia spp., Ficus spp., Bauhinia purpurea, Ficus numeralis, Albizia chinensis Morus cerrata, Salix tetrasperma,

8. Integration of Agro-Ecological Practices

- Integrates livestock feeding with sustainable land and water management practices like rotational grazing and agroforestry to enhance soil fertility and offer shade for animals.
- Wetting of Straws: Moistening dry straws during hot, dry periods helps lower the animal's internal heat load.
- Incorporation of Good Quality Green Fodder: Including high-quality green fodder in the summer diet can improve its nutritional content and aid in alleviating heat stress.
- Increasing Nutrient Density: Substituting low-quality roughage with concentrates and providing well-chopped dry fodder can boost the diet's nutrient density, helping to lower the animal's internal heat load.

9. Technology-Driven Monitoring and Management

Utilizes technologies such as hyperspectral imaging and herd management software to track pasture conditions and animal health, allowing for prompt and effective interventions. Feeding management strategies aim to reduce internal heat load in dairy animals, particularly during periods of heat stress. Low-quality feeds such as crop residues demand more energy for digestion, leading to greater heat production and additional thermoregulatory burden on the animal. Moreover, fodder particle size impacts heat generated per unit of dry matter due to variations in specific dynamic action. By optimizing feed quality and processing, farmers can minimize heat stress, improve nutrient utilization, and support better health and productivity in dairy animals under challenging climatic conditions.

10. Creation of Feed & Fodder Bank: To tackle livestock feed shortages during droughts and floods, this timely proposal suggests setting up dedicated Feed Banks stocked with safe, alternative feed resources. Ingredients stored in warehouses often rejected for human use due to aflatoxins, pesticides, or drug residues can be repurposed for livestock after clearance by State and Central labs. Once certified, these feeds can be stored for emergency use, ensuring cost-effective, sustainable nutrition while reducing food-feed competition and wastage (Makkar et al., 2016).

Fodder Banks:

Grasses: Grasses growing around forest edges, wastelands, and farmlands can be harvested and preserved as hay, either compressed into briquettes or stored in high-density stacks for efficient use.

Crop Residues: Key crop residues such as rice and wheat straw play a vital role in feed banks. Additionally, residues from coarse cereals, legumes, and haulms left after grain harvesting can also be collected and stored to support livestock feeding during emergencies.

Benefits of Climate-Resilient Smart Feeding

- **Enhanced Productivity**: Optimized feeding leads to better growth rates and higher milk yields.
- **Environmental Sustainability**: Reduces greenhouse gas emissions and minimizes resource wastage.
- **Economic Viability**: Decreases feed costs and improves farm profitability.
- **Animal Welfare**: Promotes better health and reduces stress, leading to improved fertility and longevity.
- **Adaptation to Climate Change**: Builds resilience against climate-induced challenges like heat stress and feed scarcity.

Conclusion

In a world of rising temperatures and shrinking resources, smart nutrition is the lifeline for dairy animals. Climate-resilient feeding is not just a strategy, it is a necessity to protect productivity, health, and sustainability of dairy animal production. By embracing precision diets, drought-proof fodders, and eco-friendly feed solutions, climate challenges can be turned into opportunities.

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Chapter-8

CLIMATE RISK MANAGEMENT AND FINANCE

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Abstract

Climate change presents a critical threat to global agriculture, particularly in low- and middle-income countries (LMICs) where livelihoods heavily depend on climate-sensitive livestock systems. Rising temperatures, erratic rainfall, and extreme weather events disrupt productivity, increase animal mortality, and intensify food insecurity. The agricultural sector, while highly vulnerable, also contributes significantly to greenhouse gas emissions. Climate risks now extend beyond farms to financial institutions, increasing credit constraints and threatening financial stability. Effective climate risk management and finance are essential to build resilience. This chapter explores the financial implications of climate change, highlighting adaptation strategies such as climate-smart agriculture, early warning systems, precision livestock farming, and agricultural insurance. It underscores the pivotal role of climate finance—including grants, loans, and blended instruments—in catalyzing these strategies. Despite significant barriers like weak institutions, high transaction costs, and limited access to credit, targeted investments and policy reforms can enable a sustainable, climate-resilient agricultural future.

Key Words: climate, risk, finance, adaptation

1. Introduction

Climate change, characterized by the increased frequency and intensity of extreme weather events, poses the greatest environmental challenge threatening global food systems. Its impacts are particularly severe for livestock production systems and agriculture in low- and middle-income countries (LMICs). In these nations, where millions of vulnerable people rely on livestock for critical livelihoods and food security, the agricultural sector is highly susceptible to erratic rainfall, rising temperatures, flooding, drought, and desertification. When temperatures surpass thresholds projected by the Intergovernmental Panel on Climate Change (IPCC), livestock experience heat stress, which reduces productivity, lowers conception rates, and can even be life-threatening. Beyond direct impacts on yields and animal health, climate change also profoundly affects financial stability, increasing credit constraints for farmers and financial institutions alike.

Historically, climate risk was often viewed as a reputational concern for financial firms, but it has increasingly been recognized as a material financial risk that demands integration into existing risk management frameworks. This shift highlights the urgent need for robust strategies to manage climate risk, mobilize adequate finance, and build resilience across the agricultural sector. This chapter aims to provide a comprehensive overview of climate risk management and finance within agriculture, detailing the profound impacts of climate change, its financial implications for farmers and institutions, and the innovative adaptation and mitigation strategies available. We will explore the critical role of climate finance in catalysing sustainable agricultural practices and addressing the systemic barriers that impede its flow.

2. The Challenge of Climate Change: Impacts and Contributions

The escalating impacts of climate change on agriculture and the reciprocal contribution of the sector to greenhouse gas (GHG) emissions present a complex challenge for sustainable development, particularly in LMICs.

2.1. Direct and Indirect Impacts on Agriculture and Livestock

Climate change inflicts direct and indirect impacts on livelihoods and agricultural production systems in LMICs.

- Direct impacts include events like heat stress, flooding, and other extreme weather that directly affect livestock assets and food systems. For example, when temperatures exceed IPCC projections, livestock suffer from heat stress, impairing performance, reducing productivity, lowering conception rates, and becoming life-threatening. The Horn of Africa, for instance, experienced an unprecedented multi-year drought from 2020 to 2023, leading to the perishing of approximately 13.2 million livestock across Somalia, Ethiopia, and Kenya.
- Indirect impacts extend to broader economic effects, food security, and infrastructure. These manifest as:
  - Reduced availability of livestock feed-grains, leading to increased prices.
  - Declines in both the production and quality of pastures and forage crops, essential for livestock nutrition.
  - Alterations in the distribution of livestock diseases and pests, potentially exposing animals to new threats.
  - Rising sea levels that could flood pastures with saltwater, raising salinity levels and negatively affecting feeds and grazing fields.
  - Temperature changes that may introduce vector-borne diseases, parasite infestations, and disease transmission to previously unaffected areas.

These impacts collectively result in impaired performance, high mortality rates, and loss of animals, leading to reduced revenues, increased poverty, and hunger for individuals and communities. LMICs are disproportionately affected due to their high dependence on climate-sensitive sectors like agriculture and livestock farming, coupled with limited financial and technological resources to implement large-scale adaptation measures. India, for example, is ranked as the 7th most vulnerable country to climate change impacts according to the Global Climate Risk Index of 2021, with rural areas facing high vulnerability due to dependence on natural resources and exposure to frequent climate-induced disasters. Yields of major crops in India could decline by up to 25%.

2.2. Livestock's Contribution to Climate Change

The livestock sector plays a dual role: it is a victim of climate change, but also a significant contributor. Climate change can result from both natural and human (anthropogenic) influences, with the production of greenhouse gases (GHGs) such as methane, carbon dioxide, water vapor, and nitrous oxide being major anthropogenic drivers. The primary sources of these gases include the burning of fossil fuels and agricultural activities, including livestock production. The sector is estimated to contribute 14.5% of global anthropogenic GHG emissions, a figure that has been reported to exceed emissions from the entire transport sector by some sources. These emissions intensify pressure on the environment, leading to land degradation, air and water pollution, and declines in biodiversity.

3. Climate Risk and Financial Institutions

The pervasive nature of climate change means its impacts are not confined to the farm; they extend deeply into the financial sector, influencing credit availability, repayment capacity, and overall financial stability.

3.1. Climate Risk as a Financial Imperative

Financial institutions (FIs) are increasingly recognizing climate risk not merely as a corporate social responsibility issue, but as a fundamental financial risk. This recognition has led to the coining of terms like "Green Swan," referring to unexpected calamities arising from climate change that can cause significant financial losses. These financial risks manifest primarily through three channels:

- Physical Risks: These arise from the direct impacts of climate- and weather-related events. This includes acute risks such as more frequent and severe storms, floods, heatwaves, and wildfires, as well as chronic risks like longer-term shifts in precipitation patterns, rising mean temperatures, and sea-level rise. These events can lead to the potential loss of physical assets, directly affecting the viability of businesses that FIs lend to and the value of collateral.
- Transition Risks: These emerge from the process of adjusting economies toward a lower-carbon future. Changes in policy, technology, and laws related to climate change can lead to a reassessment of asset values, potentially creating "stranded assets"—investments (e.g., in fossil-fuel-based technologies) that may be written down or off before the end of their useful life. For example, a shift to carbon-neutral financing or new, less polluting technologies can impose costs, affecting counterparties' operations and business viability.

- Liability Risks: These stem from the increasing cost of insurance as the ill effects of climate change become more frequent and severe. For low-income farmers, the cost of asset insurance for livestock or poultry is already perceived as high. As climate change exacerbates agricultural production risks, the costs for insuring against these risks will inevitably rise, impacting farmers' financial viability and indirectly affecting FIs.

These risks significantly impair the loan repayment capacity of clients, which, in turn, negatively affects the performance of financial institutions, including banks, Non-Banking Financial Companies (NBFCs), and Microfinance Institutions (MFIs).

3.2. Climate Change and Farmers' Credit Constraints

Climate change directly and indirectly exacerbates credit constraints for farmers by impacting their production efficiency and increasing losses. This dual effect weakens farmers' ability to repay debts and their willingness to take out loans, leading to heightened default risk and tighter credit access.

- Decline in Agricultural Production Efficiency: Climate change, through extreme weather events and altered hydrothermal conditions, reduces agricultural output and increases marginal production costs. This decline in efficiency translates to income instability or reduction for farmers, making them more cautious about applying for loans due to repayment uncertainty. From the perspective of lenders, reduced production efficiency signals an increased risk of loan default, prompting them to scrutinize applications more rigorously, reduce approval rates, or raise loan thresholds.
- Increase in Agricultural Losses: The increased frequency and severity of meteorological disasters caused by climate change lead to significant property and asset losses for farmers. In traditional lending frameworks, where collateral is a key risk mitigation mechanism, these losses severely weaken farmers' creditworthiness, thereby restricting their access to credit. When both credit demand (due to increased need for recovery/adaptation investments) and supply (due to perceived higher risk) are imbalanced, farmers face intensified credit constraints.

The impact of these credit constraints is not uniform. Farmers with less understanding of financial information and those located in regions with higher levels of marketization experience a more pronounced impact from climate change-induced credit constraints. In marketized areas, FIs are more sensitive to climate risks, leading to quicker tightening of credit policies in response to climate fluctuations.

4. Climate Finance and Adaptation Strategies: Building a Resilient Future

Addressing the multifaceted challenges posed by climate change requires targeted financial interventions and widespread adoption of adaptation strategies across the agricultural sector. Climate finance serves as a crucial catalyst in this transformation.

4.1. The Role of Climate Finance

Climate finance encompasses all financial flows, from public, private, and alternative sources, that support actions aimed at climate change mitigation and adaptation. Despite its critical importance, only a disproportionately small portion of total climate finance has historically flowed into agriculture—estimated at a mere US$6–8 billion out of US$391 billion in 2014, with most directed towards mitigation in the energy sector. However, there is growing recognition of agriculture's vulnerability and its potential as a climate solution.

Climate finance is instrumental in:

- Unlocking additional capital: It can catalyze and leverage diverse sources of public and private capital to fund climate-smart investments in agriculture.
- Strengthening FI-farmer links: It helps establish and reinforce effective channels for directing capital flows to smallholder farmers and Small and Medium Enterprises (SMEs).
- Providing technical assistance: It supports capacity building for both financiers and farmers, essential for identifying, implementing, and managing climate-smart interventions.

A range of financial instruments are deployed, including grants, concessional and non-concessional loans, equity, guarantees, and performance-based mechanisms. Blended finance, which strategically uses public resources (e.g., grants, low-cost debt, guarantees) to attract and de-risk private capital, is particularly effective for supporting climate-smart agriculture where upfront costs are high and risks are perceived.

4.2. Key Adaptation Strategies in Agriculture and Livestock

Various climate adaptation strategies are crucial for enhancing resilience in livestock and agricultural production systems, often requiring interdisciplinary approaches.

- Genetic Improvement and Diversification: This involves breeding programs for heat-tolerant and disease-resistant livestock, and diversification of livestock species and breeds. Exploiting indigenous livestock genetic resources can increase adaptability to climate stress and enhance biodiversity. Diversification into high-value crops and animal husbandry also acts as a risk-mitigating measure.
- Early Warning Systems (EWS): These systems provide real-time weather and market information, enabling farmers to make data-driven decisions and implement timely preventive measures. Mobile climate advisory services, for instance, have successfully reduced livestock losses and increased farm income.
- Precision Livestock Farming (PLF) and Data-enabled Innovations: PLF uses technology to monitor, manage, and optimize livestock production in real-time. This includes IoT-enabled sensors for continuous monitoring of environmental parameters (temperature, humidity, noxious gases) and animal physiological metrics (heart rate,

body temperature, activity levels), enabling early detection of heat stress or illness. Advanced analytics and machine learning can process this data for decision support, predicting risks and recommending optimal practices.

- Climate-Smart Agriculture (CSA): This comprehensive approach integrates adaptation and mitigation, focusing on optimizing resource use and reducing GHG emissions while enhancing productivity. Key interventions include precision breeding for resilience, improving feed efficiency, promoting integrated crop-livestock systems, water-efficient irrigation, enhanced pasture management, agroforestry, and rotational grazing. CSA emphasizes sustainable land management and biodiversity conservation.
- Institutional and Policy Frameworks: Strong regulatory support and integration of climate adaptation policies into national development plans are essential for sector-wide resilience and long-term sustainability. This includes developing a clear "Climate Change Adaptation Strategy for the Livestock Sector" to guide governments and stakeholders.
- Capacity-Building Initiatives: Empowering livestock keepers and farmers through training in areas like heat stress management, fodder production, and financial literacy is crucial. Strengthening local authorities, civil society organizations, and the private sector ensures robust climate risk management and scalable adaptation measures.
- Agricultural Insurance: As a critical risk management tool, agricultural insurance mitigates economic shocks from climate change, helps farmers quickly resume production, and enhances their debt repayment capacity, thereby alleviating credit constraints. It is vital to promote these systems, designing products tailored to local conditions. However, challenges like farmers' lack of liquidity, limited access to credit and information, and high administrative costs often hinder widespread adoption.

4.3. Overcoming Barriers to Climate Finance Flow

Despite the clear need and existing strategies, several significant barriers prevent climate finance from effectively reaching the agricultural sector.

- Inadequate Enabling Environments: This includes a lack of supportive policies, clear property rights systems, and collateral registries for movable assets, which impede financiers' risk management and farmers' access to loans.
- Insufficient Capacity: Both FIs and farmers often lack the capacity and expertise to assess and manage climate-specific agricultural risks, or to identify and adopt climate-smart practices. Countries may also lack the readiness to access available climate finance due to insufficient technical capacity.
- High Transaction Costs: Providing financial services to numerous smallholder farmers involves high transaction costs for FIs, making lending less attractive.
- Information Asymmetry: A mismatch of information exists between those needing financing (farmers) and potential investors, often due to farmers' limited financial literacy or investors' lack of awareness about viable climate-smart initiatives.

- Lack of Suitable Financial Products: Traditional financial products are often not customized for the unique requirements of climate-smart agricultural investments, which often require substantial upfront capital and longer repayment maturities.
- Insufficient Evidence Base and Metrics: There is a lack of adequate research to identify the most suitable context-specific climate-smart interventions and to accurately measure their impact and financial returns.
- Fragmentation of Climate Finance: A large proportion of global climate finance has historically been directed to sectors like energy, which can demonstrate "quick wins" in GHG reduction, leading to underfunding of agriculture.

To overcome these barriers, climate finance can support various initiatives:

- Promoting Public-Private Partnerships (PPPs): PPPs can combine resources, expertise, and diverse risk appetites from different stakeholders to leverage additional capital.
- Innovative Investment Vehicles: Designing layered capital structures and blended finance mechanisms can diversify risk and attract private investors by offering tailored risk-return profiles.
- Bundling Financial Instruments with Technical Assistance: Combining financial support (e.g., grants, loans, guarantees) with capacity-building services offers more comprehensive solutions to FIs and farmers.
- Improving the Enabling Environment: This involves establishing sound public policies and regulations in agriculture finance, property rights, and contract enforcement, alongside developing effective climate-smart guidelines and screening tools.
- Strengthening Risk Management Mechanisms: This includes developing rural credit ratings agencies with climate-smart components, establishing effective credit guarantee schemes, and designing appropriate agricultural insurance products.
- Reducing Transaction Costs: Innovations like branchless banking, mobile financial services, and the use of big data analytics can lower the cost of delivering financial services to remote farmers and assessing their creditworthiness.

Conclusion

Climate change poses a major threat to global food systems, especially in low- and middle-income countries. It reduces crop and livestock productivity through heat, disease, and extreme weather, leading to lower incomes and tougher credit conditions for farmers. This also increases risks for banks and insurers. Climate finance—through grants, loans, and guarantees—can support climate-smart farming, new technologies, and early warning systems. But challenges like weak institutions, low financial literacy, and high costs slow progress. To build resilient agriculture, we need stronger partnerships, better financing, and shared commitment. Adapting now is key to ensuring future food security and sustainable growth.

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Published by National Institute of Agricultural Extension Management (MANAGE), Hyderabad

SAFE GUARDING DAIRY ANIMAL HEALTH IN A CHANGING CLIMATE

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Abstract
Climate change poses significant challenges to global agriculture, particularly the dairy sector, through its impacts on animal health, productivity, and welfare. Rising temperatures, erratic rainfall patterns, extreme weather events, and changing disease epidemiology threaten the sustainability of dairy farming. High-yielding dairy breeds are especially vulnerable to heat stress and emerging diseases, while smallholder farmers often face economic and resource constraints in adapting to these challenges. This chapter explores the drivers of climate change, its direct and indirect effects on dairy animal health, and the multifaceted strategies required to mitigate these impacts. Emphasis is placed on heat stress management, disease prevention, resource conservation, technological innovations, and policy support. Drawing on recent research and case studies from India and globally, the chapter highlights practical approaches for building climate resilience in the dairy sector. The discussion underscores the importance of integrating scientific knowledge, farmer training, and collaborative networks to safeguard animal welfare and secure livelihoods in a changing climate.

Key Words:
Climate change, dairy animals, heat stress, disease management, livestock resilience, adaptation strategies, animal welfare

1. Introduction

Climate change has emerged as a defining environmental, economic, and social challenge of the 21st century. The Intergovernmental Panel on Climate Change (IPCC, 2023) has reported a 1.1°C rise in average global temperatures since pre-industrial times, with cascading effects on ecosystems and human livelihoods. In the dairy sector, climate change impacts are particularly acute due to the physiological sensitivity of dairy animals to temperature, humidity, and disease exposure. High-yielding breeds, such as Holstein Friesians, are especially vulnerable to heat stress, which reduces feed intake, reproductive performance, and milk yield. Moreover, shifts in precipitation patterns and disease vector distributions are increasing the prevalence of infectious and parasitic diseases. Addressing these challenges requires a combination of scientific research, practical farm-level adaptations, and supportive policy frameworks.

2. Climate Change and the Dairy Sector

Dairy farming is a climate-sensitive enterprise that relies heavily on stable environmental conditions, and climate change affects these systems through both direct and indirect pathways. Direct impacts include heat stress and altered metabolic functions in animals, while indirect effects involve reduced forage quality, shifts in disease epidemiology, and increased water scarcity (FAO, 2022). In regions such as South Asia, rising temperatures and more frequent heatwaves have already been linked to a 10–25% reduction in milk yields in some herds. The dual pressures of higher energy requirements for thermoregulation and reduced nutrient intake result in lower production efficiency and heightened disease susceptibility. Climate change—defined as long-term alterations in temperature, precipitation, wind patterns, and other aspects of the Earth's climate system—further compounds these challenges by causing higher ambient temperatures, erratic rainfall, prolonged droughts, the emergence of new diseases, and a decline in both the availability and quality of forage, ultimately threatening animal health, productivity, and the overall sustainability of dairy farming.

3. Drivers of Climate Change

The drivers of climate change can be grouped into natural and anthropogenic categories. Natural drivers include variations in solar radiation, volcanic eruptions, and changes in Earth's albedo. However, since the Industrial Revolution, anthropogenic greenhouse gas (GHG) emissions have been the dominant driver. The livestock sector contributes significantly to methane (CH_4) emissions through enteric fermentation and nitrous oxide (N_2O) emissions from manure management (Herrero et al., 2023). According to the FAO (2023), livestock contributes 14.5% of global anthropogenic GHG emissions, with dairy production accounting for approximately 20% of that share. This dual role of livestock—as both a victim and contributor to climate change—necessitates strategies that mitigate emissions while enhancing resilience.

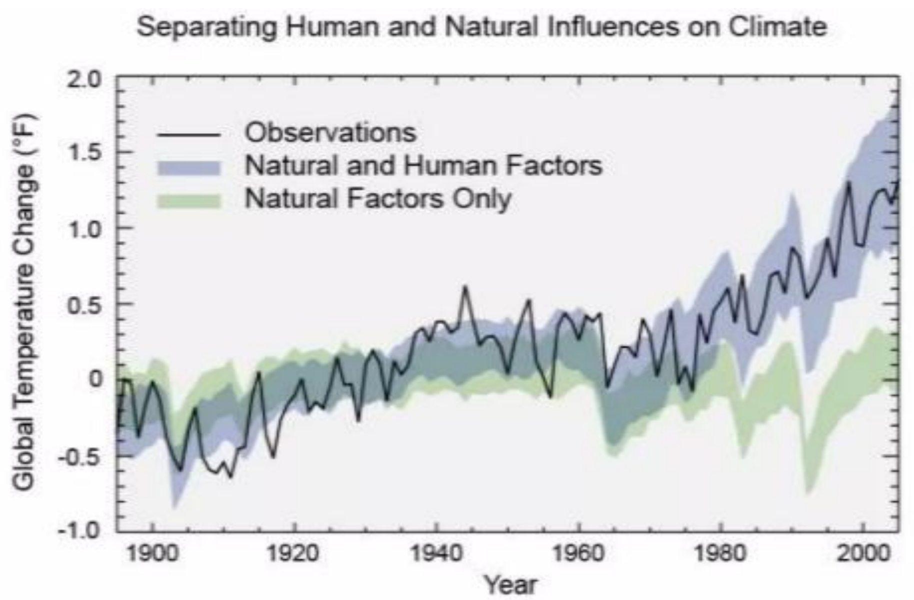


Fig.1 Human-induced climate change – mainly from increasing atmospheric concentrations of heat-trapping greenhouse gases

4. Impacts of Climate Change on Dairy Animal Health

The impacts of climate change on dairy animals are multifaceted, affecting physiology, immunity, and productivity. Heat stress occurs when the Temperature-Humidity Index (THI) exceeds 68, impairing rumination, feed intake, and milk synthesis. Physiological signs include increased respiration rate, elevated rectal temperature, and reduced blood flow to the gastrointestinal tract, impairing nutrient absorption (Polsky & von Keyserlingk, 2023). Disease dynamics are also shifting, with vector-borne diseases like bluetongue, lumpy skin disease, and Rift Valley fever expanding their geographical range. Additionally, nutritional challenges arise from drought-induced forage shortages, while mycotoxin contamination increases during humid periods. Reproductive efficiency is reduced due to suppressed estrus expression, lower conception rates, and decreased embryo survival.

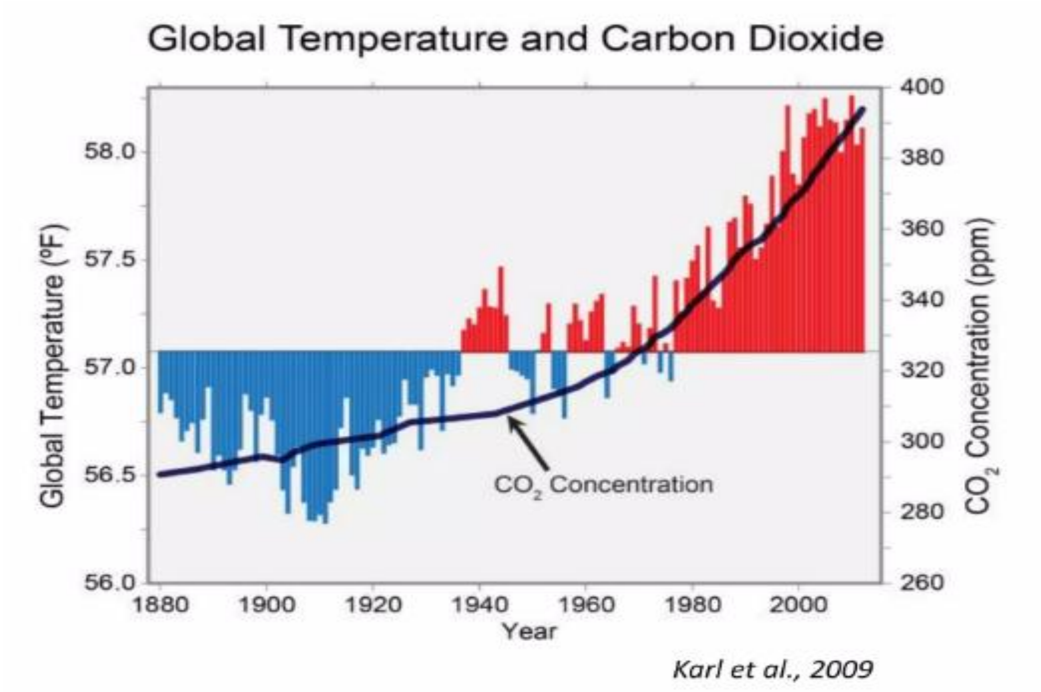


Fig.2 Temperature and CO2 Levels

Heat Stress

- Rising temperatures and prolonged heatwaves are among the most significant challenges.
- Dairy cows, particularly high-yielding breeds like Holsteins, are highly susceptible to heat stress when the Temperature-Humidity Index (THI) exceeds 68.

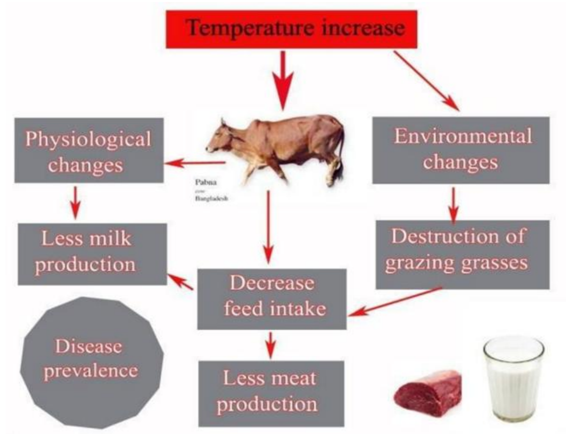
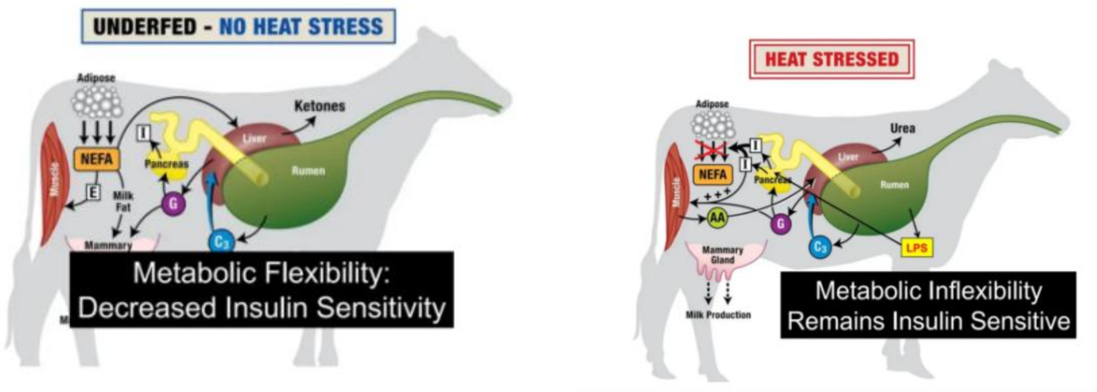


Fig.3 Effect of temperature



- Heat stress reduces feed intake, impairs reproductive performance, and lowers milk yield by 10-25% in severe cases.
- Physiological responses include increased respiration rates, elevated body temperatures, and compromised immune function, making animals more vulnerable to diseases.

5. Key Challenges in Dairy Animal Health Management

Managing dairy animal health under climate change is hindered by multiple challenges. Economic constraints limit farmers' ability to invest in cooling infrastructure and water management systems. Knowledge gaps persist, particularly in smallholder systems, where access to region-specific climate and disease data is limited. Breed vulnerability remains a concern, as high-yielding exotic breeds are less heat tolerant than indigenous breeds. Policy and institutional gaps also constrain adaptation, with insufficient extension services and financial incentives for climate-resilient farming practices.

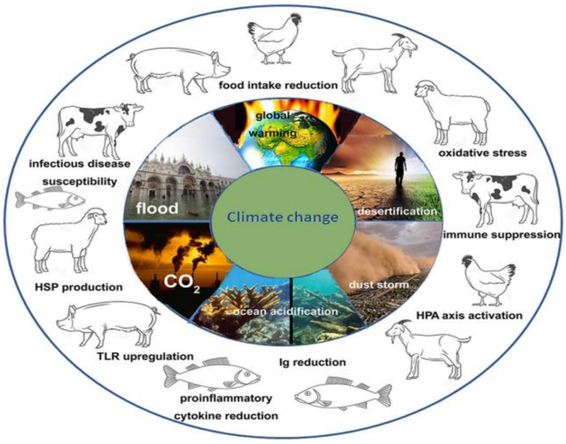


Fig.4 Indirect impacts of climate change

Reduced Forage Quality and Quantity:

Fluctuations in temperature, carbon dioxide levels, and precipitation patterns negatively affect the quantity and nutritional quality of pastures and crops used for animal feed.

Water Scarcity and Quality Degradation:

Changes in precipitation patterns, glacier melt, and increased evaporation can lead to water shortages. Floods can contaminate water sources with pathogens and pollutants, impacting animal health and water intake.

Changing Disease Patterns

Climate change is significantly altering the epidemiology of infectious diseases, with warmer temperatures and shifting precipitation patterns expanding the range of vectors such as ticks and mosquitoes, thereby increasing the prevalence of diseases like bovine anaplasmosis and bluetongue. Prolonged wet seasons can exacerbate parasitic infections such as liver fluke, while drought conditions may concentrate pathogens in scarce water sources, heightening the risk of disease transmission and posing serious challenges to livestock health and productivity.

Resource Scarcity

Climate variability directly impacts the availability and quality of feed and water, with droughts reducing pasture growth and forage quality, leading to nutritional deficiencies that weaken animal immunity. Water scarcity, especially in arid regions, compromises both hydration and cooling, thereby exacerbating heat stress in livestock. Additionally, increasing competition for limited resources between human and livestock populations can further strain dairy farm operations, affecting productivity and sustainability.

Diseases affected by climate change:

Climate change has a profound impact on the distribution, prevalence, and transmission dynamics of various infectious and vector-borne diseases. For example, increased temperatures and changes in bird migration patterns can influence the spread of avian influenza, while warmer conditions combined with higher rainfall create favorable breeding environments for mosquitoes, raising the risk of West Nile virus and mosquito-borne diseases such as Rift Valley fever. Similarly, changes in tick habitats and activity levels can contribute to the wider spread of Lyme disease and tick fever. In livestock, rising midge populations driven by climatic shifts can lead to outbreaks of bluetongue and African horse sickness, while wetter seasons may trigger the emergence or re-emergence of diseases like lumpy skin disease, Foot and Mouth Disease (FMD), and haemorrhagic septicaemia. In addition to health threats, climate variability imposes significant nutritional challenges, as droughts and floods reduce the quality and quantity of forage, hot and humid conditions increase the risk of mycotoxin contamination in feeds, and heat damage lowers feed digestibility, collectively undermining animal health, immunity, and productivity. Heat stress poses significant reproductive challenges in livestock by reducing oestrus expression, lowering conception rates, and decreasing embryo survival, ultimately impairing breeding efficiency and productivity.

Zoonotic Diseases

Many animal diseases are zoonotic, meaning they can be transmitted from animals to humans, and climate change is increasingly influencing their transmission dynamics, posing risks to both animal and human health. Warmer temperatures and increased rainfall can expand the habitat of Aedes mosquitoes, facilitating the spread of dengue fever, while changes in temperature and precipitation patterns can impact the breeding and survival of Anopheles mosquitoes, increasing malaria transmission. Similarly, shifts in climate can alter the distribution of sand-flies, enhancing the risk of leishmaniasis, and warmer temperatures coupled with milder winters can prolong tick activity, leading to a rise in Lyme disease cases.

Key Challenges in Dairy Animal Health Management

Adapting to the impacts of climate change in dairy animal health management presents several key challenges. Economic constraints are a major barrier, as implementing climate-resilient infrastructure such as cooling systems, improved housing, or water harvesting facilities requires substantial investment that may be unaffordable for smallholder farmers. Knowledge gaps further limit adaptation, with many farmers lacking access to region-specific climate impact data and practical guidance on adaptation strategies. Breed vulnerability also poses a risk, as high-yielding dairy breeds, bred for temperate climates, are often less resilient to heat stress and disease than indigenous breeds, necessitating strategic genetic management. Additionally, policy and support gaps—such as inconsistent government assistance and inadequate extension services—continue to hinder the widespread adoption of sustainable and climate-smart dairy farming practices.

Safeguards and Mitigation Strategies

Strategies for safeguarding dairy animal health can be grouped into five key areas: (1) Mitigating heat stress through housing modifications, shade provision, and misting systems; (2) Disease prevention via vaccination, vector control, and biosecurity measures; (3) Ensuring resource availability through water harvesting, feed diversification, and pasture management; (4) Leveraging technology such as precision livestock farming tools for early disease detection;

and (5) Strengthening policy and community support through training, insurance schemes, and farmer cooperatives (Rahman et al., 2021; IPCC, 2023).

Environmental Modifications:

Environmental modifications can play a crucial role in mitigating heat stress in dairy animals. Installing cooling systems such as fans, misters, and sprinklers in barns helps reduce ambient temperatures, while providing shaded areas in pastures and ensuring adequate ventilation in housing facilities improves overall animal comfort. For instance, studies have shown that misting systems can lower the Temperature-Humidity Index (THI) by 5–10 units, significantly alleviating heat stress and enhancing animal welfare and productivity.

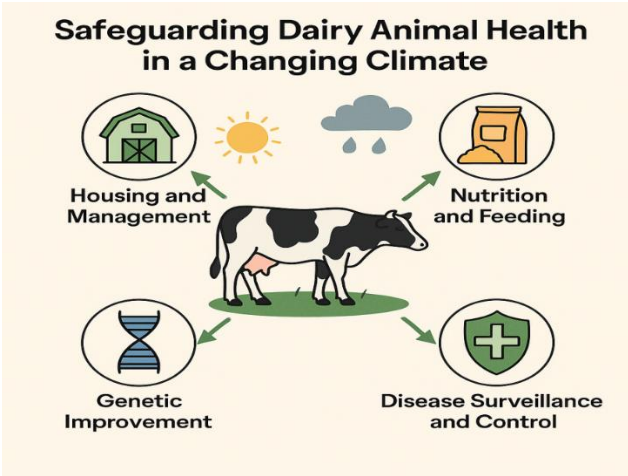


Fig.5. Safeguarding dairy animal health in a changing climate

Disease Prevention and Control

Effective dairy animal health management under climate change requires a multifaceted approach that combines disease prevention, resource security, and innovative technologies. Robust vaccination programs for climate-sensitive diseases, coupled with strengthened biosecurity measures, regular deworming, and vector control strategies such as insecticide-treated netting, can significantly reduce the risk of parasitic and vector-borne infections. Early warning surveillance systems—integrating satellite data with veterinary monitoring—can predict vector population surges, enabling timely interventions, while wearable sensors for tracking vital signs such as body temperature and activity levels facilitate early detection of health problems exacerbated by climate stress. Ensuring resource availability is equally vital, with investments in rainwater harvesting, efficient irrigation, and regular water quality testing safeguarding hydration needs, and feed security strengthened through drought-resistant crops like sorghum, silage production, and rotational grazing with climate-resilient forage species. Building resilience through technology and innovation involves leveraging precision agriculture tools, such as IoT-based climate monitoring systems, to adjust barn conditions in real time, and using climate models alongside farm management software for data-driven decision-making supported by tailored extension advisories. Additionally, renewable energy solutions, including solar-powered cooling systems and water pumps, can reduce operational costs, enhance sustainability, and ensure reliable farm operations, particularly in off-grid or resource-constrained regions.

5. Policy and Community Support

Policy and community support for climate resilience should focus on strengthening agricultural extension services to educate farmers on climate-smart practices, while organizing specialized workshops on heat stress management and disease prevention to empower smallholder farmers. Financial mechanisms such as targeted subsidies, low-interest loans for infrastructure upgrades, and climate risk–specific insurance schemes can provide essential safety nets and reduce vulnerability. Collaborative networks involving research institutions, governments, and farmer groups are vital for sharing knowledge, fostering innovation, and coordinating action. Additionally, community-based initiatives, such as cooperative feed banks, water harvesting systems, and collective marketing, can enhance local resilience and ensure resource security in the face of climate challenges.

Case Studies and Success Stories

In India, the National Dairy Development Board (NDDB) has implemented crossbreeding programs combining high-yielding breeds with indigenous breeds like Gir and Sahiwal, improving heat tolerance and productivity. In East Africa, community-led disease surveillance has reduced tick-borne disease incidence by 20%. In Australia, precision agriculture tools have enabled efficient water use, sustaining herd health during prolonged droughts.

8. Conclusion

Safeguarding dairy animal health in a changing climate demands an integrated approach that combines scientific research, farm-level adaptation, and enabling policy environments. Heat stress, emerging diseases, and resource scarcity are interconnected challenges that require collaborative action among farmers, researchers, and policymakers. By investing in technology, capacity building, and sustainable practices, the dairy sector can enhance resilience and protect both animal welfare and rural livelihoods.

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Published by National Institute of Agricultural Extension Management (MANAGE), Hyderabad

Chapter-10

TECHNOLOGICAL OPTIONS TO MITIGATE CLIMATE CHANGE FOR SUSTAINABLE LIVESTOCK PRODUCTION

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Abstract

The livestock sector is a major contributor to global greenhouse gas (GHG) emissions, particularly methane (CH_4) from enteric fermentation and nitrous oxide (N_2O) from manure management. These emissions contribute significantly to climate change, necessitating sustainable solutions that balance productivity with environmental protection. Climate-smart livestock production integrates mitigation and adaptation strategies to enhance resource efficiency, improve animal welfare, and maintain livelihoods. This chapter reviews recent technological and management interventions-improved feeding strategies, sustainable manure management, land use optimization, breeding and genetics, and advanced monitoring technologies-highlighting their potential to reduce emissions. Drawing on recent literature (2020–2024), the chapter provides a holistic perspective on sustainable livestock systems, emphasizing the need for multi-pronged, context-specific approaches. Future research directions are outlined to guide innovation in climate-resilient livestock production.

Key Words: climate change, livestock production, greenhouse gas mitigation, methane, carbon sequestration, sustainable agriculture

1. Introduction

Livestock systems contribute approximately 14.5% of total anthropogenic GHG emissions globally, with methane accounting for over 40% of the sector's climate footprint (FAO, 2023). In India, the livestock sector is the backbone of rural livelihoods, contributing nearly 4.35% to the national GDP and supporting over 70 million rural households (DAHD, 2024). However, the sector faces increasing vulnerability to climate variability, including heat stress, feed scarcity, and disease outbreaks (Patra, 2022). Climate-smart livestock production is a holistic approach aimed at enhancing productivity while reducing environmental impacts. It combines adaptation measures—such as heat-tolerant breeds and water-efficient feeding systems—with mitigation strategies that directly target emission reduction. According to the IPCC (2022), both adaptation and mitigation are critical for sustainable development in livestock systems, particularly in climate-sensitive regions like South Asia.

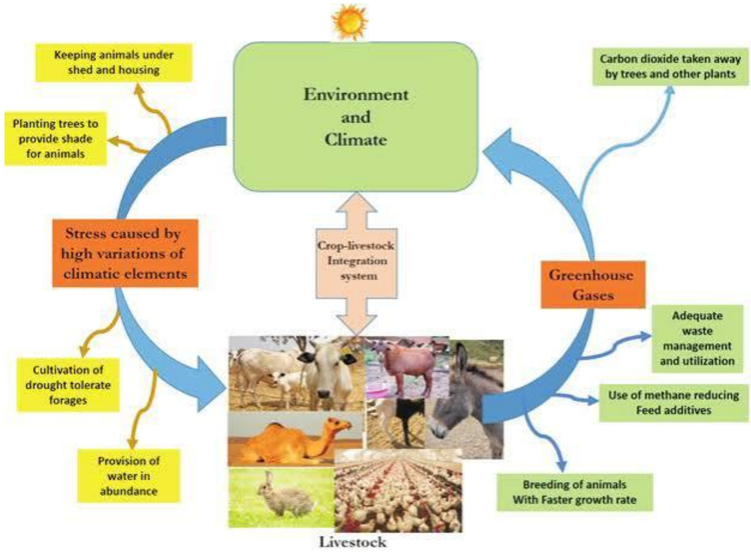

Fig.1 Climate change mitigation as defined by IPCC is the anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gasses

2. Adaptation and Mitigation Framework

Adaptation

Adaptation refers to the deliberate adjustments in natural or human-managed systems in response to observed or anticipated climatic stimuli, aimed at moderating harm or exploiting beneficial opportunities (IPCC, 2022). In the context of livestock production, adaptation is essential to safeguard animal health, productivity, and farm livelihoods under increasingly variable climatic conditions. Key adaptation strategies include:

- **Climate-resilient housing:** Designing and constructing livestock shelters with improved ventilation, reflective roofing materials, and insulation to reduce heat stress and maintain optimal microclimatic conditions.
- **Heat stress management:** Implementing cooling systems such as foggers, sprinklers, and shaded resting areas; adjusting feeding schedules to cooler parts of the day; and providing ad libitum access to clean drinking water.
- **Grazing schedule modification:** Rescheduling or rotational grazing to minimize livestock exposure to extreme heat, drought, or heavy rainfall, thereby preventing pasture degradation.
- **Breed diversification:** Incorporating heat-tolerant, drought-resilient, and disease-resistant indigenous or crossbred livestock varieties adapted to local agro-climatic zones.

Adaptation measures are location-specific and require participatory approaches involving farmers, extension agents, and researchers to ensure long-term resilience of livestock-based livelihoods.

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2.2 Mitigation

Mitigation, as defined by the Intergovernmental Panel on Climate Change (IPCC, 2022), refers to anthropogenic interventions aimed at reducing the sources or enhancing the sinks of greenhouse gases (GHGs). In livestock systems, mitigation efforts are directed towards lowering methane (CH_4) emissions from enteric fermentation, nitrous oxide (N_2O) emissions from manure and soils, and carbon dioxide (CO_2) emissions from energy use.

Key livestock mitigation pathways include:

Enhancing feed conversion efficiency: Improving forage quality, optimizing ration formulation, and adopting feed additives (e.g., tannins, 3-nitrooxypropanol, seaweed extracts) to reduce methane intensity per unit of product.

Carbon sequestration in soils and biomass: Integrating agroforestry, silvopastoral systems, and rotational grazing to increase carbon storage in pasture soils and vegetation.

Optimizing manure management: Employing anaerobic digestion to capture methane for biogas production, composting to stabilize organic matter, and covered storage to reduce gaseous losses.

Circular bio economy integration: Utilizing livestock waste streams as raw materials for energy, fertilizer, and industrial products, thereby minimizing resource loss and closing nutrient cycles.

Energy efficiency measures: Using renewable energy (solar, wind) for water pumping, lighting, and cooling systems in livestock farms to lower CO_2 emissions from fossil fuel use. Mitigation strategies must be economically viable, socially acceptable, and environmentally sustainable to ensure adoption at scale. Integrating these interventions with adaptation measures creates synergistic benefits, leading to climate-resilient and low-carbon livestock systems.

3. Technological and Management Options

3.1 Improved Feeding Strategies

Enhanced Feed Quality and Digestibility: High-quality forages, processed grains, and improved digestibility reduce methane yield per unit of product. Supplementation with feed additives such as 3-nitrooxypropanol (3-NOP) has been shown to significantly reduce enteric methane emissions in dairy cattle (Hristov et al., 2022). Seaweed Additives: Asparagopsis taxiformis supplementation has achieved methane reductions of up to 98% in beef cattle trials (Kinley et al., 2022). Precision Feeding: AI-powered platforms optimize nutrient delivery, reducing waste and improving productivity.

3.2 Sustainable Manure Management

Manure is a significant source of methane (CH_4) and nitrous oxide (N_2O) emissions due to anaerobic decomposition and nitrogen transformations. Sustainable manure management aims to minimize these emissions while recovering valuable nutrients and energy.

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- **Anaerobic Digestion:** This technology captures methane produced during manure decomposition and converts it into biogas, which can be used for electricity, heating, or as a renewable vehicle fuel. Compared to conventional storage, anaerobic digestion can reduce GHG emissions by over **30%**, while also providing pathogen reduction and odor control benefits (Wang et al., 2021).
- **Improved Storage and Handling:** Covering manure lagoons, using impermeable covers, and increasing the frequency of manure removal from animal housing reduce anaerobic conditions and subsequent methane formation. Practices such as solid–liquid separation can further reduce emissions and facilitate targeted nutrient management (Zhao et al., 2023).
- **Nutrient Recycling and Precision Application:** Composting stabilizes organic matter, reduces N_2O losses, and produces a valuable soil amendment. Precision nutrient application—applying manure at the right time, rate, and location—reduces reliance on synthetic fertilizers and prevents nutrient leaching into water bodies.

3.3 Land Use Management and Carbon Sequestration

Rotational Grazing: Improves soil organic carbon and reduces erosion (Lal, 2021). Silvopastoral Systems: Store substantially more carbon compared to open pastures (Murgueitio et al., 2022). Avoiding Land-Use Change: Preserves existing carbon sinks, especially in forest margins.

- **Rotational Grazing:** Managed rotational grazing improves pasture productivity, increases soil organic carbon, and reduces erosion by allowing rest periods for pasture recovery (Lal, 2021).
- **Silvopastoral Systems:** Integration of trees, shrubs, and forage species within grazing systems can enhance carbon sequestration by **27–163%** compared to open pastures, while improving biodiversity and providing shade for animals (Murgueitio et al., 2022).
- **Avoiding Land-Use Change:** Preventing deforestation and the conversion of grasslands to cropland helps conserve existing carbon stocks in biomass and soil, avoiding large emissions pulses.

3.4 Breeding and Genetics

Low-Methane Genotypes: Selection for feed efficiency and reduced methane intensity (Rowe et al., 2023). Disease Resistance: Healthier animals have lower emission intensities due to reduced unproductive periods. Genetic improvement offers a long-term, cumulative pathway to reducing livestock GHG emissions.

- **Low-Methane Genotypes:** Selecting animals with inherently higher feed conversion efficiency and lower residual methane production can reduce emissions per unit of output. Modern genomic tools enable the identification and propagation of such traits (Rowe et al., 2023).
- **Disease Resistance:** Breeding for disease resistance improves animal health and longevity, reducing unproductive periods and the overall emissions intensity of production.

3.5 Advanced Technological Interventions

Virtual Fencing & GPS Tracking: Reduce overgrazing and optimize land use (Anderson et al., 2023). AI and IoT Monitoring: Real-time tracking of feed intake, health, and emissions. Digital innovations and smart farming tools are increasingly important in climate-smart livestock systems.

- **Virtual Fencing and GPS Tracking:** These technologies use GPS-enabled collars and remote signals to manage livestock movement without physical fences. This reduces overgrazing, optimizes pasture utilization, and allows flexible grazing rotations (Anderson et al., 2023).
- **AI and IoT Monitoring:** Artificial intelligence (AI) and Internet of Things (IoT) sensors can track animal health, feed intake, and emission outputs in real time. This data enables precision management, early disease detection, and evidence-based mitigation planning.

4. Importance of a Multi-Pronged Approach

Mitigating climate change in the livestock sector requires an integrated approach that combines nutritional interventions, manure management, land-use optimization, genetic improvement, and digital technologies. Policies that provide financial incentives for adoption, facilitate access to markets for low-carbon livestock products, and promote participatory research with farmers are critical for scaling these solutions. Collaborative action among scientists, policymakers, industry stakeholders, and producers will be essential to transform the livestock sector into a low-emission, climate-resilient system.

5. Future Research Directions

Future research should focus on strengthening the scientific foundation and practical application of climate change mitigation strategies in livestock systems. Long-term, multi-season field trials are needed to evaluate the effectiveness of methane-reducing feed additives such as 3-nitrooxypropanol, tannin-rich legumes, and seaweed supplements under diverse tropical and subtropical farming conditions, assessing not only emission reductions but also animal health, productivity, and cost-effectiveness. Comprehensive cost–benefit analyses of biogas systems for smallholders are essential to determine their technical performance, economic viability, and socio-environmental benefits, with particular emphasis on affordability and scalability in resource-limited contexts. Integrated breeding programs that combine resilience traits-such as heat tolerance and disease resistance-with low-emission genetic profiles should be prioritized, supported by modern genomic selection tools. In parallel, context-appropriate models for integrating digital agriculture technologies, including AI and IoT-based monitoring systems, must be developed for rural and low-resource environments to ensure accessibility, ease of use, and reliable connectivity. Finally, research into market-based incentives for low-carbon livestock products, including consumer demand, certification mechanisms, and value-chain integration, will be crucial to link environmental stewardship with economic returns, thereby accelerating the adoption of climate-smart livestock practices.

Conclusion

Future progress in mitigating climate change within the livestock sector depends on strengthening both the scientific foundation and the practical application of proven and emerging strategies. Priority areas include conducting long-term, multi-season field trials to evaluate the effectiveness of methane-reducing feed additives-such as 3-nitrooxypropanol, tannin-rich legumes, and seaweed supplements-under varied tropical and subtropical farming systems, with a focus on emissions reduction, animal health, productivity, and cost-effectiveness. Equally important are comprehensive cost–benefit analyses of biogas systems for smallholders to determine technical performance, economic viability, and socio-environmental benefits, particularly with respect to affordability and scalability in resource-constrained settings. Integrated breeding programs that combine resilience traits-such as heat tolerance and disease resistance-with low-emission genetic profiles, supported by advanced genomic selection tools, will play a critical role in building climate-resilient herds. Furthermore, developing context-specific models for the integration of digital agriculture technologies, including AI and IoT-based monitoring, is essential to ensure accessibility, affordability, and reliability in low-resource environments. Finally, fostering market-based incentives for low-carbon livestock products-through consumer awareness, certification schemes, and value-chain alignment-will be pivotal in linking environmental stewardship with tangible economic rewards, thereby accelerating the widespread adoption of climate-smart livestock practices.

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Published by National Institute of Agricultural Extension Management (MANAGE), Hyderabad

WEATHER FORECASTING AND CLIMATE ADVISORY SERVICES FOR DAIRY FARMERS

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Abstract

Dairy farming is a major livelihood in India, involving around 70% of rural households and contributing nearly 30% to the agricultural GDP with a 5% share in the national economy. It ensures food security and income for over 80 million farmers, particularly smallholders and women. However, the sector is highly vulnerable to weather extremes such as heatwaves, cold spells, heavy rainfall and droughts, which adversely affect animal health and milk production. To manage these risks, the India Meteorological Department (IMD) along with AMFUs and DAMUs, provides localized daily weather forecasts, nowcasts, impact based advisories and biweekly agromet advisories. These services support climate-resilient decisions in feeding, breeding, shelter and disease control. The benefit-cost ratio of climate services were found to be 1:1.8. Exclusive advisories for Murrah buffalo farmers have proven effective in enhancing adaptive capacity. Overall, climate services are vital for promoting resilient and sustainable dairy farming under changing climate conditions.

Key Words: weather, advisory, dairy, forecasting, resilience and decision-making

1. Introduction

Livestock production is an essential component of world agriculture, contributing to food security, nutrition, poverty alleviation and economic growth. About 30% of the Earth's terrestrial areas are occupied with livestock systems, sustaining the livelihood of marginal farmers. In modern agriculture and livestock management, effective planning demands more than a basic weather report. For farmers and agribusinesses, accurate and timely weather forecast is critical, as they directly impact decisions that affect crop productivity and animal health. The influence of weather on agriculture and livestock is profound. Livestock, particularly beef and dairy cattle are highly vulnerable to temperature fluctuations. Heat stress is a major concern in warmer climates, often resulting in decreased milk production, reduced weight gain and in severe cases, even death. To monitor and manage this risk, the Heat Load Index (HLI) is used, a key indicator that integrates temperature, humidity and wind speed to assess the potential level of heat stress in cattle.

2. History

In India, milk is valued not merely as a dietary staple but as a symbol of cultural and historical importance. It holds a cherished place in the daily lives and traditions of the Indian people. The story of organized dairy development in India began in 1891, when the British administration, recognizing the crucial importance of quality milk for maintaining the health of troops stationed across the subcontinent, established the first military dairy farms. These were not mere makeshift setups in cantonment corners - they were well-planned, systematic facilities designed to ensure a consistent supply of safe and nutritious milk for soldiers serving far from home. These military dairy farms went on to become the earliest laboratories for modern dairy science in India.

The year 1920 marked a significant milestone in the history of Indian dairy development with the appointment of the first Imperial Dairy Expert. This individual played a dual role, serving both as an advisor and an implementer to bridge the gap between scientific knowledge and practical application

The Royal Commission of Agriculture, established during this period, played a vital role in evolving dairy development from a fragmented set of military-driven initiatives into a well-structured and cohesive policy framework. One of the most forward-thinking aspects of pre-independence dairy policy was its integration with broader agricultural development strategies. Policymakers recognized that dairy farming could not be developed in isolation, it had to be embedded within a comprehensive agricultural framework that encompassed crop cultivation, animal husbandry and market infrastructure development.

Dairy development initiatives undertaken during the pre-independence era laid a strong foundation that became instrumental in shaping India's post-independence progress in the sector. Building on these early efforts, institutions led by Dr. Verghese Kurien launched Operation Flood - a landmark dairy development program that catalyzed India's transformation from a milk-deficient nation to the world's largest milk producer.

3. Present status

India stands as the proud custodian of the world's largest livestock population, exceeding 537 million animals. This sector plays a vital role in driving economic growth, enhancing rural livelihoods and ensuring nutritional security for millions. As the global leader in milk production, India's livestock resources continue to be a foundational strength of the agricultural sector, contributing significantly to the sustained advancement of the national economy. Additionally, Indian households allocate nearly 45% of their food budget to dairy and packaged foods, reflecting the central role of dairy in the nation's dietary habits and nutritional security.

India's dairy industry is the largest in the world, accounting for approximately 24% of global milk production. As of 2024, the Indian dairy market was valued at ₹18,975 billion and is projected to grow at a compound annual growth rate (CAGR) of 12.35% from 2025 to 2033. By 2033, the market is expected to reach ₹57,001.8 billion. The sector contributes around 5% to the national economy and provides direct livelihood support to over 80 million farmers, with women forming a significant portion of the workforce. The per capita availability of milk in

India has improved significantly, reaching 459 grams per day in 2022-23, which is notably higher than the global average of 322 grams per day. Inspite of being the largest producer of milk globally (accounting for 24% of world production), India's share in global dairy exports is only about 0.25%. This low percentage highlights a disparity between production capacity and export activity.

From 2014–15 to 2023–24, India's milk production grew at a compound annual growth rate (CAGR) of 5.62%, rising from 146.31 million tonnes to 239.3 million tonnes. The country also possesses the world's largest livestock population, comprising 536.76 million animals - including 303.76 million bovines and 148.8 million goats.

Key milk-producing states include Uttar Pradesh, Maharashtra, Himachal Pradesh, Madhya Pradesh, Punjab, Rajasthan and Tamil Nadu. The Indian dairy sector is witnessing rapid expansion, driven by increased consumption of milk and dairy products and a growing preference for health-oriented nutritional choices among consume.

4. Structure of Indian Dairy Industry

Unlike the West, India's dairy industry is highly unorganised. About 60% surplus milk is handled by the unorganised sector (milkmen), while the remaining 40% is procured by the organised sector comprising dairy co-operatives and private companies. In developed countries, about 90% surplus milk is handled through the organised sector (Figure 1). Additionally, per animal yields remain low, raising concerns about the long-term sustainability of the sector. Inspite of being the largest producer of milk globally (accounting for 24% of world production), India's share in global dairy exports is only about 0.25%. This low percentage highlights a disparity between production capacity and export activity.

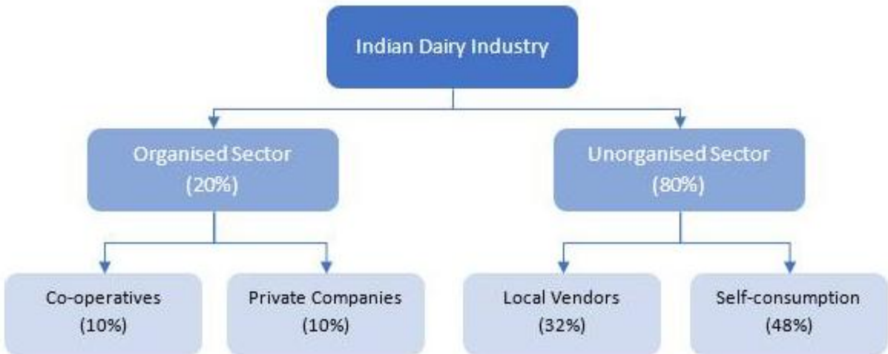

Fig. 1. Structure of Indian Diary Industry
(Source: Department of Animal Husbandry, Dairying & Fisheries, Ministry of Agriculture and Farmers Welfare &GOI)

5. State Wise Dairy Production

Uttar Pradesh emerged as the leading state in dairy production during 2023–24, contributing 16% of India's total milk output. It was followed by Rajasthan (14%), Madhya Pradesh (9%),

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Gujarat (8%) and Maharashtra (7%) (Figure 2). The country's overall milk production for the year reached approximately 239.3 million tonnes. India's dairy production is primarily concentrated in the northern and western states, with Uttar Pradesh, Rajasthan and Gujarat at the forefront. Tamil Nadu, Maharashtra and Madhya Pradesh also make significant contributions. As the most populous state with a predominantly agrarian economy, Uttar Pradesh has the highest number of dairy animals in the country, playing a central role in national milk production. The state's dairy sector thrives due to strong government support, a vast network of milk cooperatives and effective systems for milk collection and distribution.

A key pillar of India's dairy industry is its cooperative network, particularly prominent in Gujarat. The sector is vital not only for enhancing nutritional security but also for generating employment across rural India. Small and marginal farmers form the foundation of the dairy economy, and the growing population, coupled with rising incomes and urbanization, continues to drive demand for milk and dairy products, further strengthening the role of cooperatives in ensuring inclusive growth and sustainable livelihoods.

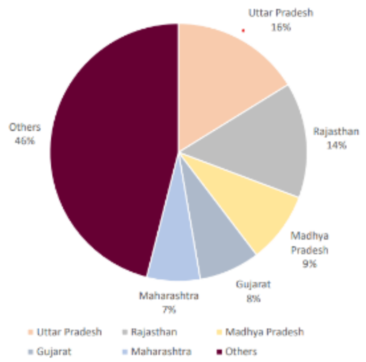


Figure 2. State-wise Break-up of India's Milk Production in 2023-24: % share

6. Exports

In the fiscal year 2023–24, India's dairy exports were valued at approximately $272.64 million. The key export destinations included the United Arab Emirates, Bangladesh, Nepal, Sri Lanka, and Bhutan (Figure 3). India exports a wide variety of dairy products, such as fresh butter, ghee, yogurt, and milk powder. Despite being the world's largest milk producer, India's contribution to global dairy exports remains modest, accounting for only 0.25% of the total international dairy trade. This highlights a considerable untapped potential for expanding India's footprint in global markets.

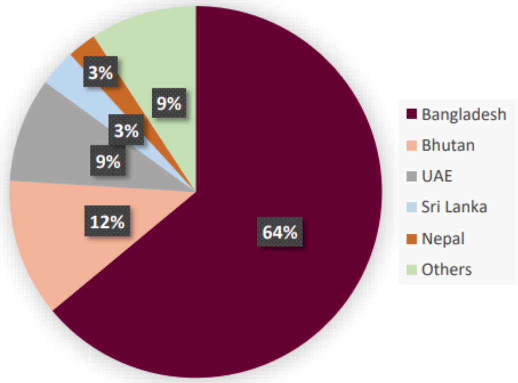


Figure 3. Key export countries of Dairy products (%)

7. Challenges Faced by India's Dairy Export Sector

- **High Domestic Demand**

A large share of milk produced in India is consumed domestically, which significantly limits the surplus available for export. This strong internal demand is a major constraint on export growth.

- **Low Productivity per Animal**

India's average milk yield is around 1.1 tonnes per animal, much lower than that of leading dairy-exporting countries such as New Zealand (3.9 tonnes) and Australia (5.9 tonnes). This low productivity affects the overall volume and competitiveness of exports.

- **Quality and Compliance Issues**

Indian dairy products often do not meet global quality standards, which restricts their acceptance in international markets. Enhancing quality control measures and ensuring compliance with WTO-sanctioned sanitary and phytosanitary regulations are essential for improving export competitiveness.

8. Risks Associated With Dairy Industry

Climate Change

Climate variability poses a considerable challenge to dairy farming in India. Fluctuating weather patterns adversely affect the availability and quality of livestock feed, often leading to nutritional deficiencies in dairy cattle. Moreover, the ongoing expansion of industrial areas continues to reduce grazing land, further aggravating feed scarcity.

Disease Outbreak.

Recurrent outbreaks of diseases such as Foot and Mouth Disease and Lumpy Skin Disease have a profound impact on livestock health and overall productivity. For instance, in affected regions like Rajasthan, Lumpy Skin Disease has resulted in a daily reduction of 3 to 4 lakh liters in milk production. These diseases also contribute to increased mortality rates among dairy animals, placing additional strain on the dairy sector.

Hygiene and Quality Control

Poor hygiene conditions in milking parlors and cattle sheds significantly compromise milk quality by increasing the risk of contamination and undermining consumer confidence. Implementing and maintaining strict sanitation measures is crucial to safeguard the safety and integrity of dairy products.

Fragmented Supply Chain

The dairy sector encounters substantial challenges in maintaining both quality and quantity across its diverse supply network. Owing to the perishable nature of dairy products, the industry necessitates highly efficient and complex supply chain and logistics systems to ensure product freshness and safety.

9. Role of Weather Forecasting and Climate Advisory Services for Dairy Farmers

The livestock sector is essential to global food security and health through its contribution to nutritious diets, economic growth, and livelihoods. It plays a crucial role in improving the lives of millions by providing reliable supplies of meat, milk, eggs, and dairy products. It also helps to create employment and generate income simultaneously strengthening rural households to achieve their livelihood. However, climate change causes severe threats to the livestock sector, ultimately reducing the profitability of farmers. Elevated temperatures and climate variability adversely affect general health, feed intake, milk production, and livestock reproductive efficiency.

Being unorganized nature of the sector which results in minimal technological adoption and high wastage rates. This lack of organization also contributes to inconsistent product quality and market access for small farmers. Among various factors, weather plays important role under changed climatic conditions.

10. What is weather forecasting?

Weather Forecasting defined as the estimating the weather conditions of a local area on the basis of various parameters like Atmospheric pressure, humidity and wind speed, temperature etc. Weather is differentiated from climate by some characteristics. Weather is the prediction of the condition of the atmosphere at a given place or time whereas the climate is the generalized weather conditions for a longer duration for a given location

Weather forecasting is indispensable to both crop cultivation and dairy farming, providing farmers with timely, location-specific data on rainfall, temperatures, humidity, wind and extreme events. For dairy operations, forecasts help anticipated heat stress and its impact on milk yield and animal health, enable fodder planning, water management and livestock shelter scheduling, all critical for sustaining animal welfare and productivity. Studies showed that weather advisory services in India deliver economic gains of up to 50% in farmer income and reduce cultivation costs by up to 25%, while raising net returns by 83% benefits that extend equally to dairy farmers leveraging such data.

India Meteorological Department (IMD) runs an operational Agrometeorological Advisory Services (AAS) *viz.*, Gramin Krishi Mausam Sewa (GKMS) scheme for the benefit of farming community in the country. Under the scheme, medium range weather forecast at district and block level for next five days is generated and based on the forecast, 130 Agromet Field Units (AMFUs) located at State Agricultural Universities (SAUs), institutes of Indian Council of Agricultural Research (ICAR) and Indian Institute of Technology (IIT) etc. and District Agromet Units (DAMUs) at Krishi Vigyan Kendras (KVKs) under ICAR network prepare Agromet Advisories on every Tuesday and Friday for the districts under their jurisdiction and for the blocks of the district of their location and communicate to the farmers to take decision on day-to-day agricultural, dairy and allied operational sectors.

District level AAS was initiated in collaboration with ICAR and SAUs through the network of 130 AMFUs located across the country with an aim of providing more relevant weather information and location and crop specific advisories. After successful implementation of district level AAS, with the introduction of upgraded high-resolution models, the service has further extended to the block level with the establishment of DAMUs in the premises of KVKs of ICAR. AAS rendered by IMD is a step towards weather-based crop and livestock management strategies and operations dedicated to enhancing crop production and food security besides reducing crop damage and loss due to unusual weather.

Along with the biweekly bulletins, daily weather forecast and nowcast information are also disseminated to the farmers by Regional Meteorological Centres (RMCs) and Meteorological Centres (MCs) of IMD. Impact based forecast (IBFs) for agriculture are also being prepared by AMFUs and DAMUs based on the severe weather warnings for different districts of various States and UTs across the country issued by National Weather Forecasting Centre (NWFC), New Delhi and RMCs and MCs of IMD.

11. Types of Weather Forecasts and Bulletins Issued By The India Meteorological Department (IMD)

a. Temporal Forecast Categories

- **Nowcast:** There are ultra-short-term forecasts covering up to 3–6 hours, used especially for predicting imminent thunderstorms, heavy rainfall, lightning and local severe events with station- or district-level (Figure 4).
- **Short-Range Forecast:** Forecasts for the upcoming 1 to 3 days, ideal for planning daily operations.
- **Medium-Range Forecast:** Covers 3 to 10 days, informing agricultural planning, water resources and local preparedness (Figure 5).
- **Extended-Range Outlook:** Forecasts spanning 10 to 30 days ahead, useful for seasonal planning (Figure 6).
- **Long-Range (Seasonal) Forecast:** Issued monthly or before key seasons like the Southwest Monsoon (June–September), these provide predictions on rainfall distribution and temperature anomalies on a seasonal scale (Figure 7).

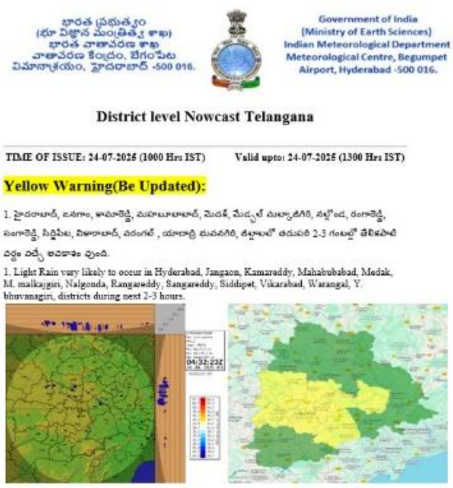


Figure 4. Nowcast Forecast

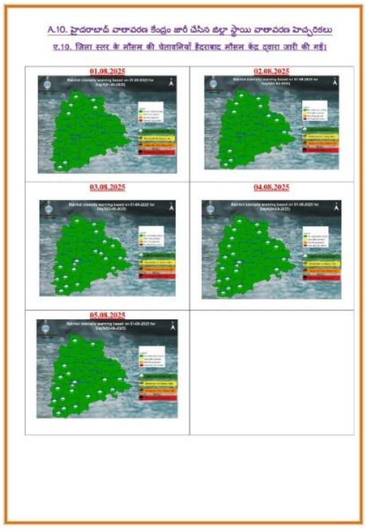


Figure 5. Medium range - rain forecast

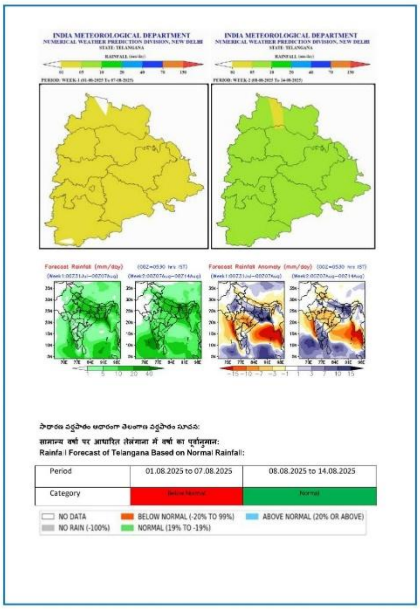
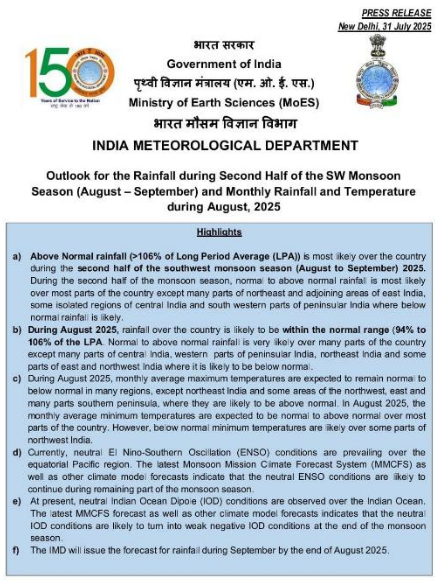


Figure 6. Extended-Range Outlook



PRESS RELEASE
New Delhi, 31 July 2025

भारत सरकार
Government of India
पृथ्वी विज्ञान मंत्रालय (एम. ओ. ई. एस.)
Ministry of Earth Sciences (MoES)
भारत मौसम विज्ञान विभाग
INDIA METEOROLOGICAL DEPARTMENT

Outlook for the Rainfall during Second Half of the SW Monsoon Season (August – September) and Monthly Rainfall and Temperature during August, 2025

Highlights

a) **Above Normal rainfall (>106% of Long Period Average (LPA))** is most likely over the country during the **second half of the southwest monsoon season (August to September) 2025.** During the second half of the monsoon season, normal to above normal rainfall is most likely over most parts of the country except many parts of northeast and adjoining areas of east India, some isolated regions of central India and south western parts of peninsular India where below normal rainfall is likely.

b) **During August 2025,** rainfall over the country is likely to be **within the normal range (94% to 106% of the LPA**. Normal to above normal rainfall is very likely over many parts of the country except many parts of central India, western parts of peninsular India, northeast India and some parts of east and northwest India where it is likely to be below normal.

c) During August 2025, monthly average maximum temperatures are expected to remain normal to below normal in many regions, except northeast India and some areas of the northwest, east and many parts southern peninsula, where they are likely to be above normal. In August 2025, the monthly average minimum temperatures are expected to be normal to above normal over most parts of the country. However, below normal minimum temperatures are likely over some parts of northwest India.

d) Currently, neutral El Nino-Southern Oscillation (ENSO) conditions are prevailing over the equatorial Pacific region. The latest Monsoon Mission Climate Forecast System (MMCFS) as well as other climate model forecasts indicate that the neutral ENSO conditions are likely to continue during remaining part of the monsoon season.

e) At present, neutral Indian Ocean Dipole (IOD) conditions are observed over the Indian Ocean. The latest MMCFS forecast as well as other climate model forecasts indicates that the neutral IOD conditions are likely to turn into weak negative IOD conditions at the end of the monsoon season.

f) The IMD will issue the forecast for rainfall during September by the end of August 2025.

Figure 7. Long-Range Forecast

b. Color-Coded Alerts and Warnings

IMD issues Green, Yellow, Orange and Red Alerts for various hazards including rainfall, heatwaves, cold waves, dust storms, thunderstorms, hail and fog (Figure 9). These alerts are forecasted up to 5 days ahead and are based on both expected severity and impact, guiding appropriate preparedness levels. Cyclone Watch / Alert / Warning / Landfall Outlook: A four-stage warning system issued 72, 48, 24 and 12 hours before a cyclone's expected impact, including forecast and advisories for coastal and inland area (Figure 8).

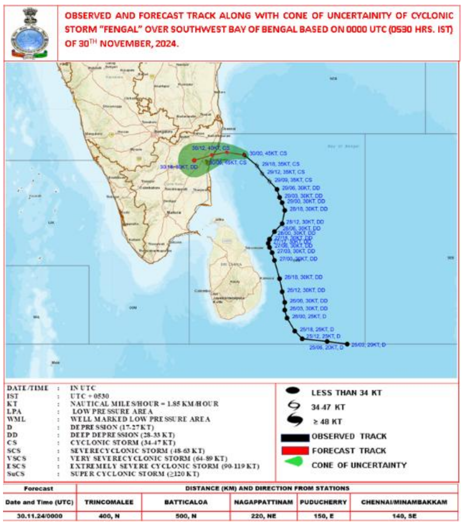


Figure 8. Forecast track for Fengal Cyclone issued by IMD on 30 Nov, 2024

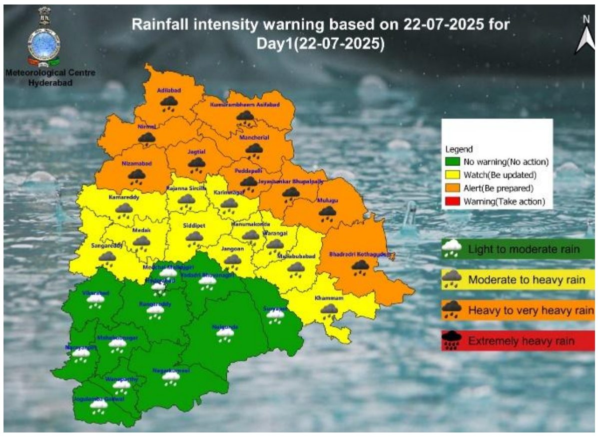
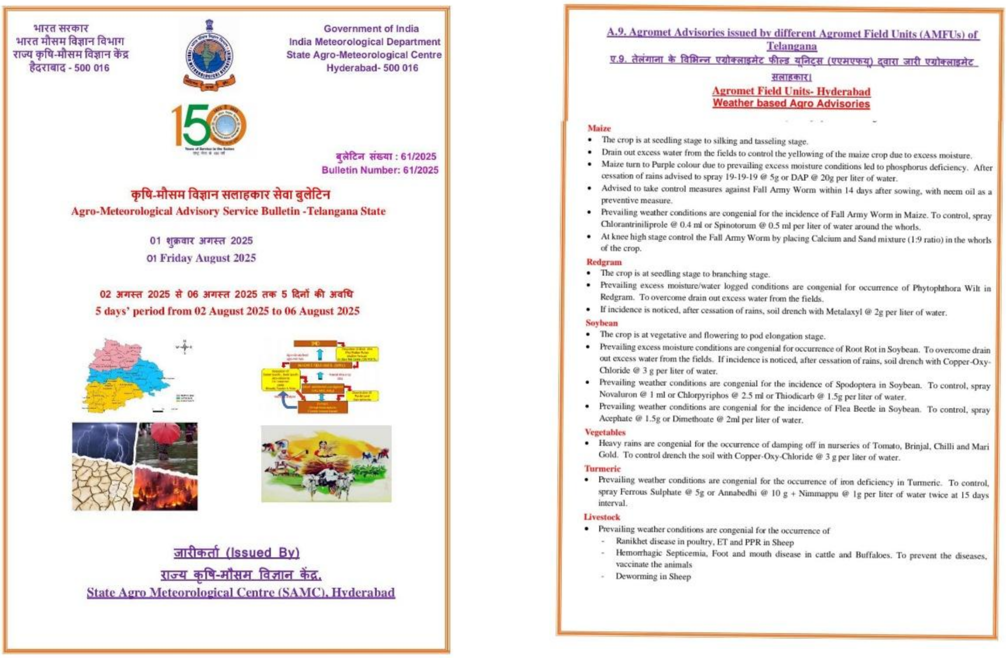


Figure 9. Reference of Rainfall Intensity colour coded warnings issued to Telangana

c. **Generals, Quantitative, Special and Thematic Bulletins**

All-India Weather Forecast Bulletin: Provides synoptic-level summaries and forecast guidance across the country.

- **Quantitative Precipitation Forecasts (QPFs)**: Detailed rainfall forecasts-e.g. 5-day district-wise or 7-day subdivision-wise rainfall outlooks—help planners anticipate water and flood risks.
- **Tourism Forecast:** A 7-day preview focusing on city-level conditions like temperature, rainfall, fog, drizzle, dust storms, and heat/cold waves for tourists and local travel planning.
- **Flash-Flood Bulletins**: Issued for rapidly evolving high-rainfall events likely to cause floods, used by disaster management agencies.
- **Cyclone Tracking and Marine Weather Bulletins**: Include coast-wise advisories, sea-state forecasts, and wind-warnings for fishermen and coastal communities.
- **Agromet Advisory Bulletins:** Biweekly medium range weather forecast based agromet bulletins (Figure 10), daily weather forecasts, nowcasts and impact-based forecasts (IBFs) (Figure 11) for agriculture are disseminated to farmers by IMD's Regional and Meteorological Centres, with IBFs prepared by AMFUs and DAMUs based on severe weather warnings from the National Weather Forecasting Centre, New Delhi and IMD units.



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Government of India
India Meteorological Department
State Agro-Meteorological Centre
Hyderabad- 500 016

बुलेटिन संख्या : 61/2025
Bulletin Number: 61/2025

कृषि-मौसम विज्ञान सलाहकार सेवा बुलेटिन
Agro-Meteorological Advisory Service Bulletin -Telangana State

01 शुक्रवार अगस्त 2025
01 Friday August 2025

02 अगस्त 2025 से 06 अगस्त 2025 तक 5 दिनों की अवधि
5 days' period from 02 August 2025 to 06 August 2025

जारीकर्ता (Issued By)
राज्य कृषि-मौसम विज्ञान केंद्र,
State Agro Meteorological Centre (SAMC), Hyderabad

A.9. Agromet Advisories issued by different Agromet Field Units (AMFUs) of Telangana
ए.9. तेलंगाना के विभिन्न एग्रोक्लाइमेट फील्ड यूनिट्स (एएमएफयू) द्वारा जारी एग्रोक्लाइमेट सलाहकार।
Agromet Field Units- Hyderabad
Weather based Agro Advisories

Maize
- The crop is at seedling stage to silking and tasseling stage.
- Drain out excess water from the fields to control the yellowing of the maize crop due to excess moisture.
- Maize turn to Purple colour due to prevailing excess moisture conditions led to phosphorus deficiency. After cessation of rains advised to spray 19-19-19 @ 5g or DAP @ 20g per liter of water.
- Advised to take control measures against Fall Army Worm within 14 days after sowing, with neem oil as a preventive measure.
- Prevailing weather conditions are congenial for the incidence of Fall Army Worm in Maize. To control, spray Chlorantriniliprole @ 0.4 ml or Spinotorum @ 0.5 ml per liter of water around the whorls.
- At knee high stage control the Fall Army Worm by placing Calcium and Sand mixture (1:9 ratio) in the whorls of the crop.

Redgram
- The crop is at seedling stage to branching stage.
- Prevailing excess moisture/water logged conditions are congenial for occurrence of Phytophthora Wilt in Redgram. To overcome drain out excess water from the fields.
- If incidence is noticed, after cessation of rains, soil drench with Metalaxyl @ 2g per liter of water.

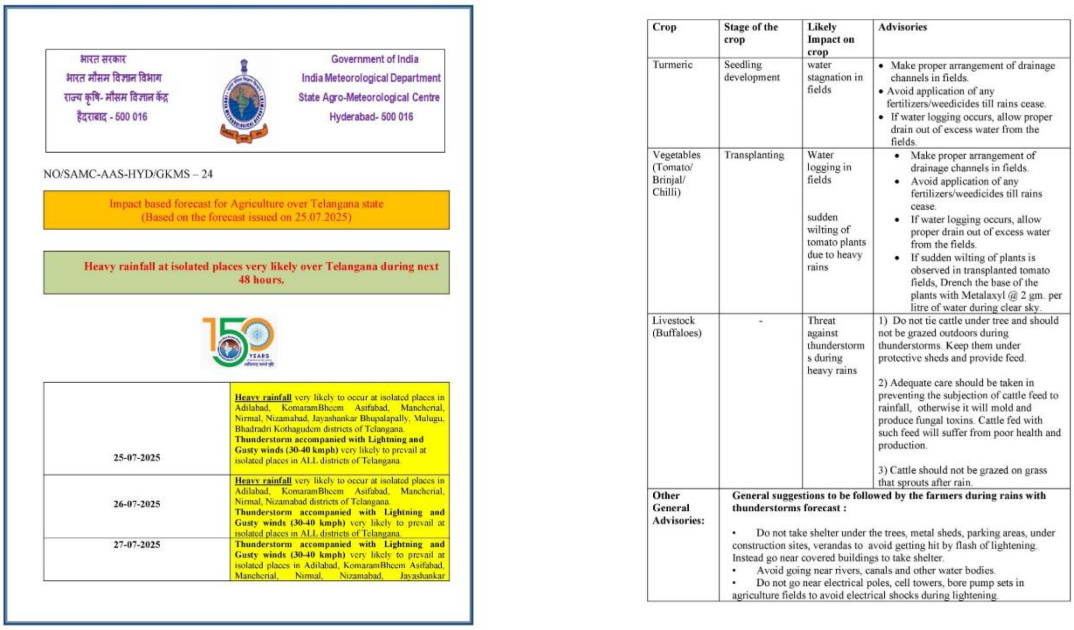
Soybean
- The crop is at vegetative and flowering to pod elongation stage.
- Prevailing excess moisture conditions are congenial for occurrence of Root Rot in Soybean. To overcome drain out excess water from the fields. If incidence is noticed, after cessation of rains, soil drench with Copper-Oxy-Chloride @ 3 g per liter of water.
- Prevailing weather conditions are congenial for the incidence of Spodoptera in Soybean. To control, spray Novaluron @ 1 ml or Chlorpyriphos @ 2.5 ml or Thiodicarb @ 1.5g per liter of water.
- Prevailing weather conditions are congenial for the incidence of Flea Beetle in Soybean. To control, spray Acephate @ 1.5g or Dimethoate @ 2ml per liter of water.

Vegetables
- Heavy rains are congenial for the occurrence of damping off in nurseries of Tomato, Brinjal, Chilli and Mari Gold. To control drench the soil with Copper-Oxy-Chloride @ 3 g per liter of water.

Turmeric
- Prevailing weather conditions are congenial for the occurrence of iron deficiency in Turmeric. To control, spray Ferrous Sulphate @ 5g or Annabedhi @ 10 g + Nimmappu @ 1g per liter of water twice at 15 days interval.

Livestock
- Prevailing weather conditions are congenial for the occurrence of
  - Ranikhet disease in poultry, ET and PPR in Sheep
  - Hemorrhagic Septicemia, Foot and mouth disease in cattle and Buffaloes. To prevent the diseases, vaccinate the animals
  - Deworming in Sheep

Figure 10. Reference of Medium range forecast based Agromet Advisory Bulletin of Telangana State



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हैदराबाद - 500 016

Government of India
India Meteorological Department
State Agro-Meteorological Centre
Hyderabad- 500 016

NO/SAMC-AAS-HYD/GKMS – 24

Impact based forecast for Agriculture over Telangana state
(Based on the forecast issued on 25.07.2025)

Heavy rainfall at isolated places very likely over Telangana during next 48 hours.

25-07-2025	**Heavy rainfall** very likely to occur at isolated places in Adilabad, KomaramBheem Asifabad, Mancherial, Nirmal, Nizamabad, Jayashankar Bhupalapally, Mulugu, Bhadradri Kothagudem districts of Telangana. **Thunderstorm accompanied with Lightning and Gusty winds (30-40 kmph)** very likely to prevail at isolated places in ALL districts of Telangana.
26-07-2025	**Heavy rainfall** very likely to occur at isolated places in Adilabad, KomaramBheem Asifabad, Mancherial, Nirmal, Nizamabad districts of Telangana. **Thunderstorm accompanied with Lightning and Gusty winds (30-40 kmph)** very likely to prevail at isolated places in ALL districts of Telangana.
27-07-2025	**Thunderstorm accompanied with Lightning and Gusty winds (30-40 kmph)** very likely to prevail at isolated places in Adilabad, KomaramBheem Asifabad, Mancherial, Nirmal, Nizamabad, Jayashankar

Crop	Stage of the crop	Likely Impact on crop	Advisories
Turmeric	Seedling development	water stagnation in fields	• Make proper arrangement of drainage channels in fields. • Avoid application of any fertilizers/weedicides till rains cease. • If water logging occurs, allow proper drain out of excess water from the fields.
Vegetables (Tomato/ Brinjal/ Chilli)	Transplanting	Water logging in fields sudden wilting of tomato plants due to heavy rains	• Make proper arrangement of drainage channels in fields. • Avoid application of any fertilizers/weedicides till rains cease. • If water logging occurs, allow proper drain out of excess water from the fields. • If sudden wilting of plants is observed in transplanted tomato fields, Drench the base of the plants with Metalaxyl @ 2 gm. per litre of water during clear sky.
Livestock (Buffaloes)	-	Threat against thunderstorms during heavy rains	1) Do not tie cattle under tree and should not be grazed outdoors during thunderstorms. Keep them under protective sheds and provide feed. 2) Adequate care should be taken in preventing the subjection of cattle feed to rainfall, otherwise it will mold and produce fungal toxins. Cattle fed with such feed will suffer from poor health and production. 3) Cattle should not be grazed on grass that sprouts after rain.
Other General Advisories:	**General suggestions to be followed by the farmers during rains with thunderstorms forecast :** • Do not take shelter under the trees, metal sheds, parking areas, under construction sites, verandas to avoid getting hit by flash of lightening. Instead go near covered buildings to take shelter. • Avoid going near rivers, canals and other water bodies. • Do not go near electrical poles, cell towers, bore pump sets in agriculture fields to avoid electrical shocks during lightening.		

Figure 11. Reference of Impact Based Forecast Bulletin issued to Telangana State

12. Weather Extremes and Their Impact on Dairy and Livestock

Dairy and livestock systems are increasingly vulnerable to weather extremes. Heat waves, floods, droughts and disease outbreaks erode productivity, profitability and welfare. But adaptive management, climate-smart practices, breed choices, and institutional support including early warning systems and insurance can build resilience. As climate continues to intensify, integrating these strategies into planning is essential to sustaining dairy livelihoods across diverse ecosystems.

13. Rainfall Extremes: Floods and Monsoon Rains

I. **Rapid Inundation and Herd Losses:** Intense floods can drown herds and decimate farm infrastructure. During severe flooding, farmers lose more of their cattle, along with barns and milking equipment, resulting in bankruptcy risks and long-term disruptions to milk suply.

II. **Disease Outbreaks and Mastitis:** Wet, muddy conditions promote mastitis, pink eye, endemic viral infections (e.g. 'Three Day Sickness'), and footrot due to environmental contamination and stress.

III. **Feed and Water Contamination:** Floodwater pollutes stored fodder and wells; moldy feed leads to malnutrition and metabolic disorders and animals must often subsist on suboptimal rations for months after a flood.

IV. **Long-Term Productivity Loss**: Severe flooding causes long-term productivity loss in dairy farming by killing or injuring cattle, damaging sheds, destroying feed stocks, and disrupting animal health and breeding cycles. Infrastructure and market disruptions further delay recovery, pushing farmers into debt and affecting their ability to sustain operations and income for months or even years.

14. Rainfall Deficits: Drought and Feed Shortages

Reduced Pasture Growth: In drought-prone districts, lower rainfall severely limits fodder availability. Buffalo milk productivity improves significantly with increased annual rainfall, underscoring dependence on timely rains for forage supply.

Feed Scarcity and Nutritional Stress: Drought forces reliance on expensive or limited-quality supplementary feed, compromising body condition, milk yield, calving rates and herd size.

Cascading Operational Impact: Poor rainfall coinciding with high temperature amplifies heat stress, disease susceptibility and lowered growth or production efficiency.

Rains with Thunderstorms

During thunderstorms, cattle often crowd together under trees or structures making lightning strikes more lethal. On occasion, entire herds have been found dead in a line under a single tree struck by lightning.

15. Cold Nights and Sustained Cold Days

Cold Stress and Increased Energy Demands : When ambient temperatures fall below an animal's Lower Critical Temperature (LCT) which ranges from ~18°C (dry heavy winter coat) to as high as 15°C (wet coat), cows must increase metabolic heat production to maintain core temperature, which raises maintenance energy needs by ~0.5% per °C below the LCT. Energy demands may increase by 10–50%, depending on coat quality, wind and moisture.

Decline in Milk Yield and Growth:

Dairy cows show reduced milk secretion during cold stress, glucose gets diverted to thermoregulation, mammary blood flow declines, leading to lower lactose output and up to 2 kg/day drop in milk yield. For growing calves and beef cattle, cold stress slows weight gain and feed conversion by shifting energy to heat rather than growth.

Body Condition, Reproduction and Calving Impacts:

When dietary intake doesn't meet increased needs, cows mobilize body reserves losing weight and insulation. This leads to poor body condition and reduced reproductive performance, longer days open, lower colostrum quality, delayed conception and weak calf births.

Respiratory risks and Frost Injury:

Cold, wet or windy conditions increase risk of respiratory illnesses, frostbite (ears, teats) and hypothermia, particularly in calves and older cows. Torn or frozen teats after milking can impair udder health and increase masitis risk.

Feed and Water Management Challenges:

Animals tend to reduce water intake in cold conditions, while feed intake rises limiting dry matter digestibility and reducing nutrient absorption. Frozen or icy feed and water sources discourage eating and drinking; cows prefer water at 4–18°C.

16. Heatwaves and High Temperatures

- Studies show that just one hour of wet-bulb temperature above 26 °C can reduce daily milk yield by 0.5%, with cumulative losses up to 10% and effects that linger up to 10 days post exposure. A rise of 1 °C in average high temperature can depress cattle milk yield by around 2.4% and buffalo yield by 2.1% translating to significant income losses for smallholders.
- Temperature Humidity Index (THI) is categorized as No Heat stress when THI < 72, Mild Heat stress when THI is between 72-76 and Moderate Heat stress when THI >76.
- Heat stress also severely impairs reproductive performance when Temperature Humidity Index (THI) exceeds thresholds of 72 (cattle) or 75 (buffalo), reducing conception and pregnancy rates (Figure 12).
- Above ~30 °C, cows eat 3–5% less feed per °C, produce less milk and show metabolic issues like ketosis and ruminal acidosis.

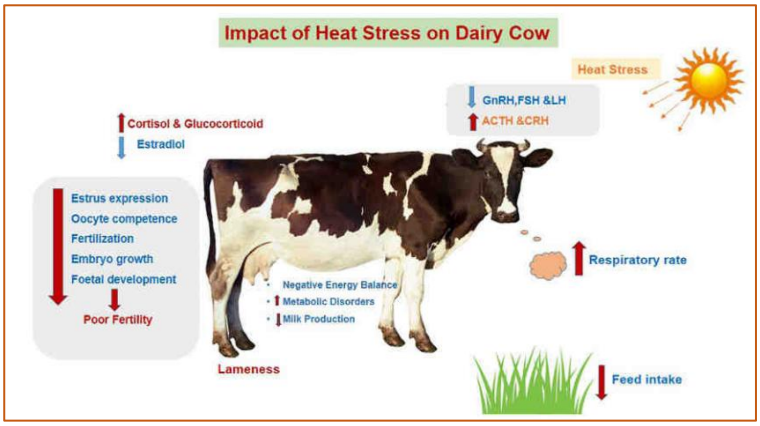

Figure 12. Impact of Heat stress on Diary cow

Published by National Institute of Agricultural Extension Management (MANAGE), Hyderabad

17. Disease and Parasite Pressure Linked To Weather

Shifts in temperature and humidity support proliferation of vectors like ticks and fly populations, resulting in diseases such as tick fever, buffalo fly lesions, Bovine Respiratory Disease and mastitis. These are often triggered or worsened in humid and warm weather conditions.

18. Wild Fires

Climate change is a significant factor contributing to the increasing severity and frequency of wildfires. While wildfires are a natural part of many ecosystems, climate change is exacerbating their intensity and spread. Warmer temperatures, altered precipitation patterns and increased drought conditions, all influenced by climate change, create conditions that make wildfires more likely and more damaging.

- Smoke plus elevated temperature–humidity index (THI) disrupts metabolism: blood urea nitrogen (BUN) drops, nonesterified fatty acids (NEFA) increase initially, indicating stress-induced fat mobilization; over multiple days, these patterns shift.
- Blood tests show reduced red blood cells and hemoglobin, elevated eosinophils and basophils with signs of inflammation, allergic response and oxygen transport disruption.
- Immune cell populations (e.g. neutrophils) decline, weakening disease resistance and raising vulnerability to respiratory infections -a leading cause of death in calves and cows.

Respiratory & Reproductive Effects

- Inhaled particulate matter penetrates deep into the lungs, causing inflammation and impaired function; cows cannot avoid exposure as they live in open-air barns.
- Similar studies in primates (e.g. rhesus macaques) show increased miscarriage rates during smoke exposure—suggesting possible reproductive effects in livestock too.

Milk Production & Composition

- Exposure to wildfire-derived $PM_{2.5}$ (fine particulate matter) reduces milk yield by roughly 1.2 kg per day for every 100 $\mu g/m^3$ increase in $PM_{2.5}$. The effects persist for at least seven days post-exposure.
- On particularly heavy smoke days, production might drop by around 4 kg/day per cow (e.g. 65 → 62 pounds/day).
- Milk protein and lactose content also decline, especially under combined heat and smoke exposure.

19. Mitigating Weather Related Risks in Dairy Farming: Agromet Recommendations During Rainy Season

Shelter and Housing

- Ensure proper drainage around cattle sheds to prevent water stagnation.
- Maintain clean, dry and well-ventilated shelters to avoid fungal and bacterial infections.
- Use lime or bleaching powder around sheds to prevent fly and mosquito breeding.

Health and Disease Management

- Deworm animals regularly as monsoon increases the risk of internal parasites.
- Vaccinate against common monsoon diseases like Foot and Mouth Disease (FMD), Hemorrhagic Septicemia (HS) and Black Quarter (BQ).

- Watch for signs of mastitis, pneumonia and other infections that increase with damp conditions.

Feeding and Watering

- Avoid feeding moldy or fermented feed that may accumulate due to moisture.
- Store feed in dry, elevated places and cover with plastic sheets.
- Provide clean, cool drinking water and ensure water troughs are cleaned regularly.

Grazing and Movement

- Avoid letting animals graze during heavy rains or in waterlogged areas to prevent hoof infections and accidental injuries.
- Limit outdoor movement during lightning and thunderstorms.

Thermal Comfort and Stress Management

- Ensure good airflow in shelters to reduce heat stress during humid weather.
- Use fans or foggers if necessary to reduce the temperature-humidity index (THI).

Hygiene and Milking Practices

- Maintain strict udder and teat hygiene before and after milking.
- Wash milking utensils with hot water and antiseptic solution.

Record Keeping and Monitoring

- Keep a record of rainfall and local weather bulletins to plan feeding, sheltering and disease control activities.
- Coordinate with veterinary officers for timely advice during disease outbreaks.

27. DURING WINTER SEASON

Shelter and Housing

- Provide warm, dry and well-insulated shelters to protect animals from cold winds.
- Use straw bedding or rubber mats to reduce heat loss through the floor.
- Cover open sides of sheds with gunny bags, curtains or plastic sheets during cold nights.

Health and Disease Management

- Watch for respiratory infections like pneumonia, especially in calves and older animals.
- Avoid sudden exposure to cold; let animals out only when the sun is up and winds are mild.
- Ensure timely vaccination and deworming; consult a veterinarian for winter-specific disease risk.

Feeding and Nutrition

- Increase energy-rich feed to help animals maintain body heat (e.g., jaggery, grains).
- Provide warm water for drinking to maintain body temperature and hydration.
- Ensure availability of green fodder to avoid vitamin deficiencies during winter.

Water and Hygiene

- Prevent water from freezing in troughs; supply lukewarm water if possible.
- Clean sheds regularly to avoid dampness, which increases infection risks.

Animal Comfort and Management

- Allow animals to bask in sunlight during the warmer parts of the day.

- Avoid bathing animals in the early morning or evening; use lukewarm water if needed.
- Monitor body temperature, especially in newborns and pregnant animals.

Special Care for Calves and Weak Animals

- Use calf jackets or cover them with jute sacks during cold spells.
- Keep them in warmer sections of the shed and provide extra bedding.
- Special Care for Pregnant Cows: Avoid long travel, overexertion or sudden environmental changes. Ensure clean, dry bedding to prevent infections. Provide balanced ration with extra energy and protein during the last 3 months of pregnancy. Add calcium and phosphorus supplements to support fetal growth and prevent milk fever. Ensure access to fresh, clean water at all times. Watch for signs of pregnancy-related disorders (e.g., vaginal discharge, lethargy). Deworm cows in the second trimester and vaccinate before calving (as per vet advice). Prevent exposure to infections through good hygiene and biosecurity.

28. During summer and Heat Wave Events

1. Shelter and Housing

- Provide well-ventilated, shaded shelters with thatched roofs or reflective coverings (e.g., white paint, straw or gunny cloth).
- Use fans, foggers or sprinklers in sheds to reduce heat load and improve air circulation.
- Avoid over-crowding in cattle sheds to minimize heat accumulation.

2. Water Management

- Cattle drink a significant amount of water, potentially exceeding 100 litres/day in summer. Ensure round-the-clock access to clean, cool drinking water to prevent dehydration.
- Add electrolytes to drinking water during heatwaves to restore lost minerals.
- Clean water troughs regularly to avoid bacterial contamination.

3. Feeding and Nutrition

- Feed animals during cooler hours (early morning and late evening).
- Reduce dry roughage; provide moist, green fodder (like maize, napier) and energy-rich supplements. Add Vitamin A, E and selenium supplements to improve reproductive health.
- Avoid feeding hot fermented feed and ensure proper storage to prevent spoilage.

4. Health and Stress Management

- Monitor animals for signs of heat stress: panting, reduced feed intake, increased respiration rate and lethargy.
- Use mineral mixtures and salt licks to support thermoregulation and electrolyte balance.
- Avoid transportation, vaccination or dehorning during peak heat hours.
- Avoid breeding during peak heat: schedule artificial insemination or natural mating in early morning or late evening. Heat tolerant breeds like Sahiwal, Gir or cross breeds can be chosen for better summer fertility.

5. Grazing and Outdoor Activity

- Restrict grazing during midday; allow only in early mornings or late evenings.
- Provide portable shade (e.g., tree cover, shade nets) in open grazing areas.

6. Special Attention during Heatwave alerts

- Follow local agromet advisories and heatwave warnings issued by IMD/Agromet Field Units.
- Apply wet gunny cloths or sprinkle water on animals during extreme heat.
- Increase frequency of watering and feed cooling (e.g., soaking hay or silage).

7. Calves and Lactating Animals

- Calves are more vulnerable, keep them in cooler parts of the shed and hydrate frequently.
- Monitor milk yield and udder health; heat stress can reduce milk production and immunity.
- Deworming of calves to be done (accordingly after faecal examination) before the onset of *kharif*. Broad spectrum antihelmenthics like liquid albendazole @10 mg/kg body weight- oral administration with first dose at the age of 2 weeks followed by every month till 6 months age and then every 6 months for life time.

Agromet Advisories are disseminated to the farmers through multichannel dissemination system like print andelectronic media, Door Darshan, radio, internet etc. including SMS using mobile phones through Kisan Portal and also through private companies under Public Private Partnership (PPP) mode.

Farmers access the weather information including alerts and related agromet advisories specific to their districts through the mobile App *viz.*, 'Meghdoot' launched by Ministry of Earth Sciences, Government of India (Figure 13). These weather details are also accessible by farmers through another App 'Kisan Suvidha', launched by Ministry of Agriculture & Farmers Welfare (Figure 14).

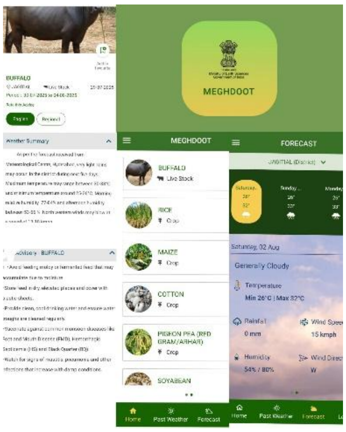

Figure 13. Meghdoot mobile app of IMD

Figure 14. Kisan Suvidha mobile app

Social media like 'WhatsApp' is also used for quicker dissemination of weather forecast and agromet advisories. WhatsApp groups of farmers have been created by various AMFUs and DAMUs to disseminate agromet services. State Agriculture Department officials of District and Block level are also included in these WhatsApp groups.

The recent economic study of 2020 concluded that, 98% of surveyed farmers (3,965 farmers across 121 districts of 11 states of India) made modifications to at least one of nine practices based on weather advisories. The average annual income of farming households increased from ₹1.98 lakh for those who adopted no modifications to ₹3.02 lakh for those who implemented all nine recommended practices. An additional annual income was estimated of Rs. 12,500 per agricultural household belonging to Below Poverty Line category in rain-fed areas, while total income gain was estimated at Rs. 13,331 crore per annum in rain-fed districts. An investment of Rs 1000 crores will yield economic benefits of about Rs 50000 crores over a period of 5 years (www.pib.gov.in, Soumya *et al*., 2022).

According to Manjunath *et al*. (2024), the benefit-cost ratio of climate services was found to be 1:1.8. Hence, the exclusive climate services developed for Murrah buffalo farmers were found to be an effective adaptive mechanism for helping vulnerable dairy farming to adapt to the climate of today and of the future.

Agromet advisories empower dairy farmers to adapt to the challenges posed by a changing climate and manage their operations more efficiently and sustainably. Therefore, dairy farmers need to regularly follow agromet advisories due to increasing weather risks. These advisories, which provide information on weather patterns and potential hazards are crucial for making informed decisions about livestock management and minimizing potential losses from extreme weather events.

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Chapter-12

THE ROLE OF INFRASTRUCTURAL DEVELOPMENT IN MITIGATING THE IMPACT OF CLIMATE CHANGE IN THE DAIRY SECTOR

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Abstract

Climate change poses significant challenges to the dairy sector, including heat stress, reduced fodder availability, declining milk yield, and increased vulnerability to disease. Infrastructural development plays a critical role in building resilience and reducing the sector's susceptibility to climate-induced disruptions. This article explores how strategic investments in infrastructure—such as climate-resilient housing, efficient water management systems, cold chain logistics, renewable energy, and digital monitoring technologies—can mitigate the adverse effects of climate change on dairy production. By enhancing adaptive capacity and promoting sustainable practices, infrastructural innovations contribute to improved animal welfare, productivity, and economic stability for dairy farmers. The study highlights successful models, identifies gaps, and emphasizes the need for policy support and inclusive planning to ensure long-term sustainability and food security in the face of evolving climate challenges.

Key words: Infrastructure, Climate Mitigation, Dairy, Resilience, Cold Chain and Sustainability

1. Introduction

The global dairy sector is a cornerstone of rural livelihoods, nutrition, and economic development, particularly in agrarian economies. However, this vital industry is increasingly vulnerable to the impacts of climate change, which threaten its sustainability and productivity. Rising temperatures, erratic rainfall, droughts, floods, and shifting weather patterns have a direct effect on animal health, milk production, fodder availability, and water resources. These challenges are more severe in regions where dairy farming already operates under low-input, resource-constrained systems.

In the face of these threats, infrastructural development emerges as a critical pathway for climate change adaptation and mitigation. Infrastructure refers not only to physical structures like roads, buildings, and water storage systems but also to facilities and services that support efficient, climate-resilient dairy operations. This includes temperature-controlled shelters, solar-powered cooling units, improved storage and transportation, climate-smart feeding systems, and digital technologies for early warning and farm management.

Despite the growing evidence of climate risks, many dairy systems, especially in developing countries, lack adequate infrastructure to withstand and adapt to these pressures. Poor housing for livestock, unreliable electricity, water scarcity, and limited access to cold chain logistics result in significant production losses and reduced income for farmers. Therefore, strengthening and modernizing dairy infrastructure is not just a matter of development—it is a necessity for climate resilience and sustainability. This paper aims to provide insights into how targeted infrastructure investment can secure the future of dairy farming in an increasingly uncertain climate.

2. Climate Change and Its Impact on the Dairy Sector

2.1 Heat Stress and Animal Productivity:

Dairy animals, particularly high-yielding breeds, are extremely sensitive to temperature variations. Prolonged exposure to heat results in heat stress, which negatively impacts feed intake, metabolic efficiency, milk production, and reproductive performance. Heat stress also alters hormonal levels, making animals more prone to infertility and miscarriage. Moreover, thermal stress suppresses immune function, making animals vulnerable to infections and diseases. According to West (2003), every 1°C rise above the thermal comfort zone can cause a significant drop in milk yield.

2.2 Feed and Fodder Crisis:

Climate change affects the growth and availability of fodder crops. Erratic rainfall and rising temperatures reduce pasture productivity and degrade natural grazing lands. Droughts reduce the biomass of cultivated fodder while floods damage stored feed. The result is increased reliance on expensive commercial feeds, which smallholders may not afford, thereby increasing production costs and decreasing profitability. Thornton and Herrero (2010) emphasized that reduced availability of green fodder contributes to greenhouse gas emissions as animals rely more on low-quality, methane-producing roughage.

2.3 Water Scarcity:

Water is essential for drinking, cleaning, and maintaining hygiene in dairy farms. Rising temperatures and irregular rainfall patterns lead to reduced water availability. Overextraction of groundwater, often necessary to meet the increased water demand, further depletes aquifers. Scarcity of water not only stresses the animals but also limits fodder production and affects the operation of cooling systems. Singh *et al.* (2020) note that the dairy sector in India consumes over 100 liters of water per animal per day, and any water deficit significantly hampers productivity.

2.4 Spread of Vector-Borne Diseases:

Changes in climate, especially rising humidity and temperature, encourage the spread of disease vectors such as ticks, flies, and mosquitoes. This increases the incidence of diseases like mastitis, foot-and-mouth disease (FMD), and tick-borne fevers. Veterinary expenses rise, and production losses due to sick animals become significant, affecting the economic viability of dairy enterprises. Das *et al.* (2016) found that higher ambient temperatures can increase microbial loads in dairy environments, raising the risk of mastitis and milk contamination.

3. Infrastructural Development: A Climate Strategy

Infrastructural development acts as both an adaptation and mitigation strategy. Adaptation involves making systems resilient to climate-induced shocks, while mitigation focuses on reducing greenhouse gas emissions. Infrastructure supports these strategies by improving efficiency, reducing losses, and enhancing resource conservation. Investments in physical, technological, institutional, and ecological infrastructure form a comprehensive approach to climate resilience.

4. Climate-Resilient Physical Infrastructure

4.1 Livestock Housing Systems:

Proper housing is crucial for shielding animals from environmental extremes. Structures should be designed to allow adequate ventilation, shade, and drainage. Open-sided sheds with sloped roofs and ridge ventilation enable natural airflow, cooling the animals. Insulated roofing materials such as aluminum sheets or thatch help reduce heat absorption. Some farms use mechanical cooling systems like misting fans or foggers to further mitigate heat stress. These measures improve animal comfort, reduce mortality, and enhance milk yield. NDDB (2021) reports that well-ventilated housing can improve milk productivity by 15–20% in hot regions.

4.2 Elevated Platforms and Flood Shelters:

In regions prone to flooding, elevated platforms protect animals from drowning and exposure to water-borne diseases. Mobile flood shelters allow quick relocation of livestock during emergencies. These shelters are constructed using durable and waterproof materials, and often include provisions for feed and water storage, ensuring continuity of care during floods. Their use reduces livestock loss and economic disruption. The FAO (2015) emphasizes the importance of such infrastructure in the resilience planning of flood-prone areas.

5. Efficient Water and Waste Management Infrastructure

5.1 Rainwater Harvesting and Storage Tanks:

Rainwater harvesting involves capturing and storing rainwater for farm use. Rooftop catchment systems channel water into storage tanks or ponds, ensuring water availability during dry spells. These systems reduce dependency on external sources and help recharge groundwater. They also provide a sustainable supply of water for cleaning sheds, watering animals, and irrigating fodder crops. According to World Bank (2020), rainwater harvesting can reduce freshwater extraction by 40% in medium-sized dairy farms.

5.2 Wastewater Recycling:

Recycling wastewater for non-potable uses like cleaning floors or irrigating non-edible plants conserves freshwater resources. Treatment units remove pathogens and organic matter, ensuring safe reuse. Using recycled water reduces the environmental footprint of dairy farms and minimizes freshwater extraction, aligning operations with environmental standards.

5.3 Biogas Units:

Biogas units decompose animal dung anaerobically to produce methane-rich gas used for cooking and electricity. The leftover slurry serves as an organic fertilizer. Biogas technology reduces methane emissions from open dung storage and decreases reliance on fossil fuels. It provides a circular economy model that integrates waste management, energy production, and agriculture. According to FAO (2013), adopting biogas units can cut methane emissions by 50% compared to open dung pits.

6. Cold Chain and Milk Storage Infrastructure

6.1 Bulk Milk Coolers (BMCs):

BMCs rapidly chill milk to 4°C, preserving its quality and reducing bacterial growth. Installed at village collection centers, these coolers allow farmers to store milk safely until transport. BMCs reduce spoilage and milk rejections, thereby increasing farmer income and market access. They are often powered by grid electricity or solar panels in off-grid areas. The National Dairy Plan Phase I resulted in over 8,000 BMC installations across India (World Bank, 2020).

6.2 Solar-Powered Coolers: Solar-powered milk coolers are ideal for rural and remote regions with limited electricity. They use photovoltaic panels to power refrigeration units. These systems reduce dependence on diesel generators, lower carbon emissions, and offer sustainable refrigeration solutions. Government schemes like the Rashtriya Gokul Mission promote their adoption and offer financial incentives.

7. Sustainable Feed and Fodder Infrastructure

7.1 Fodder Banks and Silage Units:

Fodder banks store surplus fodder during the growing season for use during lean periods. Silage units ferment green fodder, preserving its nutrients and enhancing digestibility. These units enable year-round availability of quality feed, stabilize market prices, and reduce the risk of feed shortages during droughts or floods. NDDB (2021) reported improved animal health and consistent milk yields in districts with fodder banks.

7.2 Hydroponic and Vertical Fodder Systems:

Hydroponic systems grow fodder without soil, using nutrient-rich water in controlled environments. Vertical farming maximizes space usage and is ideal for peri-urban dairies. Both methods use less water and land, making them suitable for regions facing resource constraints. They offer consistent and hygienic feed supply, improving animal nutrition and productivity. GIZ (2017) highlights that hydroponic fodder systems reduce water use by 80% compared to traditional systems.

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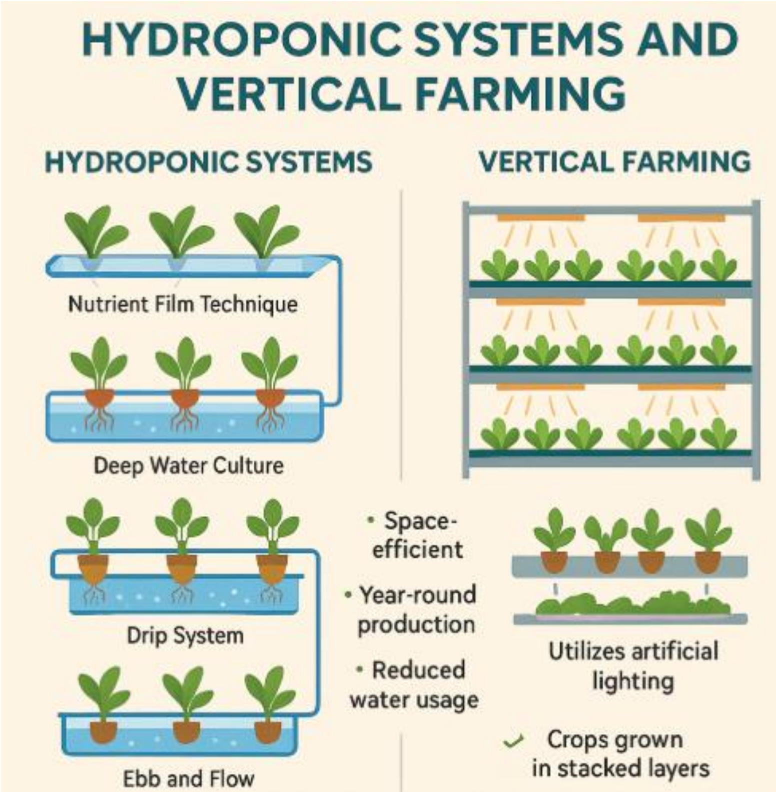

Fig.1 Hydroponic and Vertical Fodder Systems

7.3 Storage Warehouses

Warehouses for dry feed and concentrates protect against moisture, pests, and contamination. Proper storage ensures feed quality, reduces spoilage, and minimizes losses. They are equipped with ventilation, insulation, and rodent-proofing. Efficient inventory management within warehouses ensures timely feed availability and cost control.

8. Transport, Market Access, and Processing Infrastructure

All-weather roads enable timely access to veterinary services, input supplies, and markets. Efficient transport systems with refrigerated vehicles preserve milk quality during transit. Milk processing plants located close to production centers reduce travel time, improve value addition, and enhance shelf life. These infrastructures strengthen the dairy value chain, reduce post-harvest losses, and increase farmer profitability. UNEP (2022) highlights the role of rural roads in improving income stability in climate-vulnerable regions.

9. Energy Infrastructure: Decarbonizing Dairy

9.1 Renewable Energy Systems

Solar panels on rooftops, wind turbines, and bio-digesters provide clean energy for farm operations. Solar-powered pumps irrigate fodder fields, reducing dependence on diesel. Adoption of renewables reduces operational costs, cuts emissions, and enhances energy security. Government incentives and subsidies encourage adoption among smallholders. IREDA (2019) noted that solar adoption in Rajasthan dairy clusters reduced diesel use by 70%.

9.2 Smart Grids and IoT: Smart meters and IoT-based monitoring systems track energy consumption, milk temperature, and equipment efficiency. These technologies optimize resource use, detect faults early, and prevent breakdowns. Integration of smart systems in BMCs and processing plants enhances operational efficiency and supports data-driven decision-making.

10. Institutional and Capacity-Building Infrastructure

10.1 Training and Extension Centers: Training centers educate farmers on climate-resilient practices, animal health management, infrastructure maintenance, and market trends. Extension services provide on-field guidance, demonstrations, and support for adopting new technologies. These centers bridge the knowledge gap and empower farmers to implement best practices. FAO & ILRI (2015) emphasized that training programs significantly boost adoption rates of sustainable practices.

10.2 E-Governance and ICT Platforms: Digital tools like mobile apps, SMS alerts, and online portals disseminate information on weather forecasts, veterinary care, market prices, and government schemes. ICT platforms like the e-Gopala App connect farmers to services and enhance decision-making. They reduce dependency on middlemen and promote transparency.

Table.1 Climate Change Impacts on Dairy and Related Infrastructural Mitigation Measures

Sl. No.	Climate Impact	Effect on Dairy Sector	Infrastructural Solution
1	Heat Stress	Reduced milk yield, fertility issues	Climate-smart animal housing with ventilation and cooling systems
2	Water Scarcity	Poor hygiene, reduced fodder growth, dehydration	Rainwater harvesting, solar pumps, water storage tanks
3	Feed Shortage	Malnutrition, lower productivity	Silage pits, fodder banks, hydroponics
4	Disease Spread	High veterinary costs, mortality	Improved drainage, biogas sanitation, vector control
5	Flooding	Animal loss, feed spoilage, transport issues	Elevated platforms, mobile shelters, all-weather roads
6	Milk Spoilage	Economic losses, reduced market access	Solar milk chillers, BMCs, cold chain logistics

Table.2 Comparison of Traditional vs Climate-Resilient Dairy Infrastructure

S.No	**Component**	**Traditional Infrastructure**	**Climate-Resilient Infrastructure**
1	Animal Housing	Closed brick sheds, poor ventilation	Elevated, open sheds with insulation and cooling
2	Water Supply	Borewells, tanker water	Rainwater harvesting, solar-powered pumps
3	Feed Storage	Open stacks, prone to spoilage	Silage units, sealed warehouses with ventilation
4	Waste Management	Open dung heaps, odor issues	Biogas digesters, compost pits
5	Milk Storage	Manual collection, high spoilage	Solar-powered chillers, BMCs
6	Energy Source	Diesel generators, grid dependency	Solar panels, wind turbines, biogas units

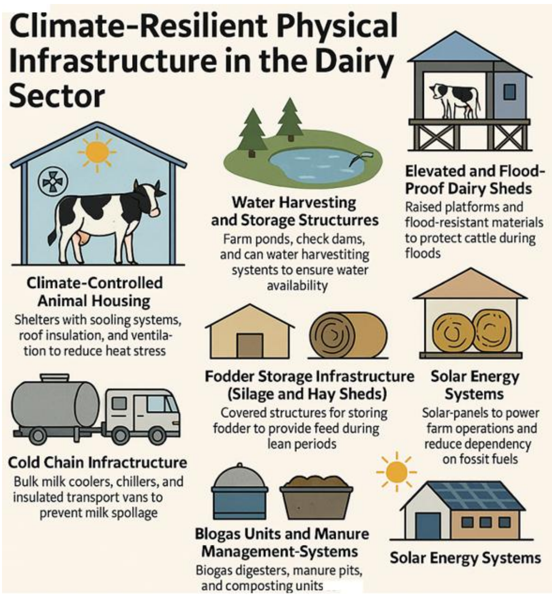

Fig.2 Climate-resilient physical infrastructure in dairy sector

11. Challenges and Limitations

High costs of infrastructure development deter smallholders from adoption. Technical complexity, lack of skilled personnel, and inadequate maintenance limit infrastructure longevity. Gender disparities in asset ownership and decision-making hinder equitable access. Policy fragmentation and lack of coordination among departments delay implementation. Addressing these challenges requires targeted support, inclusive policies, and capacity building.

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12. Future Directions

Future infrastructure should prioritize low-emission materials, energy efficiency, and climate resilience. Integrating infrastructure with climate finance and carbon credit mechanisms can unlock new funding avenues. Community-based infrastructure models promote collective ownership and sustainability. Climate risk insurance linked to infrastructure loss can enhance resilience. Public-private partnerships and multi-stakeholder platforms will be crucial.

Conclusion

Climate change presents a formidable challenge to the dairy sector. However, through strategic infrastructural development, it is possible to enhance resilience, reduce emissions, and promote inclusive growth. Investments in animal housing, water systems, energy sources, feed management, and ICT can transform vulnerabilities into opportunities. A climate-smart, infrastructure-enabled dairy sector is not only necessary for sustainability but also for equitable development and food security in a changing climate.

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Chapter-13

CLIMATE RESILIENT BREEDS AND BREEDING TECHNIQUES

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Abstract

Climate resilience means the ability of livestock to withstand or adapt, recover and survive from challenges posed by climate change. Climate-resilient livestock breeds and breeding techniques are crucial for maintaining food security and sustainable agriculture in the face of climate change. Indigenous breeds, which have evolved to thrive in specific climates, offer valuable genetic traits for heat tolerance, disease resistance, and resource utilization. Breeding strategies like crossbreeding with these indigenous breeds and utilizing genomic selection can accelerate the development of climate-smart livestock.

Key Words: livestock, climate, breed and management

1. Introduction

Climate change negatively affects livestock through its impact on health, physiology, behavior, milk production, and animal reproduction. Indirectly, it affects water availability, quality, and quantity of forage crops due to drought situations because of increased temperatures. Breeds raised in different agroecological conditions develop genetic footprints in their genomes as a result of climate-induced selective pressure. The importance of climate resilience is increasing owing to rapid climate change. Livestock are socio-culturally and economically significant worldwide, providing milk, meat, and energy sources. Indigenous cattle breeds are vital because of their disease resistance, low-input management needs, and better survival rates in adverse weather conditions (Savalia *et al*., 2019; Panigrahi *et al*., 2022a). Identifying the specific genetic factors that enable these adaptations can help researchers develop more effective strategies for conserving threatened species. It is an attempt to gather information on various breeding strategies for enhancing climate resilient cattle breeds.

2. Effect of rising temperatures on Dairy Production

Dairy cattle have been identified as being most susceptible to heat stress because they have a high metabolic rate, which affects several biological processes (Liu *et al*., 2017). India, which is characterized by various agroclimatic zones, is experiencing frequent rise in temperatures and irregular monsoon patterns thus effecting its ability to sustain the milk production. The same could be contemplated in a global scenario with severe consequences in overall production of milk and meat for human consumption thus impacting human nutrition and health. The major factor affecting milk production is heat stress (Rashamol *et al*., 2019) which forces the animal to make several physiological adjustments in order to maintain homeostasis thus, bringing about changes in its feeding pattern, udder health and rumen functions which results in reduction of feed intake, daily weight gain, feed conversion efficiency, milk production efficiency and milk quality (Dahl *et al*., 2016). It was observed that 1°C increase in the average maximum temperature resulted in a 2.4% decrease in cattle milk yield and a 2.1% decrease in buffalo milk yield. A report in the Lancet forecasts that the rise in temperature in India threatens to reduce milk production by 25% by 2085.The feed intake of lactating cows starts to decrease at room temperatures of 25–26°C and decreases more quickly above 30°C in temperate climates. Garner *et al*., (2017) reported that during heat stress, 53% decline in milk production in lactating animals. Heat stress affects both milk protein fraction and lipid profile, causing a significant decrease in milk yield and casein percentage, and changes in the polar and triacylglycerol lipid profiles (Bernabucci *et al*., 2002; Liu *et al*., 2017).

The Thermal Humidity Index evaluates the impact of heat stress on cattle and buffaloes. An index value of 72 is optimal for milk production, and if the THI value increases beyond 72, the milk production in cattle starts declining by 200 g per day (Lamesegn 2019). Heat stress is projected to cause significant losses of 339,000 tonnes of milk during 2020-29, rising to 629,000 tonnes by 2030-39. This equates to monetary losses of ₹15.25 billion from 2020-29, increasing to ₹28.30 billion in the next decade (Choudhury and Sirohi 2022). Beyond the quantity of milk, climate change is also compromising its quality, particularly the fat content, which is a crucial determinant of milk prices in India. During the hot and humid lean period, typically from April to September, a noticeable drop in milk fat content has been observed. A decrease in buffalo milk fat from an average of 6.6% to 6.0% and in cow milk from 4.5% to 4.0% was observed. The main contributor to reduced milk production during heat stress is the reduction in Dry Matter Intake (DMI) as enough energy and nutrients will not be available to the animal to maintain normal levels of production. Studies have reported that the decrease in DMI from 40 to 48% would result in decrease milk yield from 25 to 53% respectively when compared to animals in thermoneutral environments (Tao *et al*., 2017, Garner *et al* 2017).

3. Effect of Heat stress on Reproduction

Heat stress can disrupt the normal hormonal balance, leading to irregular or suppressed animal estrus cycles, making it difficult to artificially inseminate. It has been shown that during times of heat stress 80% of estrus goes undetected, even though ovulation actually occurs (De Rensis *et al*., 2015). This is likely because, heat stress reduces the signs of estrus. High temperatures can negatively affect the viability of both sperm and ova, leading to a lower chance of successful fertilization. It has also been observed that high ambient temperature causes increased uterine temperatures, which may be detrimental to the survival of gametes. Even if fertilization occurs, the early-stage embryo is highly vulnerable to heat stress, resulting in a higher incidence of embryonic death and early abortions. The conception rates of dairy cow could be dropped by 20-27% in summer. A number of studies have shown that the calves from dams that experiences heat stress late in gestation gave birth to calves with lower weight, weighing from 3.5 to 4.8 kg lighter than calves born to dams that were reared under cooler environment. (Dahl *et al*.,2016, Laporta *et al*.,2016, Monteiro *et al*.,2016, Skibiel *et al*.,2017). Studies have shown that gestation length in heat stressed dams is reduced up to 4 days, which shortens the time the calf has to grow in utero. During heat stress the dam will consume less dry matter in order to reduce her metabolic heat load, which would result in less nutrients being provided to the calf during the last few months of pregnancy which is the time when the most growth occurs. Selection for milk and meat traits without considering adaptations to extremeclimatic conditions may increase animals' susceptibility to elevated temperatures (Bayssa *et al*., 2020). So, it is necessary to identify suitable genetic improvement strategies for breeding livestock for adaptability rather than focusing high productivity alone.

4. Climate Resilient Cattle Breeds

In the current scenario with the escalating challenges of climate change, the resilience of livestock, particularly indigenous cattle, is paramount for ensuring food security, and sustaining rural livelihoods as these indigenous cattle breeds have evolved over centuries to withstand harsh environmental conditions. These hardy animals possess a unique genetic makeup that makes them exceptionally resilient to heat, drought, and tropical diseases, qualities that are increasingly valuable in a warming world. Indigenous breeds, which have evolved to thrive in specific climates, offer valuable genetic traits for heat tolerance, disease resistance, and resource utilization. Breeds with heat tolerance often possess traits like lower productivity levels, smaller body size, and specific coat colors (e.g., black coat breeds being better thermo-regulators). Indigenous breeds may also exhibit resistance to certain diseases prevalent in their respective regions, making them valuable for breeding programs.

Table. 1 Indigenous breeds Characteristics and Features

Breed	**Region of origin**	**Unique Characteristics and Features**	**Primary Use**
Sahiwal	Punjab and Rajasthan	• Considered one of the best indigenous dairy breeds. • Exceptional heat tolerance maintains milk production in high temperatures. • Resistance to parasitic infections. • High milk yield (2,000-3,000 kg/lactation) with rich butterfat content	Milch
Gir	Gujarath	Prominent convex forehead and long, pendulous ears for heat dissipation. Highly tolerant to heat and resistant to various tropical diseases. Known for its docile temperament. High milk yield (up to 3,000+ kg/lactation). Milk is famous for its A2 beta-casein protein content	Milch
Tharparkar	Rajasthan and Gujarat	Exceptionally high tolerance to heat and drought. Light-colored coat reflects sunlight. Excellent forager can survive on scanty vegetation. Strong resistance to tropical diseases. Good milk yield (1,800-2,500 kg/lactation) even in harsh conditions	Dual-Purpose
		Large, powerful build. Extremely hardy and adaptable to a wide range of climates. High	

Ongole	Andhra Pradesh	resistance to common cattle diseases. Strong draft animals, suitable for heavy work. Cows have excellent maternal instincts. Milk yield is 600-2700 kg/lactation.	Dual-Purpose
Hariana	Haryana, parts of UP and Rajasthan	Well-adapted to hot and aridconditions. Bullocks are strong, active, and willing workers. One of the most prominent breeds in northern India. Moderate milk yield (1,000-1,500 kg/lactation)	Dual-Purpose
Deoni	Maharashtra & parts of Karnataka Telangana	Well-adapted to the hot, dry climate of the Deccan plateau. Known for its hardiness and disease resistance. Good for draft purposes with moderate milk production. Milk yield is 638 to 1229 kg/lactation.	Dual-Purpose
Kankrej	Rann of Kutch, Gujarat	Distinctive lyre-shaped horns. Highly resistant to heat stress and tick fever. Powerful and sturdy build, excellent for draft work. Adapts well to both arid and semi-arid climates. Reliable milk producer (1,500-1,800 kg/lactation).	Dual-Purpose
Boran Cattle	Ethiopia	Boran cattle are integral to low-input systems and are being improved through selective breeding for milk and beef traits. Heat tolerance - Disease resistance (e.g., tick-borne diseases) Efficient feed utilization	Dual-Purpose Haile *et al*., (2011), Katiyatiya *et al*., (2017)
Nguni Cattle	South Africa	Highly valued for extensive grazing systems and as a genetic resource for climate resilience. Tolerance to extreme temperatures Resistance to tick-borne diseases	Dual-Purpose Bayer *et al*., (2004), Mapiye *et al*., (2009), and Katiyatiya *et al*., (2017)
Mashona Cattle	Zimbabwe	Used in community breeding schemes to improve productivity and maintain adaptability traits. Adaptation to semi-arid conditions Efficient use of poor-quality forage	Dual-Purpose Nymushamba *et al*., (2016) and Tavirimirwa *et al*., (2019)

5. Breeding strategies for improvement of Climate resilient dairy cattle

Selection of cattle for breeding should consider traits associated with heat-tolerance, fertility, feed conversion efficiency, relative adaptability to low-quality feed, and disease resistance and give more consideration to the genotype by environment interaction apart from high productivity, to address climate change. Following breeding techniques have been recommended for genetic improvement of cattle

6. Selective Breeding

In many developing countries the existing animal genetic improvement method has been mainly relying on selective breeding by scoring animals based on their phenotypes to determine their breeding value. These conventional methods of selective breeding were mainly for higher productivity, which has limitations in terms of environmental adaptation such as climate change. Although, selective breeding has significantly improved cattle breeds, several challenges remain such as low genetic progress in some important traits like feed conversion efficiency, fertility and adaptation to warmer climatic conditions. Selection of cattle for increased output, by ignoring traits of conservation interest such as adaptation can reduce breed distinctiveness and between-breed variation. Selection of cattle for breeding should consider traits associated with heat-tolerance, fertility, feed conversion efficiency, relative adaptability to low-quality feed and disease resistance and given more consideration to the genotype by environment interaction in addition to high productivity, to address climate change. Breeding for climate change adaptation or mitigation will not necessarily be different from prevailing programs. Recently emerged modern biotechnological tools have shown an indispensable promise for genetic improvement of beneficial traits and climate change adaptation and mitigation by improving intake, digestibility and nutritive value of low-quality forage, as well as improving animals' health. To balance the mechanism of breeding and optimize the animal breeding program, the use of molecular genetics techniques in combination with conventional animal breeding tools is necessary. Improvement of indigenous cattle breeds by selective breeding in the original breeding tract of the breeds to meet the huge requirement of superior bulls of important zebu cattle breeds, the superior milch cattle breeds like Sahiwal, Red Sindhi, Gir and dual-purpose breeds like Hariana, Ongole, Tharparkar and kankrej need to be improved by selective breeding.

7. Grading up

Improvement of non-descript local cows by Grading up with elite indigenous climate resilient dairy breeds in remote village areas. The low producing, local non-descript cattle constituting more than 75% of the total cattle population in the country is the target population to be improved. Grading up breeding option is recommended to implement in remote areas where lacking of sufficient feed and fodder resources, resourceful farmers, infrastructure development facilities, and lack of good marketing opportunities for milk and milk products.

The non-descript cows of that area can be genetically improved through grading up by using elite bulls of best dairy breeds. The bulls to be used for this purpose should be produced from superior dams, which have more than 2000 kg as lactation milk yield for Sahiwal, Red

Sindhi, Gir and Tharparkar and more than 1500 kg for dual purpose type cattle like Hariana, Kankrej and Ongole.

8. Crossbreeding

Crossbreeding indigenous breeds with climate resilient breeds can introduce desired traits like heat tolerance, disease resistance, and improved productivity into the local cattle population. Focus on backcrossing to indigenous breeds to reestablish the climate resilient traits while retaining some productive traits. Crossbreeding of low producing nondescript zebu cows with exotic breeds like Holstein Friesian, Jersey and Brown Swiss is recommended for rapid genetic improvement for enhancing the productivity of non-descript zebu cows. The optimum level of exotic inheritance should be 50% but may go up to 62.5%. HF and Jersey crossbreds perform well at 50% exotic inheritance in tropical climate. The crossbred cows so produced through crossbreeding programme should be mated ***inter-se*** with crossbred bulls of high genetic merit selected on the basis of pedigree, sib and progeny performance in such a way that the level of exotic inheritance ranges from 50 to 62.5%.

It was suggested that this process was rather adopted by cattle herders aiming to improve the resilience of B. taurus cattle population to high-intensity and frequent droughts at that time. Over the centuries, thermal environmental stressors have compromised the productivity and welfare of high-producing B. taurus dairy cattle living in tropical climates or and even those in temperate regions that frequently encounter extreme weather events. In the tropical climate of Brazil, for example, with Frontiers in the development of the dairy industry in the early twentieth century, there were attempts to introduce several European cattle breeds such as Holstein, Jersey, and Brown Swiss. Although more productive, these animals were not able to adapt to the new environment by not expressing their genetic potential due to high susceptibility to heat stress and diseases, which was exacerbated by the extensive farming system. Under such conditions, the animals were faced with high levels of solar radiation and mean radiant temperature in addition to tick infestations and other diseases (Vilela et al.,2017). Around the 1940s, Brazilian farmers began to cross the Gir cattle (an imported B. indicus breed) with the Holstein (Joshi *et al*.,1953), aiming to produce a phenotype (F1) with better thermal tolerance and yet good productive performance. Analyses of the milk yield of Holstein × Gir crosses an average of 2,574 kg per 305 days, which was significantly higher than the 1,600 kg yielded by a natural population of Gir in India (Joshi *et al*.,1953). As a result, most of the dairy cattle population in Brazil is now represented by crossbreds (mainly 5/8 Holstein × Gir). By this approach, it was established that such crossbreds possessed both productive as well as adaptive characteristics as compared to the contemporary Holstein cattle of temperate regions (Barbosa *et al*., 2008). Heat tolerance is determined by the relationship between metabolic heat production and the ability to dissipate body heat by employing evaporative cooling mechanisms, mainly through sweating. There are clear evidence of crossbreeding improving heat tolerance of dairy cattle living in hot conditions. For example, the mean coat thickness (2.7mm) was similar in Gir, Gir × Holstein F1, >75 % Holstein × Gir, and tropical purebred Holstein cattle population.

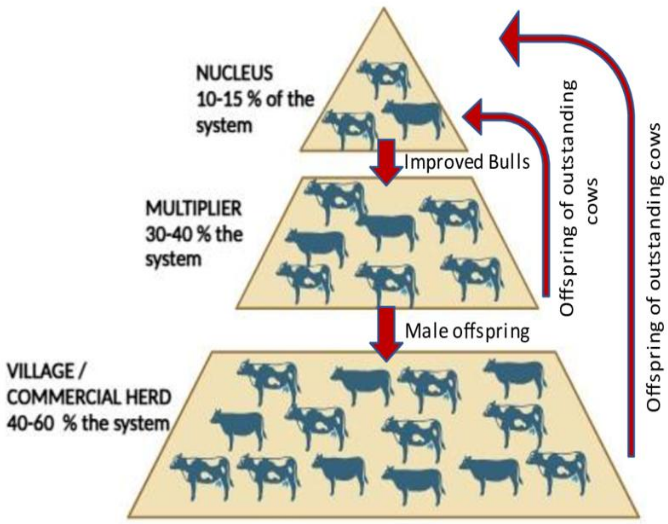

Fig. 1 Schematic representation of the Open Nucleus Breeding System, showing the hierarchical structure with gene flow (Dempfle and Jaitner, 2000)

An Open nucleus breeding scheme (ONBS) holds significant potential for developing cattle breeds that are resilient to the effects of climate change, such as heat stress and disease susceptibility. These schemes offer a structured approach to genetic improvement, especially in regions with limitations like inadequate infrastructure for artificial insemination (AI) and scattered herds. It involves establishing a central herd of elite animals with superior climate resilience traits, while a larger base population in the surrounding area contributes to the nucleus herd through a selection process. This system aims to accelerate genetic improvement for climate resilience in cattle populations by combining the benefits of both elite and local breeds.

Understanding the ONBS structure

Nucleus Herd: This central herd, optimally around 10% of the total population, comprises genetically superior animals with desirable climate resilience traits (e.g., heat tolerance, disease resistance) selected based on their performance, pedigree, or genomic data and genetic evaluation. The nucleus herd serves as a source of superior genetics for the wider cattle population

Base Population: A larger population of cattle, often indigenous breeds adapted to local conditions, forms the base. Animals from the base population are periodically selected and introduced into the nucleus herd to maintain genetic diversity and improve the overall population. These Base/Village Herds or local herds support the nucleus by contributing cows (around 10% annually in dairy cattle) selected through visual judgment for desired traits like milking ability, size, and conformation. The key advantage of ONBS is the two-way gene flow. Elite animals from the nucleus are used for breeding in the base population to disseminate superior genetics. Conversely, high-performing animals from the base herds can be introduced into the nucleus to maintain genetic diversity and adaptability this two-way gene flow helps to combine the desirable traits of the nucleus and base populations.

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India has a rich diversity of cattle breeds, many of which are known for their resilience and adaptability to local conditions. Integrating these indigenous breeds, such as Gir, Red Sindhi, Sahiwal, and Ongole, into the ONBS framework can enhance the overall resilience of the cattle population. Also integrating Modern technologies like Multiple Ovulation Embryo Transfer (MOET), genomic selection , and embryo sexing and cloning can be effectively integrated within the ONBS to accelerate genetic gain and improve selection accuracy, particularly for traits like heat tolerance. Cooperation among farmers, breeders, government agencies, and research institutions is crucial for successful implementation of ONBS, particularly in managing the nucleus and multiplier herds and facilitating the exchange of genetic material.

ONBS can achieve higher rates of genetic improvement 10 -15% compared to traditional breeding programs by concentrating elite animals and applying intensive selection, helps maintain genetic diversity and prevents a significant rise in inbreeding levels, which is crucial for long-term genetic progress. ONBS can serve a dual purpose of both conserving indigenous breeds and upgrading local populations by incorporating desirable traits. Further, the open nature of the scheme allows for the introduction of new genetic material, potentially incorporating genes for traits essential for climate resilience, such as heat tolerance or disease resistance, which can be particularly advantageous in changing environmental conditions. ONBS can be more cost-effective than other breeding strategies, as it utilizes a combination of elite and local animals.

9. Identification and Utilization of Biomarkers:

The identification and utilization of these biomarkers are crucial for developing effective breeding strategies and management practices to enhance the climate resilience of dairy herds.It is important to note that many of these biomarkers are most effective when used in combination, providing a more holistic assessment of an animal's resilience.Biomarkers associated with thermo-tolerant dairy cattle genetically designated thermal-resilient cattle would help to ameliorate dairy animals' production during the high environmental temperature (Silpa *et al*., 2021). Researchers have identified biomarkers in bovine genome having association with thermos tolerance. They include 1. Heat Shock Proteins (HSP) Genes (e.g., *HSP70*, *HSP90*). These genes produce proteins that protect cells from damage caused by stressors like heat. Higher expression can indicate a more robust stress response. 2. *SLICK*haplotype: prolactin receptor gene (PRLR) mutation. This gene is associated with a short, sleek hair coat, which enhances heat dissipation and is a strong indicator of thermo tolerance (Osei-*et al.,* 2019). 3. Toll-like Receptor 4 (*TLR4*): Genes involved in immune response and cellular signaling pathways that have been linked to milk production and thermotolerance.

10. Breeding Strategy for Disease resistance:

Climate change is expected to expand the geographical range of many pests and diseases that affect cattle. Ticks are a major concern as they can transmit a variety of debilitating and fatal diseases. Genome Wide Association Studies (GWAS) has proven to be a valuable tool in identifying cattle with a natural resistance to tick infestations. The resistance to a particular disease is moderately to highly heritable, direct selection among the breeding stock for this desirable trait could bring about improvement. Marker-assisted selection (MAS) for disease resistance involves identification of markers aided through polymorphism for the immune-response genes or identification of single-nucleotide polymorphisms (SNPs). The SNPs for certain immune-response genes have been reported for the CD14 gene in goat and cattle (Pal and Chatterjee, 2009). Examples of Immune response genes in dairy animals as mentioned below (Gogoi *et al*., 2022).

Table. 2 Immune response genes in dairy animals

Species	Example	References
Cattle and Buffalo	1. The MHC of cattle, known as the bovine leukocyte antigen (BoLA) complex, plays an integral role in disease and parasite susceptibility and immune responsiveness of host.	Fries *et al*. 1986
	2. Higher hemolytic complement activity in Bos indicus breeds is associated with higher resistance to tick infestation as compared to Bos taurus breeds.	Wambura *et al*. 1998
	3. The Nramp1 (Natural resistance-associated macrophage protein) gene has been linked with resistance to brucellosis, tuberculosis and salmonellosis diseases.	Adams *et al.* 1999
	4. The association of bovine leukocyte antigen major histocompatibility complex class II DRB3*4401 allele with host resistance to Amblyomma americanum tick.	Untalan *et al.* 2007
	5.The relationship between Bovine Lymphocyte Antigen DRB3.2 alleles, somatic cell counts and milk traits in Iranian Holstein population suggesting higher susceptibility to subclinical mastitis	Pashmi *et al*. 2009
	6. A region on chromosome 1 was associated with infectious keratoconjunctivitis (pinkeye) in cattle, which is heritable.	Kizilkaya *et al*. 2013

11. Genotype-by-environment (GxE) interactions

Breeding programs should consider how genes interact with the environment to select animals that perform well across a range of conditions.Genotype × environment interaction (G × E) studies help to evaluate the level of this uncertainty and can predict the extent to which an animal may perform in the new environment (Montaldo *et al.,*2017).The existence of genetic resistance to disease challenge implies a genotype-environment (G-E) interaction since the resistant genotype could be expected to perform relatively better in a high challenge than in a low-challenge environment. The genotype environment interaction also plays a significant role in the process of selection. Thus, selection programs have to be environment specific, with the selection environment matching the commercial production environment.

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12. Use of sexed semen technology

Artificial Insemination (AI) revolutionizes climate-resilient breeding by the use of sexed semen technology. It enables livestock producers to rapidly select and propagate animals with desirable traits for a changing climate, such as heat tolerance and disease resistance. It will be directed towards the most resilient cows to produce a new generation of high-value, climate-adapted replacement heifers. This rapidly accelerates the overall resilience of the herd.

13. Conservation of indigenous animal genetic resources (AnGR)

Conserving indigenous animal genetic resources involves both in situ and ex situ methods. In situ conservation focuses on maintaining breeds within their natural environment, while ex situ methods involve preserving genetic material outside of the natural habitat, like through cryopreservation. Effective conservation strategies also include establishing National Animal data bank, Gene banks, and animal conservation boards. In conservation, animal genetics helps preserve endangered species by maintaining genetic diversity, identifying adaptive traits, and informing breeding programs that support species recovery. By applying genetic principles, breeders and conservationists can develop more efficient, sustainable, and resilient animal populations, ultimately contributing to global food security, biodiversity conservation, and ecosystem health.

Climate change is profoundly impacting animal populations, affecting their health, productivity, and survival. Rising temperatures are leading to heat stress, reduced fertility, and increased mortality, while changes in precipitation patterns and increased frequency of extreme weather events are altering resource availability, impacting animal nutrition and survival. Additionally, climate-driven shifts in ecosystems are facilitating the spread of disease-carrying insects, increasing the risk of disease transmission among animals. As a result, animal populations are facing unprecedented challenges, highlighting the need for adaptive strategies to mitigate these impacts and ensure their long-term survival.

Genetic diversity provides the raw material for adaptation, enabling animal genetic resources to respond to changing environmental conditions. A diverse gene pool allows populations to tap into existing genetic variation, increasing the likelihood of individuals possessing traits that confer advantages in the face of environmental challenges. This diversity enhances the population's ability to adapt to shifting temperatures, altered disease patterns, and changing resource availability, ultimately improving their resilience and chances of survival. By maintaining genetic diversity, populations can better withstand environmental stressors and evolve to thrive in a rapidly changing world.

Climate change poses a significant threat to genetic diversity, as rapidly shifting environmental conditions can lead to population declines, fragmentation, and even extinction. As populations become isolated or reduced in size, genetic variation is lost due to genetic drift, inbreeding, and reduced gene flow. This loss of genetic diversity can compromise a population's ability to adapt to future environmental challenges, making them more vulnerable to disease, climate extremes, and other stressors. Furthermore, the loss of genetic diversity can also limit the potential for populations to evolve and adapt to changing conditions, ultimately threatening their long-term survival.

14. Pathway to reduce GHGs for sustainable dairy

According to the Global Livestock Environmental Assessment Model (FAO, 2013), emissions from the livestock sector is the major contributor for greenhouse gases (GHG) emissions are primarily through methane 44% (CH_4) from enteric fermentation, nitrous oxide 29% (N_2O) from manure management, and carbon dioxide 27% (CO_2) from energy use and feed production. The Intergovernmental Panel on Climate Change (IPCC) concluded that there is a clear link between rising greenhouse gas (GHG) concentrations in the atmosphere and the increasing frequency and intensity of extreme weather events (IPCC, 2021). Climate change, with its rising temperatures and extreme weather events, negatively affects cow health, fertility, and milk production. A holistic approach that integrates climate resilience into breeding goals is therefore required. Direct Methane Measurement is still a developing field; technologies are emerging to measure the methane emissions of individual animals. Incorporating this data into genetic evaluations will allow for direct selection of low-methane-emitting cattle.

15. Advanced Techniques:

Genomic Selection:

This powerful tool utilizes genetic markers to estimate the breeding value of animals for specific traits, even in the absence of phenotypic data. Genomic selection accelerates the rate of genetic gain and allows for the selection of multiple traits simultaneously. Genomic selection involves making breeding decisions based on genomic estimated breeding values (GEBVs), which are calculated by integrating SNP/genotypic data with phenotypic and pedigree data to enhance the accuracy of breeding value predictions. Genomic selection is an ideal alternative to overcome the limitation to select elite animals based on their GEBV for heat tolerance. This methodology uses genome-wide DNA markers which capture the effects of several genomic variations that influence complex traits. Genomic selection is effective in the introgression of favorable alleles of a low heritable trait from donor to a target population. Strategies use genomic-based analysis breeding principles, which can accelerate the process of cattle breeding with higher and more productive as well as adapted to the changing environments as a result of climate change, taking epigenetic influence into account.

GWAS (genome-wide association studies):

Traditional breeding methods for resilience have been a slow process, relying on observable traits. GWAS offers a more precise and rapid path forward by delving into the animal's genetic blueprint. In cattle GWAS has been utilized widely to map the QTL of essential traits like production, reproduction, and adaptive traits for heat tolerance, methane emission traits (Seabury *et al.,* 2017; Macciotta *et al.,* 2017; Liu *et al.,* 2018; Abdoli *et al.,* 2019; Sarghale *et al.,* 2020). Genome-wide association studies were also used to evaluate the milk production per lactation, persistency, milk yield at an initial stage, and age at 1st calving in multiple breeds of cattle in Thailand (Yodklaew *et al.,* 2017).By integrating GWAS findings with other advanced reproductive technologies, such as multiple ovulation and embryo transfer technology (MOET) and gene editing (CRISP-cas9), at the pace of developing cattle breeds that are not only productive but also well-suited to the changing climate can be further be accelerated. This will be critical in ensuring the sustainability of livestock agriculture and safeguarding global food security in the face of an uncertain environmental future.

Selection signature analysis applications:

Studying the genetic signatures of adaptation to climate change helps us to understand the mechanisms and genetic pathways involved. Selection signature analysis provides insights into the historical selective pressures that have shaped cattle breeds. This knowledge helps understand the genetic mechanisms underlying adaptation and can guide future breeding strategies. A study was led by Bahbahani *et al.*, 2018 toidentify signatures of positive selection in two African dairy cattle breeds. They genotyped Butana and Kenana breed of zebu-type dairy cattle using the BovineHD Genotyping BeadChip and explored for positive selection signatures using iHS and Rsb analysis. The statistical analysis revealed 87 and 61 selection regions in Butana and Kenana breeds, respectively, which included a number of genes and QTL having an association with different traits like milk production, immunity, thermotolerance, and reproduction.

Gene editing:

Emerging technologies like CRISPR-Cas9 also allow precise modifications of genes associated with thermotolerance, such as ATP1A1 in dairy cattle. Research has shown that modifying this gene improves cellular resilience to heat; indicating CRISPR’s potential to produce climate-resilient livestock that can sustain productivity under rising temperatures (Shandilya *et al.*, 2023). There is significant potential to use CRISPR-Cas9 to edit genes involved in metabolism and digestion. The goal is to develop cattle that can more efficiently convert lower-quality feed into energy and protein and utilize water more effectively. This could lead to animals that maintain their body condition and productivity even when faced with resource scarcity.

Conclusion

Dairy production is a vital source of income and livelihoods for many communities, particularly in rural areas. Heat stress has both direct and indirect effects on dairy cattle, affecting milk production and milk quality as well as the reproductive performance of the animal. We're now looking at how heat stress impacts a cow's ability to produce milk and exploring genomic tools that can help us find and breed more climate-resilient dairy cattle. Essentially, we're using advanced statistical models and cutting edge molecular techniques to pinpoint the specific genetic traits that influence milk yield and, more importantly, thermo-tolerance. In the current scenario, investigators are now concentrating on incorporating heat-tolerance, disease resistance and shallow methane emission traits into breeding strategies, which were principally focused on improving productive traits. Climate-resilient livestock rearing systems contribute to sustainable development by promoting resource efficiency, reducing greenhouse gas emissions, and enhancing the resilience. By utilizing these strategies, livestock production can adapt to the challenges of climate change thus ensuring food security, and promoting sustainable development.

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Chapter-14

INTEGRATED CROP–LIVESTOCK SYSTEMS WAY TOWARDS CLIMATE SMART AGRICULTURE

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Abstract

Climate-Smart Agriculture (CSA) aims to sustainably increase agricultural productivity, build resilience to climate change, and reduce greenhouse gas (GHG) emissions. Integrated Crop–Livestock Systems (ICLS), encompassing both poultry and dairy enterprises, align well with the CSA framework. These systems enhance nutrient cycling, optimize land and water use, and diversify income sources, making them particularly suitable for smallholder and mixed farming contexts. This chapter examines the role of ICLS as viable strategies for climate adaptation and mitigation. It explores their functional mechanisms, empirical benefits, implementation challenges, and potential strategies to promote their wider adoption.

Key Words: integrated crop–livestock systems, climate-smart agriculture, sustainable intensification, nutrient cycling, climate resilience.

1. Introduction

Global agriculture is under increasing pressure due to the combined impacts of climate change, environmental degradation, and population growth. Climate-smart agriculture (CSA) has emerged as a holistic framework that seeks to improve agricultural productivity, enhance adaptive capacity, and mitigate GHG emissions. Integrated Crop–Livestock Systems (ICLS) are at the core of CSA, involving the strategic combination of crop and animal production components within the same management unit. While traditional ICLS primarily emphasized large ruminants, the integration of poultry and dairy into cropping systems has shown particular promise in resource-constrained environments. These systems facilitate circular bioeconomies, where outputs from one component serve as inputs for another, leading to ecological intensification and enhanced system resilience.

2. Functional Principles of Integrated Crop-Livestock systems

2.1 Biophysical Integration

Biophysical integration refers to the spatial and temporal interconnection between crop and livestock components, leading to optimized resource use and mutual reinforcement. In ICLS, the interactions between poultry, dairy, and cropping systems enhance productivity and sustainability through:

- **Manure recycling**: Poultry litter and dairy manure are rich in nitrogen (N), phosphorus (P), potassium (K), and organic matter. When properly managed, these by-products enhance soil fertility, promote soil aggregation, and increase water retention capacity. This contributes to improved soil structure and long-term productivity.
- **Utilization of crop residues**: Crop residues such as maize stover, rice straw, and legume haulms serve as supplementary feed for dairy cattle and bedding for poultry. This reduces feed costs and facilitates a zero-waste model within the farm.
- **Temporal complementarity**: By aligning cropping and livestock cycles, farmers can stagger labor demands and resource utilization. For example, dairy animals may be provided with fresh fodder during the lean crop season, while crop residues are fed during the off-season. Similarly, poultry batches can be managed between crop harvests, ensuring continuous farm output and optimized land use.

2.2 Resource Optimization and Nutrient Cycling

Resource circularity is a defining feature of sustainable ICLS, wherein resources are cycled efficiently within the farm to minimize external inputs and environmental degradation:

- **Feed and nutrient loops**: Poultry droppings and dairy slurry are composted and applied to fields, reducing the need for chemical fertilizers. In turn, crop residues and agro-industrial by-products serve as feed, closing the loop.
- **Composting and energy generation**: Dairy manure is used in biogas digesters, producing renewable energy for cooking or lighting while the slurry is applied as nutrient-rich fertilizer. Poultry litter, after composting, is similarly utilized to improve soil health.
- **Water recycling**: Effluents from livestock sheds, once treated, can be used for irrigation, while integrated rainwater harvesting systems support both crop and animal needs.
- **Reduction in environmental losses**: Proper management of nutrient flows reduces leaching, runoff, and greenhouse gas emissions, contributing to agroecological sustainability.

2.3 Ecological Intensification

Ecological intensification aims to achieve high productivity through the enhancement of ecosystem services rather than through external inputs. In poultry and dairy-based ICLS, ecological intensification is realized through:

- **Pest and disease suppression**: Crop diversification and organic manures improve soil and plant health, thereby reducing vulnerability to pests and diseases. Poultry can help reduce weed seeds and insect larvae in the fields, acting as natural biological control agents.
- **Soil microbial health**: Regular application of organic matter from poultry and dairy improves microbial biomass, enzymatic activity, and overall soil health. This leads to better nutrient availability and resilience under climate stress.

- **GHG emission reduction**: ICLS reduce emissions by replacing synthetic fertilizers with manure, minimizing transport-related emissions via on-farm inputs, and improving feed efficiency. Biogas from dairy manure substitute's fossil fuel usage, while poultry exhibits lower methane emissions per unit of protein compared to ruminants.

These principles make ICLS not just an option but a necessary step toward achieving sustainable and climate-resilient farming systems, especially in regions vulnerable to climatic shocks and resource constraints.

3. Role of ICLS in Climate-Smart Agriculture

3.1 Productivity Enhancement

Integrated Crop–Livestock Systems (ICLS) markedly elevate agricultural productivity by harnessing synergies between crop and livestock enterprises. In India, advanced Integrated Farming System (IFS) models that combine cereals, horticulture, dairy, goats, poultry, vermicompost, and azolla achieved an impressive maize-equivalent yield of approximately 162 t/ha, compared to around 98 t/ha under conventional monocropping systems—a ~65% increase in total productivity. Correspondingly, net returns were about ₹318,000/ha/year, more than 2.5 times greater than ₹75,000/ha in conventional systems. Within these systems, the poultry component delivered ~4.76 tons of rice equivalent yield, net returns of ₹58,500, and a robust benefit:cost (B:C) ratio of ~2.6, while dairy operations contributed ~7.65 tons REY and ₹55,800 net income, albeit with a lower B:C ratio (~1.6) due to higher feed costs. Furthermore, FAO-IAEA coordinated research demonstrated that Indian ICLS improved livestock reproductive efficiency and average body weight by approximately 15%, boosting overall farm productivity.

Nutrient recycling efficiency is also high: a 0.4 ha model integrating crops, poultry, and goats generated 55 kg N, 17 kg P, and 76 kg K per season from internal manure and compost cycles, significantly minimizing synthetic fertilizer dependence. Notably, smaller farms following ICLS were found to have lower energy use and global warming potential than larger high-input farms, thanks to reliance on on-farm feed and compost loops.

These findings confirm that integrating poultry and dairy into cropping systems in India—underpinned by strong nutrient recycling and enterprise complementarities—delivers substantial gains in productivity, profitability, and sustainability aligned with Climate-Smart Agriculture objectives.

3.2 Climate Adaptation

CSA Function	Poultry Contribution	Dairy Contribution
Livelihood Diversification	Eggs and birds offer income and food	Milk sales support cash flow and food security
Soil and Water Management	Poultry manure improves soil health	Dung enhances compost and water retention

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CSA Function	Poultry Contribution	Dairy Contribution
Risk Buffering	Fast-growing flocks offset crop failure	Dairy animals provide stable returns
Inclusive Resilience	Women and youth manage poultry	Cattle rearing supports household livelihood

3.3 GHG Mitigation

Integrated Crop–Livestock Systems (ICLS), particularly those incorporating poultry and dairy, contribute significantly to greenhouse gas (GHG) mitigation through multiple mechanisms that optimize nutrient use, reduce emissions, and enhance carbon sequestration.

- **Reduced reliance on synthetic fertilizers**: The recycling of animal waste—poultry litter and dairy manure—provides an organic source of nitrogen (N), phosphorus (P), and potassium (K), decreasing the need for energy-intensive chemical fertilizers. The substitution of synthetic fertilizers with organic manures has been shown to reduce N_2O emissions by up to 25%, particularly in cereal-based cropping systems.
- **Enhanced soil carbon sequestration**: Regular application of organic amendments from livestock operations contributes to the buildup of soil organic matter (SOM). This not only improves soil health and water retention but also facilitates long-term carbon storage. Integrated systems that include cover crops, conservation tillage, and manure application can sequester an estimated 0.3 to 1.2 tons of carbon per hectare per year, depending on the agroecological context.
- **Improved feed conversion efficiency (FCE) in poultry**: Poultry, especially broilers, exhibit one of the lowest feed conversion ratios (FCRs) among livestock species (typically 1.6–1.9), translating to less methane and carbon dioxide emission per unit of edible protein. Compared to ruminants, poultry generate significantly lower enteric methane emissions, making them a climate-efficient protein source when integrated into crop-livestock systems.
- **Biogas from dairy manure**: Anaerobic digestion of dairy manure in biogas plants captures methane that would otherwise escape into the atmosphere. This methane is converted into a renewable energy source, reducing dependence on fossil fuels for cooking, heating, or electricity generation. A single household-scale biogas unit processing 20–25 kg of cattle dung per day can offset up to 1,800 kg CO_2-equivalent emissions annually.
- **Reduced emissions from transportation and external inputs**: On-farm nutrient and energy cycles reduce the need for off-farm inputs and transport, which are major contributors to agricultural emissions. By internalizing inputs, ICLS cut down on emissions associated with fertilizer manufacture and logistics.

Together, these mechanisms position ICLS as a pivotal tool in climate mitigation strategies, aligning with global commitments to reduce agricultural emissions under frameworks like the Paris Agreement and India's Nationally Determined Contributions (NDCs).

4. Challenges to Adoption of Integrated Crop–livestock Systems

Despite the clear benefits of Integrated Crop–Livestock Systems (ICLS), especially those incorporating poultry and dairy, widespread adoption remains limited due to multifaceted challenges:

4.1 Technical and Knowledge Barriers

The successful implementation of ICLS requires comprehensive knowledge and skills in managing complex interactions between crops, poultry, and dairy. Many smallholder farmers lack access to adequate extension services or technical training on:

- Proper manure handling, composting techniques, and nutrient management to avoid nutrient losses and environmental pollution.
- Optimal feeding strategies to balance crop residues and formulated feeds for poultry and dairy cattle.
- Disease management and biosecurity practices crucial for integrated systems to prevent cross-species transmission.
- Adoption of climate-resilient breeds and varieties suitable for integrated systems.

4.2 Capital and Infrastructure Limitations

Initial investments in infrastructure such as poultry housing, dairy sheds, feed storage, water harvesting, and biogas digesters can be substantial. Small and marginal farmers often face:

- Limited access to affordable credit or financial products designed for integrated systems.
- Lack of physical infrastructure for cold chains and processing units to add value to milk and poultry products.
- Inadequate market access for diversified outputs, reducing incentives to intensify integration.

4.3 Resource Competition and Environmental Constraints

- Competition for land and water between crop production and forage cultivation for livestock is a key constraint, particularly in water-scarce regions.
- Overgrazing or improper residue removal for feed can degrade soil organic matter and reduce long-term productivity.
- Waste management challenges arise when poultry litter and dairy manure are produced in excess or improperly handled, potentially causing nutrient runoff and greenhouse gas emissions.

4.4 Institutional and Policy Gaps

- Fragmented policies and lack of coordination between crop and livestock development programs reduce synergies.
- Limited policy incentives or subsidies targeted specifically at integrated systems.
- Insufficient regulatory frameworks for safe manure use, animal welfare, and environmental compliance.
- Weak market infrastructure and value chain linkages hinder farmers' ability to realize full economic benefits.

4.5 Social and Cultural Factors

- Gender roles and labor dynamics may restrict women's and youth's participation in integrated enterprises, particularly in dairy and poultry sectors.
- Traditional farming practices and risk aversion slow adoption of new integrated approaches.
- Limited community-based institutions and cooperatives reduce collective action for input procurement, marketing, and knowledge sharing.

5. Strategies for Promotion and Scaling Up of ICLS

To overcome these challenges and maximize the benefits of integrated crop-poultry-dairy systems, coordinated multi-level strategies are essential:

5.1 Capacity Building and Knowledge Dissemination

- **Targeted Training:** Provide farmer field schools, demonstrations, and participatory workshops focusing on integrated nutrient management, animal husbandry, disease prevention, and climate adaptation practices.
- **Extension Innovations:** Use ICT tools, mobile apps, and decision support systems to disseminate timely information on weather forecasts, feed formulations, and market prices.
- **Farmer-to-Farmer Learning:** Encourage peer learning and local innovation platforms for sharing best practices and troubleshooting system constraints.

5.2 Access to Finance and Inputs

- **Credit Facilities:** Develop tailored microfinance schemes and loan products that consider the mixed nature of ICLS investments and cash flow patterns.
- **Input Supply Chains:** Facilitate availability of quality feeds, veterinary services, improved breeds, and composting equipment through public-private partnerships.
- **Subsidies and Incentives:** Design subsidies or cost-sharing models that promote adoption of biogas units, water harvesting systems, and improved animal housing.

5.3 Policy and Institutional Support

- **Integrated Policies:** Formulate coherent policies that integrate crop, livestock, and environmental objectives, fostering synergy and reducing conflicting directives.
- **Market Development:** Support value chain development for poultry and dairy products with quality standards, certification schemes, and aggregation centers.
- **Environmental Regulations:** Implement guidelines on manure management and nutrient recycling to safeguard environmental health while promoting sustainable intensification.

5.4 Technological Innovations

- **Improved Animal Genetics:** Develop and disseminate climate-resilient poultry breeds and dairy cattle with enhanced productivity and disease resistance.
- **Low-Cost Infrastructure:** Promote affordable and locally adaptable poultry housing, dairy sheds, and biogas digesters that suit smallholder conditions.
- **Feed Innovations:** Develop feed formulations incorporating agro-industrial by-products and locally available resources to reduce feed costs and dependency on external inputs.
- **Digital Tools:** Employ precision agriculture and livestock monitoring technologies to optimize resource use and enhance system resilience.

5.5 Research and Development

- **Systems Research:** Conduct multi-disciplinary research to optimize crop-livestock integration at farm and landscape scales, including nutrient cycling, economic analysis, and resilience assessments.
- **Participatory Approaches:** Engage farmers in co-designing ICLS models that fit local agroecological and socio-economic contexts.
- **Climate Impact Studies:** Monitor long-term impacts of integrated systems on carbon sequestration, GHG emissions, and climate vulnerability reduction.

5.6 Social Inclusion and Gender Empowerment

- Promote women's participation in poultry and dairy management through training, access to inputs, and financial services.
- Facilitate youth engagement by introducing entrepreneurship models linked to integrated farming.
- Strengthen community-based organizations to support collective action in marketing, input procurement, and knowledge exchange.

6. Case Studies and Empirical Evidence from India

Indian agricultural research institutions and development programs provide ample empirical evidence on the benefits and scalability of crop-poultry-dairy integrated systems:

6.1 Tamil Nadu Model of ICLS

In Tamil Nadu, integrated farming involving maize, poultry, goats, and dairy cows improved system productivity and income diversification. Poultry provided quick cash flow through egg and meat sales, while dairy ensured stable income via milk production. Manure management practices improved soil fertility indicators such as organic carbon content by 12% over three years. This integrated model increased net farm income by 40-50% compared to conventional monoculture.

6.2 ICAR Integrated Farming System Modules

The Indian Council of Agricultural Research (ICAR) developed modular ICLS models tailored for different agro-climatic zones, combining cereals, legumes, poultry, dairy, and vermicomposting. Trials indicated maize-equivalent yields increased by up to 60%, with benefit-cost ratios exceeding 2.5. Nutrient recycling efficiencies were high; farms reported reductions in synthetic fertilizer use by 30-40% due to manure application.

6.3 FAO Climate-Smart Agriculture Programs

FAO-supported programs in India emphasize integrating poultry and dairy with crops as a core CSA strategy. Participatory farmer field schools led to adoption rates exceeding 70% in pilot districts, accompanied by 20% increases in household income and improved dietary diversity. The programs also promoted biogas digesters using dairy manure, reducing indoor air pollution and fossil fuel use.

6.4 Smallholder Poultry and Dairy Contributions

Recent surveys reveal that small-scale poultry enterprises contribute 20-30% of rural household income, with women playing a dominant role in management. Dairy income provides cash flow continuity and is often used to finance inputs for crop production. Manure recycling from these systems improved soil organic carbon stocks by approximately 10-15% annually, contributing to climate mitigation and soil health.

7. Conclusion

Integrated Crop–Livestock Systems that incorporate poultry and dairy and other livestock enterprises provide a viable and scalable pathway toward Climate-Smart Agriculture. By promoting resource optimization and nutrient recycling, ecological intensification, and diversified livelihoods, these systems improve productivity, enhance resilience to climate variability, and reduce greenhouse gas emissions. While challenges persist related to knowledge, infrastructure, and policy environments, targeted strategies including capacity building, technological innovation, and inclusive policies can accelerate adoption. Given the significant empirical evidence from India and global contexts, ICLS should be central to sustainable agricultural development agendas seeking to address the complex challenges of climate change.

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