REVIEW ARTICLE

Indian Journal of Animal Research, Volume 60 Issue 9: 1535-1546 (September 2026)

Climate-resilient Forage Systems for Enhancing Livestock Health and Nutritional Security: A Review

Bishal Kumar Mishra[1], Amit Kumar Yadav[2], Tanu Sharma[3], Kamaran Azam[4], Neeraj Sharma[5], Ashok Kumar Yadav[5], Vibha Yadav[6]

10.18805/IJAR.B-5867

ABSTRACT

Climate change is transforming the patterns of production of forage by changes in temperature, rainfall, seasonality and extreme weather conditions, posing health and nutritional security threats to livestock. Therefore, climate-resilient forage systems combine plant genetics, species diversity, adaptive management, soil and water conservation and landscape-scale planning to stabilize feed availability and quality in changing conditions is required. This review is based on detail of climate-resilient forage systems, its design strategies (diversification, mixed-species swards, perennial integration, agroforestry), management strategies (grazing management, nutrient preservation, irrigation strategies) and applications for enhancing livestock health and nutritional Security. It reflects on animal health and productivity for ecosystem service delivery.

Key words: Climate-resilient, Forage, Livestock, Nutritional security.

Climate change has been created a significant challenge for the sustainable agriculture system in the world. Crop and livestock systems are being directly impacted by rising global temperatures, atmospheric CO_2 levels, unpredictable rainfall, extended droughts and frequent extreme weather events. Rural livelihoods, agricultural GDP and the livestock sector, which is a major source of nutrition in the world. As population pressure rises, more land is allocated to food and cash crop cultivation, leaving limited arable land for fodder production. This highlights the importance of focusing on fodder production in modern agriculture. To meet the high demand for fodder, excessive and continuous application of large quantities of high-analysis chemical fertilizers has had detrimental effects, resulting in decreased productivity due to nutrient limitations. Consequently, it faces major difficulties in optimizing the use of available land to produce adequate and high-quality animal feed. Hence, to address the critical gap in crude protein and total digestible nutrients (TDN) availability in India. Rangasami *et al.* (2024) As per statement of Food and Agriculture Organization (FAO), livestock systems contribute around 40 per cent of world agricultural production and help to subsist more than one billion people in the world. Nevertheless, the health of animals, their reproductive performance and overall production levels are at risk due to the impact of climate-related stressors, including heat stress, water shortages and decreased pasture productivity (FAO, 2013; IPCC, 2022). Many areas, especially arid and semi-arid ones are already experiencing the effects of the climate change that is making the rangelands and forage crops less productive. Heat stress lowers the feed consumption, disturbs the metabolic processes and predisposes livestock to diseases, thus lowering the milk production, growth rates and reproductive activities (IPCC, 2022). This has been made the creation of resilient feed and forage systems the focus of climate adaptation strategies in animal agriculture. The nutritional basis of ruminant livestock production is comprised of forage systems. Natural pastures, cultivated fodder crops, forage legumes, shrubs and silvopastoral systems are important sources of nutrients needed to maintain, grow, reproduce and lactate. In most developing regions, up to 70-80% of the total feed intake in ruminant diets is forages (FAO, 2018). Sustainable forage production does not only decrease the usage of expensive concentrate feeds but also improves soil fertility, carbon sequestration and ecosystems resiliency.

[1]Department of Agronomy, School of Agricultural Science, IIMT University, Ganganagar, Meerut-250 001, Uttar Pradesh, India.
[2]School of Computer Science and Artificial Intelligence, SR University, Warangal, Hyderabad-500 001, Telangana, India.
[3]Department of Chemistry, School of Sciences, IIMT University, Ganganagar, Meerut-250 001, Uttar Pradesh, India.
[4]Department of Agronomy, School of Agricultural Science, IIMT University, Ganganagar, Meerut-250 001, Uttar Pradesh, India.
[5]College of Education, IIMT University, Ganganagar, Meerut-250 001, Uttar Pradesh, India.
[6]School of Agricultural Science, IIMT University, Ganganagar, Meerut-250 001, Uttar Pradesh, India.

Corresponding Author: Vibha Yadav, School of Agricultural Science, IIMT University, Ganganagar, Meerut-250 001, Uttar Pradesh, India. Email: yvibha3@gmail.com

ORCID: 0009-0005-8616-0287

How to cite this article: Mishra, B.K., Yadav, A.K., Sharma, T., Azam, K., Sharma, N., Yadav, A.K. and Yadav, V. (2026). Climate-Resilient Forage Systems for Enhancing Livestock Health and Nutritional Security: A Review. *Indian Journal of Animal Research.* **60(9):** 1535-1546. doi: 10.18805/IJAR.B-5867.

Submitted: 28-05-2026 **Accepted:** 06-07-2026 **Online:** 23-07-2026

Forage systems resistant to climate that are typified by drought-tolerant species, deep-rooted perennials, pastures with mixed species and integrated crop livestock strategies are very important in maintaining the feed supply in the fluctuating climatic conditions. The studies show that diversified and adaptive forage systems are able to amortize the production losses in the cases of extreme weather and preserve soil health and biodiversity (Thornton *et al.,* 2009; Dumont *et al.,* 2015. Nutrient availability and metabolic efficiency are determined by parameters like the crude protein content, fiber fractions (NDF and ADF), mineral composition, digestibility and the presence of bioactive compounds. Good-quality forages are beneficial because they make the rumen more efficient, boost the immunity, reproductive efficiency and yield of milk and meat. On the other hand, malnutrition, metabolic diseases, impaired immune system and decreased productivity are possible outcomes of low-quality forage (Van Soest, 1994; McDonald *et al.,* 2011). The better quality of forage is not only beneficial to the health of animals, but also to the nutritional content of animal food. Nutritionally balanced forage diets yield milk and meat with better fatty acid profile, increased micronutrient density and overall quality. Therefore, animal-based food is vital in food and nutritional security because climate-resilient and nutrient-dense forage systems help provide protein and key micronutrients in animal-source food in the areas where they are essential (FAO, 2019). Livestock can play a vital role in improving the lives of millions by providing the sufficient and reliable supplies of meat, milk, eggs and dairy products, diversifying food basket with animal-source foods; helping to generate income and creating employment and strengthening the rural household assets thus improving the livelihood. Pampori and Sheikh, (2023). Maintaining a good supply and quality of forage under adverse climatic conditions is thus essential in supporting the health and human food of the livestock. The purpose of this review is to present a synthesis of the current knowledge on climate-resilient forage systems and how they contribute to improving livestock health and nutritional security. The climate resilient forage systems, therefore, play a crucial role in ensuring the livestock productivity and human nutritional security in the face of increased global temperatures. These systems incorporate certain species of plants and management methods to supply high-quality feed when there is a drought and in extreme weather conditions. This review shows the implication of resilient forage systems which reinforce livestock production systems and create a long-term sustainable system followed by climate variability with combination of agronomic, environmental and nutritional thinking. This article addresses a critical knowledge gap by bridging these isolated domains into a unified framework. It provide a mechanistic synthesis of how climate-induced biochemical alterations in forages directly influence livestock gut health, immunity and the ultimate nutritional density (proteins, micronutrients and fatty acid profiles) of meat and dairy products.

Review design and literature survey

This review is a systematic approach to identify, assess and synthesize scientific literature related to climate-resilient forage systems and their role in enhancing livestock health and nutritional security. It aims to compile the current knowledge on resilient forage characteristics, adaptive management strategies, ecosystem interactions and their implications for sustainable livestock production under changing climatic conditions (Table 1 and Table 2).

Research gap identified

A research gap analysis identifies a radical gap between how common climate adaptation practices are applied and how they work in practice in livestock production systems. Existing research can find drought-tolerant plant species and generally fails to address the direct effect of climate-stressed plants on the digestion of animals, their metabolic balance and the production of food chains over a longer period of time.

Progress on climate resilient forage systems

The current baseline for climate-smart livestock nutrition is largely based on changing less resilient, water-intensive crops to alternatives that are more resilient (Fushai *et al.,* 2025).

Drought-tolerant cultivars

Agronomic attention is given to small cereal grains, *e.g.*, sorghum (*Sorghum bicolor*) and pearl millet (*Pennisetum glaucum*) and native legumes such as cowpea (*Vigna unguiculata*) as alternatives to conventional energy and protein feeds (Fushai *et al.,* 2025).

Circular and alternative feedstocks

There is growing focus on circular agricultural systems that utilise agro-industrial byproducts such as macadamia, castor and Jatropha oilseed cakes and alternative proteins such as Black Soldier Fly larvae (Fushai *et al*., 2025).

Thermo-functional supplementation

Presently, precision nutrition models are based on dietary strategies, including electrolyte and antioxidant supplementation, to support livestock's internal acid-base equilibrium and oxidative cell damage caused by heat stress (Fushai *et al*., 2025).

Critical research gaps

In spite of these advances, evidence of how climate-resilient forage production can impact livestock health and nutrition security is sparse.

Gap A: Nutritional dilution under elevated CO_2 and thermal stress

Some forage species can withstand severe environmental conditions, but their nutritional quality decreases.

Table 1: Climate-resilient forage systems and their implications for livestock health and nutritional security.

Author	Focus area forage strategy	Climate resilient	Major findings health and nutritional security	Implications for livestock
Chapman *et al.* (2020)	Future forage systems	Climate-resilient forage breeding and management	Advanced breeding strategies may improve adaptation to climatic stress	Improved forage performance supports livestock productivity and food security.
Rojas-Downing *et al.* (2017)	Climate change impacts on livestock systems	Climate-smart livestock and forage management	Climate stress affects feed availability, animal productivity and health status	Improved forage systems can reduce nutritional stress and sustain livestock productivity
Lee *et al.* (2017)	Effects of climate change on forage quality	Heat- and drought-tolerant forage cultivars	Environmental stress alters digestibility and nutrient composition of forage	Maintenance of forage quality supports animal growth and health
Ergon *et al.* (2018)	Climate adaptation in forage crops	Breeding climate-resilient forage species	Drought and temperature tolerance traits are essential for future forage systems	Supports continuous feed availability and resilient production systems
FAO (2018)	Climate-smart agriculture and livestock systems	Sustainable forage and adaptive feeding systems	Diversified feed systems improve resilience and reduce climate vulnerability	Enhances nutritional security and stabilizes livestock systems
Soni *et al.* (2020)	Climate effects on forage and pasture production	Climate adaptation and forage mitigation strategies	Elevated CO_2 and climatic extremes influence forage productivity and quality	Adaptive forage management reduces feed scarcity risks
Das *et al.* (2021)	Climate-resilient animal husbandry	Climate-resilient livestock feeding systems	Feed and fodder shortages are major climate-induced constraints	Resilient forage systems improve livestock productivity and health outcomes
Chapman *et al.* (2020)	Future forage systems under climate variability	Resilient forage breeding and management	Forage adaptation requires integrated breeding and management approaches	Supports long-term nutritional security and sustainable livestock production
Gomara *et al.* (2024)	Climate variability and forage productivity	Climate-informed grassland management	Climate variability strongly affects forage production patterns	Better prediction and management can stabilize feed resources
Kuju *et al.* (2025)	Climate-smart Agriculture: A pathway to food security	Climate smart agriculture responds to the practices and climate resilience livestock productivity in spite of climate adversities	Climate Smart (CSA) has the potential to revolutionize that enhance crop and three key areas: Making it more sustainable, more resilient and better adapted to climate change.	It is applicable for policies, innovative technologies of stakeholders the global food system in and active involvement by using climate smart agriculture at the centre to bring about a transformation in mitigating the intensifying impacts of climate change toward ensuring global food systems.

Table 2: Climate resilient characteristics, adaptive management and ecosystem relationships for enhancing livestock health and nutritional security.

Authors	Study focus	Resilient characteristics, adaptive management and ecosystem relationship	Major findings	Implications for livestock health and nutritional security
Rojas-Downing *et al.* (2017)	Climate impacts on livestock systems	Climate-resilient livestock and forage adaptation strategies	Heat stress and feed scarcity significantly influence animal productivity and health	Resilient feeding systems reduce nutritional stress and improve animal performance
Lee *et al.* (2017)	Climate change effects on forage quality	Heat- and drought-tolerant forage cultivars	Climatic stress reduces forage digestibility and nutrient content	Improved forage resilience supports balanced nutrition and livestock productivity
Ergon *et al.* (2018)	Climate adaptation in forage crops	Selection of drought and temperature tolerant forage traits	Adaptive forage traits improve persistence under climatic stress	Continuous feed availability improves animal health and nutritional status
FAO (2018)	Climate-smart livestock systems	Sustainable and climate-resilient livestock management	Diversified feed and management systems enhance resilience	Strengthens food and nutritional security in livestock-based systems
Van Wijk *et al.* (2020)	Integrated crop-livestock systems	Ecosystem interactions and integrated farming approaches	Crop-livestock integration enhances resilience and resource-use efficiency	Improves feed security and dietary diversity at farm level
Soni *et al.* (2020)	Climate effects on forage and pasture production	Adaptive forage management and mitigation strategies	Climate variability affects pasture productivity and forage quality	Adaptive management reduces seasonal feed shortages
Castro montoya and Dickhoefer (2020)	Tropical forage nutritional quality	Diverse tropical forage legumes and feeding forms	Nutritional quality differs among forage species and feeding systems	Supports improved nutrient utilization and animal health
Rao *et al.* (2021)	Agroecosystem services of forage legumes	Ecosystem services through forage diversification	Forage legumes improve biodiversity, soil fertility and sustainability	Better forage quality enhances animal nutrition and health
Rao *et al.* (2021)	Tropical forages and agroecological transformation	Mixed crop-tree-livestock systems and ecosystem resilience	Improved tropical forages support multiple ecosystem functions	Enhances year-round feed resources and long-term system sustainability
Das *et al.* (2021)	Climate-resilient animal husbandry	Resilient livestock management strategies	Climate stress affects feed availability and animal productivity	Integrated resilience approaches support livestock health and livelihood security
Gauly and Ammer (2020)	Dairy production under climate change	Adaptive herd and feeding management	Heat stress negatively affects animal performance and welfare	Climate adaptation improves health and productivity outcomes

An increase in CO_2 in the atmosphere effects the internal composition of the plant, which results in significant decreases of key proteins, iron and zinc levels (Session, 2026). Furthermore, climate change-induced changes accelerate the process of lignification, the build-up of fiber and lignin (Hossein-Zadeh, 2026). This means a very intricate balancing act:

$$\text{Climate resilience (survival)} \propto \text{lignin content} \propto \frac{1}{\text{Rumen digestibility}}$$

Highly lignified forage, which is very fibrous, has a slow rate of rumen fermentation and unavoidably causes increased enteric methane emissions and thus lower net energy intake (Hossein-Zadeh, 2026).

Gap B: Toxicological and food safety vulnerabilities

Changes in precipitation and temperature provide a breeding ground for environmental pathogens. In particular, toxigenic fungi can multiply quickly because of warm conditions, which can result in significant feed contamination with mycotoxins during storage (Session, 2026). Current forage research does not trace the geographical range expansion of toxic weeds, crop diseases and pests as a result of changing climate, which is directly impacting livestock health and export food safety standards (Alotaibi, 2023; Session, 2026).

Gap C: Disarticulated technological and institutional scaling

There is a significant gap between the laboratory scale multi-omics and/or AI based phenotyping and the application in the field by smallholders (Thingujam *et al.,* 2025). Vulnerable farming communities are not well protected by current local support systems that offer access to affordable networks of seed distribution and precision data tools, which can withstand rapid climate disruptions (Mmbando, 2025).

Comparative synthesis

The following table highlights key differences between the current agriculture emphasis and the research gaps identified that constrain long-term nutrition security (Table 3).

Methodology and key concepts

Climate change and its impact on forage production

The effect of climate change is causing substantial change in the productivity, distribution and nutritional content of forage resources across the globe. Temperature and precipitation changes, atmospheric CO_2 levels and the occurrence of extreme climatic conditions have a direct impact on the plant growth, species make up, soil well-being and persistence of pastures. As the major feed base of the ruminant livestock, these effects are critical in the development of climate resilience in forage systems (IPCC, 2022; FAO, 2013). Climate-resilient forage systems combine better forage species and cultivars, adaptive management systems and ecosystem-based systems to absorb climatic shocks and not compromise livestock nutritional adequacy. The objective of these systems is not only to sustain the production of biomasses under stress but to retain or even improve the levels of crude proteins and digestibility and energy value, which are frequently lost by heat and water stress (Hatfield and Prueger, 2015; Ergon and others, 2018). In recent reviews, the focus on diversification of species (especially integration of legumes), genetic enhancement to increase stress tolerance, soil health improvement and effective use of water is highlighted as the base principles (FAO, 2018; Lemaire *et al.*, 2019).

The representation of climate change and its impact on forage production are given as follows (Fig 1).

(a) Temperature rise

Increasing global temperatures influence the dynamics of forage growth, phenology and productivity. Raising temperatures by moderate amounts could increase photosynthesis and lengthening growing seasons in cooler areas; but excess heat stress tends to lower biomass production, hasten plant maturation and decrease vegetative growth periods. Increased temperature causes more rapid rates of plant respiration that lowers net carbon gain and

Table 3: Comparative synthesis.

Functional vector	Current status	Identified research gap
Agronomic selection	Yield and survival under severe drought (Fushai *et al.*, 2025).	Overlooking the dilution of vital proteins and micronutrients under elevated CO_2 (Session, 2026).
Rumen metabiome	Utilizing traditional, slow-digesting fibrous feedstocks (Hossein-Zadeh, 2026).	Mitigating the increased enteric methane emissions caused by highly lignified plant material (Hossein-Zadeh, 2026).
Animal bioenergetics	Relying on short-term electrolyte or antioxidant therapy to manage heat stress (Fushai *et al.,* 2025).	Developing long-term data on the metabolic heat increments of alternative forage varieties (Fushai *et al.*, 2025).
Biosecurity and Safety	Standard monitoring of typical storage mold and pasture degradation.	Tracking unpredictable spikes in mycotoxins and toxic weeds driven by volatile weather changes (ALOTAIBI, 2023; Session, 2026).

forage yield (Hatfield *et al.,* 2011). Cool-season (C_3) grasses are more susceptible to heat stress than warm-season (C_4) species and may change the composition of pasture species. Based on the report by the Intergovernmental Panel on Climate Change (IPCC, 2022) warming patterns will cause agro ecological zones to shift, affecting the appropriateness of forage species in different locations. Also, higher temperature may decrease the level of crude proteins and increase the lignification process, thus lowering the level of digestibility and general quality of feed (Dumont *et al*., 2015).

(b) Altered rainfall patterns and drought stress

According to the Food and Agriculture Organization (FAO, 2013), drought has been among the biggest limitations to forage production in the arid and semi-arid areas. Nutrient uptake suffers as well due to water inadequacy and results in a decrease in protein content and mineral imbalance of forage crops. Habitual droughts can prefer drought-resistant yet lower-quality species leading to reduced nutritive value of the total pasture (Thornton *et al*., 2009). This has resulted in seasonal shortages of feed, loss of weight and decreased productivity of livestock that rely on natural pasture.

(c) Elevated CO_2 and forage nutritional quality

Increased levels of atmospheric CO_2 will have the potential to enhance photosynthesis, especially in C_3 and thus CO_2 fertilization effect may boost forage biomass production. Nevertheless, biomass can rise, although in the process, the nutritional qualities of forage can tend to decrease under high CO_2 situations. Research shows that the concentration of crude protein, the amount of nitrogen and essential minerals like zinc and iron reduce under a dilution effect (Myers *et al.,* 2014). Higher CO_2 can promote non-structural carbohydrate storage and decrease digestibility by altering fiber composition. Dumont *et al.* (2015) further propose that scenarios of climate change with high CO_2 and high temperatures are expected to reduce the protein content of forage and raise fiber levels, thus reducing the efficiency of feed. These nutritional changes may cause adverse changes in rumen activity, growth rate of animals as well as milk production, which eventually influences the well-being of livestock and food quality.

(d) Extreme weather events and pasture degradation

The rising rate and severity of extreme weather conditions such as floods, heat waves, storms and wildfires have significant threats to the pasture ecosystems. Waterlogging, destruction of roots, loss of nutrients and soil erosion may occur due to flooding and extended heatwaves will increase evapotranspiration and desiccation of plants. Wildfires, which become more and more associated with climate change, destroy pasture biomass and decrease vegetation cover, triggering soil erosion and loss of biodiversity. IPCC (2022) highlights that repeated extreme events decrease resilience and recovery of pastures in susceptible areas, which increase the speed of land degradation and desertification. In addition to reducing forage yield, pasture degradation reduces soil organic matter and potential to sequester carbon, which exacerbates climate vulnerability. The long-term degradation may change the composition of plant species, promote invasive species and decrease the ecosystem services needed to sustain livestock production.

Framework concept

The conceptual framework is framed in three pillars of resilience are represented below:

This framework is consistent with the principles of climate-smart agriculture (CSA) that is geared towards the sustainable growth of productivity, greater resilience and minimizing greenhouse gas emissions wherever feasible (FAO, 2013). This in forage systems includes choosing the stress-resistant species, diversifying pasture mixes, using legumes to increase nitrogen fixation and employing

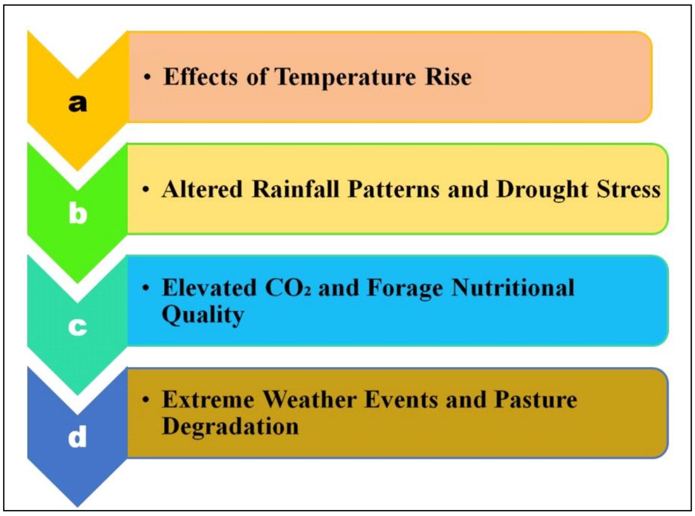

Fig 1: Effect of different climatic variables.

conservation strategies that enhance the store of soil carbon and water retention (Lemaire *et al.,* 2019). Climate-resilient forage species have the following traits: Climate-resilient forage species also have morphological, physiological and biochemical characteristics that make them tolerant to abiotic and biotic stresses without compromising nutritional quality (Fig 2).

Key traits include

A. Large and deep root system to enhance water and nutrient uptake during drought conditions. Effective water-use efficiency (WUE) and osmotic adjustment. Heat tolerance, including steady photosynthetic enzymes and membrane integrity at high temperatures.
B. Quick recovery and survival following grazing or climate stress.
C. Maintained or improved nutritive quality, such as crude protein and stress-induced digestibility.

Leguminous forages tend to be more resilient because of the biological fixation of nitrogen and a relatively high level of crude protein that keeps the quality of forages intact despite stress (Ergon *et al.,* 2018; Lüscher *et al.*, 2014). Equally, the warm-season C_4 grasses are more resistant to heat and drought than most temperate C_3 species (Hatfield and Prueger, 2015). Combined traits, including stress tolerance, resistance to disease and better fiber digestibility, are becoming a target of breeding programs to guarantee productivity and feed value (Rogers *et al.,* 2021).

Different strategies adopted for climate resilient forage systems

From recent scientific literature, it is a clear indication that climate resilient forage systems are at a crossroads of agricultural science. They can be used in one and the same way as an adaptive barrier and as a mitigating measure for regulating greenhouse gas (GHG) emissions from the livestock sector. Few strategies suggested here.

Climate-resilient forage systems incorporate both adaptive and mitigative strategies

Adaptive strategies aim at modulating production of forage to deal with climate variability. These include:

- Planting of drought and heat-tolerant forage species and cultivars.
- Diversification of pasture mixtures (grass-legume systems).
- Changing sowing dates, rotating grazing and better water management.
- Adoption of silvopastoral systems to stabilize temperatures.
- The main goal of these measures is to stabilize nutritive value and yield in the face of stress (Dumont *et al.,* 2015; FAO, 2018).

The company carries out structural and technical changes. The company implements changes to the structure and technology.

(i) Integrated Crop-livestock systems (IFS)

Dynamic integration of forage production with arable crops helps to buffer against shocks in the system including crop residues, green manuring, contingency cropping. There are recent case studies of island and tropical smallholder systems which show that IFS improves farm climate-readiness.

(ii) Silvopastorism

The introduction of trees in the forage area (silvopasture) can help to control the ambient temperature for forage crop and livestock. This helps to reduce heat stress in cattle and maintain adequate moisture levels in pasture.

(iii) Water-smart infrastructure

In-situ rain water harvesting, introduction of special drainage systems (such as raised-bed furrows) and strategic management of forage harvesting during season reduces the risk of yield gaps during dry periods.

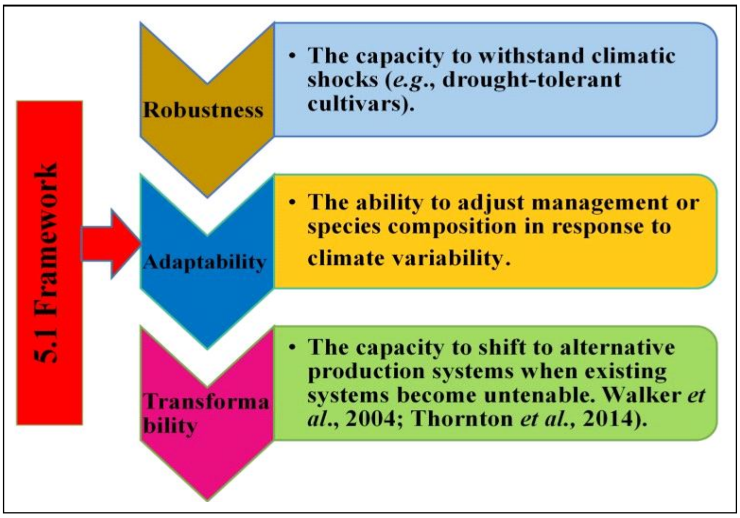

Fig 2: Framework concept.

Mitigation strategies: Making forage a carbon sink

(i) Below-ground biomass allocation

Pastures and rangelands naturally have a higher below-ground biomass allocation than harvested croplands. Recent research has shown that rangelands are able to take up a significant share of emissions from the annual global emissions.

(ii) Minimizing Emissions of Enteric Methane (CH_4) and Nitrous Oxide (N_2O)

Poor quality forage leads to longer fermentation times in ruminants and causes increased CH4 output. This significantly lowers the amount of methane released for every litre of milk or pound of meat produced.

(ii) Nutrient and crop residue recycling

Use of nitrogen-fixing forage legumes, rather than heavy synthetic nitrogen fertilizers, reduces the amount of N_2O released at the field level.

Synergies and trade-offs (The Dynamic Balance)

There is a growing emphasis in the literature on the need for both adaptation and mitigation to be used in combination to prevent maladaptation.

The major barrier

These two adaptation-mitigation approaches are not yet on the ground without coordinated regional policy mixes, adequate climate finance and solid extension support. (Table 4).

Relationship between forage nutritional composition and livestock health outcomes

The most important factor to maintain the optimum health, growth, reproduction and lactation of animals is adequate forage nutrition directly affecting global food security (Rangasami *et al.*, 2024). Nutritional value of forage, including fiber content, digestibility and nutrient bioavailability, is a decisive factor of ruminant physiological health and productive efficiency (Xiao and Meng, 2024). In particular, the complex proportions of the macronutrients (*i.e.*, crude protein and degradable carbohydrates) and micronutrients in forages determine the rumen microbial activity and further nutrient usage, which directly affects animal performance and health outcomes (Darwin *et al.,* 2023). On the other hand, the lack of or unequal quality of forage may trigger slowed growth, reduced productivity, increased vulnerability to diseases and significant economic losses (Rangasami *et al.,* 2024). As an example, a higher concentration of acid detergent fiber and neutral detergent fiber, which are signs of a greater amount of indigestible elements, is associated with decreased digestible energy and intake capability, respectively, which leads to inability to absorb nutrients and overall animal activity (Adepoju and Faniyi, 2025). Moreover, the mode of cultivation also plays an important role in determining the quality of fodders and hydroponically grown forages tend to have a higher crude protein and lipid content than their conventionally grown counterparts, which may benefit animal health and productivity (Islam *et al.*, 2024). As an example, the hydroponic wheat seeds have a crude protein level of 15.83 on a dry matter basis and a crude fat level of 4.74 on a dry matter basis with a low lignin level of 2.3, which leads to high digestibility (Tuo *et al.,* 2025). This improved nutritional composition especially the increased levels of protein and fat and the decreased levels of lignin, help to increase nutrient absorption and energy use in livestock (Tuo *et al.,* 2025).

Role of forage systems in enhancing livestock health

The climate-resilient forage systems do not only ensure the availability of feed during the fluctuating weather conditions; but are also important in enhancing the health of livestock, their immune systems, reproductive effectiveness, growth rate, as well as environmental sustainability. Quality forage supplements key nutrients, bioactive compounds and dietary fiber that impact physiological functions, disease resistance and productivity in livestock.

Immunity and disease resistance

The quality of the forage has a direct effect on immune competence in ruminants due to its direct effects on the balance of macro and micronutrients necessary to support immune system functions. Antioxidant defences, antibody production and resistance to pathogens are promoted by high-quality forages that contain a lot of crude protein, vitamins (A, E), trace minerals (selenium, zinc) and bioactive plant compounds. Studies have shown that animals grazing on high nutritional value pastures have high leukocyte activity and parasitic infections are less common than when

Table 4: Synergies and trade-offs (The Dynamic Balance).

Strategy	Adaptive benefit	Mitigative Co-benefit
Silvopastoral systems	Protect livestock and grass from heat stress.	Increases carbon stocks in the above and below ground pools.
Biodiverse legume mixtures	Ensures survival of pasture under inconsistent rainfall.	Reduces the need for synthetic fertilizers and affects animal digestion (reduction of CH_4).
Rotational grazing	Broadly prevents overgrazing and maintains soil moisture.	Increases SOM in soil.

on low quality forages or on concentrates only diets (Patra *et al.,* 2025). It has been linked with leguminous forage (*e.g.*, clovers, lucerne) that have been linked to higher serum protein and essential amino acid supply, which form the basis of immune response metabolic pathways. Moreover, some forages contain phytochemicals with anthelmintic activity (*e.g.*, condensed tannins in birds foot trefoil), which may help to reduce internal parasite loads, providing a natural means to increase disease resistance without the use of chemical dewormers (Min *et al.*, 2024).

Reproductive performance

The nutritional status of livestock is extremely sensitive to their reproductive efficiency, particularly at critical stages of reproduction (conception, early gestation and lactation). Balanced energy and protein forages are useful in sustaining ovarian activity, conception rates and early embryonic growth. Research indicates that cows that graze pastures rich in nutrients have greater pregnancy rates and reduced gestation periods between calving and conception compared to cows receiving low-quality roughages (Fernandez *et al.*, 2023). In addition, the micronutrients like selenium, vitamin E and essential fatty acids in the various pasture systems help in enhancing the gamete quality and antioxidant defence of the reproductive tissues. Multi-species swards are associated with better body condition score and hormonal profiles that facilitate successful reproduction (Singh *et al.,* 2024).

Growth and productivity

The performance of the livestock is directly proportional to the forage digestibility, crude protein, metabolizable energy and palatability. Forage grasses resistant to climate and having enhanced fiber composition (reduced neutral detergent fiber [NDF] and increased digestible energy) enhance improved feed consumption, nutrient capture resulting in enhanced average daily weight gain (ADG) in growing livestock. As an illustration, drought-tolerant sorghum hybrids and better pearl millet varieties have been found to have equivalent growth rate with more resistance to heat and water stress than the conventional grasses (Zhao *et al.,* 2025). Moreover, when legumes, which are high-protein, are incorporated in pastures, it improves the quantity and quality of milk in dairy systems because of increased intake of nitrogen along with microbial protein synthesis in the rumen. The mixed pasture systems also decrease the use of high-cost concentrates because they enhance the quality of the basal diets. (Gomez *et al.,* 2024).

Reduction in methane emissions and environmental stress

The forage systems not only affect the health of the animals but also the sustainability of the environment especially greenhouse gas emission. High-quality, highly digestible forage diets lower the amount of enteric methane (CH 4) per pound of animal product since nutrients are better utilized to generate energy and tissue instead of being emitted as methane during ruminal fermentation. As an illustration, legumes like alfalfa and sainfoin can lead to reduced levels of methane emissions compared to low-quality grass diets because of higher rumen passage rates and increased fermentation efficiency (Beauchemin *et al.*, 2025). The new breeding objectives of forages include high leaf-to-stem ratio and better fiber digestibility to enhance efficient nutrient utilization and further reduce methane production. Also, forage systems that include tannin-containing species have also been shown to have a reduction in ruminal methanogenesis without the loss of feed intake. These forage-based mitigation measures help to enhance environmental performance of livestock systems and animal health and productivity (Waghorn and Hegarty, 2024).

Detailed process dynamics

To systematically operationalize the integration of climate-smart agriculture with animal and human well-being, this review proposes a multi-tiered, closed-loop framework:

Phase 1: Climate-adaptive agronomic initiation

The process begins at the soil-plant interface, where specific agronomic systems are selected based on localized climate vulnerability indices (*e.g.*, severe prolonged drought, soil salinization, or ambient thermal spikes). To secure stable biomass yields under extreme environmental conditions where conventional C_3 crops fail.

Phase 2: Phytochemical and nutrient stabilization

Once the resilient forage is established, the framework focuses on the plant's altered biochemical profiles under climate stress. To minimize ANFs and optimize the structural-to-soluble carbohydrate ratio (NDF/ADF), ensuring the forage remains highly palatable and metabolically safe for consumption.

Phase 3: Ruminant physiological and immunological assimilation

This phase represents the core veterinary contribution of the framework, mapping how the stabilized feed matrix interacts with livestock biology. To mitigate animal heat stress, lower somatic cell counts, boost cellular immunity and reduce greenhouse gas emissions (CH_4 per unit of meat/milk) through improved metabolic efficiency.

Phase 4: Human nutritional security realization

The final phase of the framework converts livestock physiological health into tangible public health outcomes. To prevent the nutrient dilution effect typically seen in climate-stressed livestock supply chains, ensuring the continuous delivery of nutrient-dense, functional animal-source foods to vulnerable human populations.

The framework insight the paradigm of Climate-Resilient Forage Systems for Enhancing Livestock Health and Nutritional Security provides researchers and policy makers with a transparent blueprint showing that safeguarding human food security under climate stress requires an initial, calculated investment in forage biochemical selection.

CONCLUSION

The key to the protection of livestock health and nutritional security in a changing climate lies in climate-resilient forage systems. The climate-resilient forage systems improve the health of livestock by:

- Enhanced immune capacity and resistance to diseases due to adequate nutrition and bioactive substances.
- Promoting reproductive efficiency through energy, protein and micronutrient balance.
- Fostering growth and productivity with enhanced digestibility and nutrient density.
- Helping to sustain the environment by decreasing the amount of methane gas released and maximizing the utilization of nutrients.

Integrating species and functional diversity, perennial and agroforestry integration, soil- and water-oriented management and adaptive grazing have the potential to stabilize feed availability and quality, increase animal welfare and augment ecosystem services. Adoption needs conducive policies, funding, local research and robust extension. Emphasizing resilient forage systems will help to build stronger livestock-based livelihoods and food systems as climate variability increases. These integrated advantages emphasize the direct relationship between the quality of forage and system design and the animal welfare and environmental impacts in contemporary livestock production.

ACKNOWLEDGEMENT

I would like to acknowledge IIMT University and co-authors for their support and contribution.

Funding statement

Not applicable.

Conflict of interest

This manuscript hasn't submitted anywhere else.

REFERENCES

Adepoju, S.A. and Faniyi, T.O. (2025). Synergizing plant breeding and animal nutrition: A review on the development of drought-tolerant and high-nutrient forage grasses and legumes. *Innovative Agriculture.* **8(1):** 1-12.

Alotaibi, M. (2023). Climate change, its impact on crop production, challenges and possible solutions. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*. **51(1):** 13020. https://doi.org/10.15835/nbha51113020.

Beauchemin, K.A., Ungerfeld, E.M., Eckard, R.J. and Wang, M. (2025). Forage quality and enteric methane emissions: Mechanisms and mitigation strategies. *Animal Feed Science and Technology*. Advance online publication. https://doi.org/10.1016/j.anifeedsci.2024.115950.

Castro-Montoya, J.M. and Dickhoefer, U. (2020). The nutritional value of tropical legume forages fed to ruminants as affected by their growth habit and fed form: A systematic review. *Animal Feed Science and Technology*. **269:** 114641. https://doi.org/10.1016/j.anifeedsci.2020.114641.

Chapman, D.F., Dalley, D.E., Edwards, G.R., Cameron, K.C., Malcolm, B.J., Clement, A., *et al*. (2020). Production, profit and nitrogen flows in irrigated dairy systems representing different industry development pathways: The Pastoral 21 experience in Canterbury. *New Zealand Journal of Agricultural Research*. **64(1):** 3-35. https://doi.org/10.1080/00288233.2020.1807367.

Darwin, D., Bulan, R., Humaira, T.H., Muliwati, A., Augustina, F. and Baszanova, G.S.T. (2023). Impact of concentrate supplementation on biodegradability and acidosis in *in vitro* rumen fermentation of forage. *International Journal of Design and Nature and Ecodynamics.* **18(4):** 1877-1885. https://doi.org/10.18280/ijdne.180430.

Das, S.K., Karunakaran, M., De, S., Babitha, V. and Mondal, G. (2021). Climate resilient animal husbandry-A review. *International Journal of Livestock Research*. **11(4):** 1-11. https://doi.org/10.5455/ijlr.2021011806321.

Dumont, B. and ueza, D., Niderkorn, V., Lüscher, A., Porqueddu, C. and icon-Cochard, C. (2015). A meta-analysis of climate change effects on forage quality in grasslands. *Global Change Biology*. **21:** 1347-1359.

Ergon, Å., Kirwan, L., Bleken, M.A., Skjelvåg, A.O. and Collins, R.P. (2018). Climate change impacts on forage crops and grasslands. *Agronomy.* **8(9):** 1-17. https://doi.org10.3390/agronomy8090173.

Ergon, Å., Seddaiu, G., Korhonen, P., Virkajärvi, P., Bellocchi, G., Jørgensen, M. and Østrem, L. (2018). Forage crops in a changing climate: Challenges and opportunities for production in Northern Europe. *Frontiers in Plant Science*. **7:** 294. https://doi.org/10.3389/fpls.2016.00294.

FAO (2013). Tackling Climate Change through Livestock. Rome: Food and Agriculture Organization.

FAO (2018). The Future of Food and Agriculture. Rome: FAO.

FAO (2019). The State of Food Security and Nutrition in the World. Rome: FAO.

FAO. (2018). Climate-smart agriculture case studies 2018: Successful approaches from different regions. Food and Agriculture Organization of the United Nations.

Fernandez, M., Soder, K.J. and Brito, A.F. (2023). Pasture nutrition and reproductive performance in dairy cows: A meta-analysis. *Livestock Science.* **268:** 105142. https://doi.org/10.1016/j.livsci.2022.105142

Fushai, F., Chitura, T. and Oke, O.E. (2025). Climate-smart livestock nutrition in semi-arid Southern African agricultural systems. *Frontiers in Veterinary Science*. **11(12):** 1507152. https://doi.org/10.3389/fvets.2025.1507152.

Gauly, M. and Ammer, S. (2020). Review: Challenges for dairy cow production systems arising from climate changes. *Animal.* **14(S1):** s196-s203. https://doi.org/10.1017/S1751731119003239.

Gómara, I., Bellocchi, G., Martin, R., Rodríguez-Fonseca, B. and Ruiz-Ramos, M. (2024). Influence of climate variability on the potential forage production of a mown permanent grassland in the French Massif Central. *Agricultural and Forest Meteorology*. **280:** 107768. https://doi.org/10.1016/j.agrformet.2019.107768.

Gomez, A., Morales, J., Hernandez, F. and Castillo, A.R. (2024). Multi-species pasture effects on dairy yield and feed efficiency. *Journal of Dairy Science.* **107(2):** 1456-1468. https://doi.org/10.3168/jds.2023-23456.

Hatfield, J.L. and Prueger, J.H. (2015). Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*. **10:** 4-10. https://doi.org/10.1016/j.wace.2015.08.001.

Hatfield, J.L., Boote, K.J., Kimball, B.A., Ziska, L.H., Izaurralde, R.C., Ort, D., Thomson, A.M. and Wolfe, D. (2011). Climate impacts on agriculture: Implications for crop production. *Agronomy Journal.* **103(2):** 351-370.

Hossein-Zadeh, N.G. (2026). Advancing climate-resilient livestock systems: Next-generation emission mitigation strategies and integrated technological innovations. *PMC*. **31:** 100588. doi: 10.1016/j.vas.2026.100588

IPCC (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability.

Islam, M.B., Ahmed, M.G.U., Islam, M.S. and Akhtar, F. (2024). Assessment of nutrient content in grain, hydroponics and conventional fodder with focus on maize, wheat and Sudan grass. *International Journal of Biosciences.* **24(3):** 45-56. https://doi.org/10.12692/ijb/24.3.45-56.

Kujur, N.A., Barla, S. and Upasani, R.R. (2026). Climate-smart agriculture: A pathway to food security and climate resilience- A review. *Agricultural Reviews*. **47(3):** 446-450. doi: 10.18805/ag.R-2777.

Lee, M.A., Davis, A.P., Chagunda, M.G.G. and Manning, P. (2017). Forage quality declines with rising temperatures, with implications for livestock production and food security. *Global Change Biology*. **23(6):** 2241-2252. https://doi.org/10.1111/gcb.13532

Lemaire, G., Franzluebbers, A., Carvalho, P.C.F. and Dedieu, B. (2019). Grassland-cropping rotations: An integrated approach to sustainable agriculture. *European Journal of Agronomy.* **107:** 1-9. https://doi.org/10.1016/j.eja.2019.04.003.

Lüscher, A., Mueller-Harvey, I., Soussana, J.F., Rees, R.M. and Peyraud, J.L. (2014). Legumes in forage production systems. *Grass and Forage Science.* **69(2):** 206-228. https://doi.org/10.1111/gfs.12124.

McDonald, P., Edwards, R.A., Greenhalgh, J.F.D., Morgan, C.A., Sinclair, L.A. and Wilkinson, R.G. (2011). *Animal nutrition* 7th Edition, Pearson Education Limited.

Min, B.R., Solaiman, S., Gurung, N. and Behrends, J. (2024). Effects of forage-derived phytonutrients on parasitic resistance in grazing livestock. *Animal Feed Science and Technology.* **309:** 115820. https://doi.org/10.1016/j.anifeedsci.2023.115820.

Mmbando, G.S. (2025). Recent possible agriculture techniques for supporting climate resilient crops in Africa. *Cogent Food and Agriculture.* **11(1):** 2557341. https://doi.org/10.1080/23311932.2025.2557341.

Myers, S.S., Zanobetti, A., Kloog, I., Huybers, P., Leakey, A.D.B., Bloom, A.J., Carlisle, E., Dietterich, L.H., Fitzgerald, G., *et al*. (2014). Increasing CO_2 threatens human nutrition. *Nature.* **510:** 139-142. https://doi.org/10.1038/nature13179.

Pampori, Z.A. and Sheikh, A.A. (2023). Climate smart livestock production-call for food security: A review. *Asian Journal of Dairy and Food Research.* doi: 10.18805/ajdfr.DR-2000.

Patra, A.K., Jayanegara, A. and Yu, Z. (2025). Forage quality implications on immune markers and disease resistance in ruminants. *Journal of Animal Physiology and Animal Nutrition*. https://doi.org/10.1111/jpn.14085.

Rangasami, S.S.R., Purnima, M., Pushpam, R., Ajaykumar, R., Thirunavukkarasu, M., Sathiya, K., Rajanbabu, V. and Yazhini, G. (2024). Enhancing animal nutritional security through biofortification in forage crops: A comprehensive review. *Indian Journal of Animal Research.* **58(11):** 1838-1845. doi: 10.18805/IJAR.B-5466.

Rao, I.M., Peters, M., Castro, A., Schultze-Kraft, R., White, D., Fisher, M., Miles, J., Lascano, C. and Douxchamps, S. (2021). Agroecosystem Services of Forage Legumes. In: Ecosystem Services Through Forage Diversification, [Peters, M. and Schultze-Kraft, R. (Eds.)]. *International Center for Tropical Agriculture (CIAT)*. pp. 14-62.

Rogers, M.E., Colmer, T.D., Frost, K. and Henry, D.A. (2021). Breeding forage crops for resilience to climate change. *Crop and Pasture Science.* **72(6):** 491-504. https://doi.org/10.1071/CP20505.

Rojas-Downing, M.M., Nejadhashemi, A.P., Harrigan, T. and Woznicki, S.A. (2017). Climate change and livestock: Impacts, adaptation and mitigation. *Climate Risk Management*. **16:** 145-163. https://doi.org/10.1016/j.crm.2017.02.001.

Session, T. (2026). Opportunities for mitigation in climate resilient agrifood systems in Asia and the Pacific. FAO Knowledge Repository.

Singh, D.K., Kumar, S., Yadav, R. and Meena, R. (2024). Effects of pasture diversity on breeding performance and body condition in beef cattle. *Animal Reproduction Science.* **256:** 107420. https://doi.org/10.1016/j.anireprosci. 2023.107420.

Soni, S., Rathore, A., Sheoran, R.S. and Kumar, S. (2020). Impact of climate change on forage and pasture production and strategies for its mitigation: A review. *Journal of Forage Research*. **26(2):** 85-98.

Thingujam, D. (2025). Climate-resilient Crops: Integrating AI, Multi-Omics and advanced phenotyping to address global agricultural and societal challenges. *Plants*. **14(17):** 2699. https://doi.org/10.3390/plants14172699.

Thornton, P.K., Ericksen, P.J., Herrero, M. and Challinor, A.J. (2014). Climate variability and vulnerability in livestock systems. *Nature Climate Change.* **4(3):** 175-179. https://doi.org/10.1038/nclimate2087

Thornton, P.K., van de Steeg, J., Notenbaert, A. and Herrero, M. (2009). The impacts of climate change on livestock and livestock systems. *Agricultural Systems*. **101:** 113-127.

Tuo, Y., Li, J., Amat, G., Cheng, Z., House, L., Zang, C. and Guo, T. (2025). Effects of dietary supplementation with hydroponic wheat seedlings on rumen fermentation, meat quality, amino acid and fatty acid contents and rumen bacterial diversity in sheep. *Frontiers in Microbiology.* **16:** 1356789. https://doi.org/10.3389/fmicb.2025.1356789.

Van Soest, P.J. (1994). Nutritional ecology of the ruminant. *Choice Reviews Online.* **32(8):** 32. https://doi.org/10.5860/choice.32-4505.

Van Wijk, M.T., Hammond, J., Gorman, L., Adams, S., Ayantunde, A., Baines, D., Bolliger, A., Bosire, C., Carpena, P., Chesterman, S., Chinyophiro, A. and Goopy, J. (2020). Integrated crop-livestock systems and resilience in agricultural production. *Agricultural Systems*. **184:** 102901. https://doi.org/10.1016/j.agsy.2020.102901.

Waghorn, G.C. and Hegarty, R.S. (2024). Impact of forage phytochemicals on rumen methanogenesis. *Frontiers in Veterinary Science.* **11:** 1324567. https://doi.org/10.3389/fvets.2024.1324567.

Walker, B., Holling, C.S., Carpenter, S.R. and Kinzig, A. (2004). Resilience, adaptability and transformability in social-ecological systems. *Ecology and Society.* **9(2):** 5. https://doi.org/10.5751/ES-00650-090205.

Xiao, D. and Meng, T. (2024). Nutritional value evaluation and processing technology of feed and nutritional regulation measures for ruminant animals. *Animals.* **14(21):** 3153. https://doi.org/10.3390/ani14213153.

Zhao, L., Wang, Y., Liu, H., Zhang, Q. and Chen, X. (2025). Growth performance of beef cattle grazing drought-tolerant forage cultivars under water stress. *Grassland Science*. Advance online publication. https://doi.org/10.1111/grs.12456.