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CLIMATE RESILIENT STRATEGIES FOR SUSTAINABLE FORAGE PRODUCTION: A REVIEW

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ABSTRACT

The forage and livestock sector are increasingly recognized for its crucial role in sustainable production, job creation, drought resilience, natural resource conservation, nutritional security, and export opportunities. As climate change becomes more evident, its effects are expected to vary across regions and sectors, depending on their resilience and vulnerability. Notably, forages and livestock both contribute to climate change and offer solutions for adaptation and mitigation.

Adopting climate-resilient, resource-efficient food and fodder production systems holds significant promise, particularly in semi-arid regions. These systems address soil and water challenges, boost farm productivity, and improve the incomes of farming families. Scaling up such innovative technologies requires strong research and development efforts, along with supportive policies.

This review examines the impact of climate change on the forage and livestock sector and explores potential adaptation and mitigation strategies to reduce negative effects while promoting sustainable production.

***Key words*:** Climate change, Climate resilience, Fodder productivity, Sustainability

Introduction

According to the 20[th] Livestock Census, India's livestock population has reached 536.76 million, marking a 4.6% increase from the 2012 census. The livestock sector's contribution to the Gross Value Added (GVA) in agriculture and allied sectors rose from 24.32% in 2014-15 to 30.38% in 2022-23, representing a 4.66% share in the total GVA. India continues to be the world's largest producer and consumer of milk. Urbanization has notably impacted dietary preferences, driving increased demand for milk products, meat, and eggs. Higher consumer incomes and strong farm-gate prices have further boosted milk production, supported by growing private investments in dairy processing facilities. However, the productivity of Indian livestock remains among the lowest globally, largely due to challenges related to breeding and feeding. Fodder in India is sourced from crop residues, cultivated fodder, and common property resources like forests, permanent pastures, and grazing lands. There is a significant gap between regional and seasonal fodder availability and demand. India faces a deficit of 35.6% in green fodder, 10.95% in dry crop residues, and 44% in concentrate feed ingredients, as projected in the IGFRI Vision 2050. Climate change presents additional risks, potentially worsening these challenges and further affecting the forage and livestock sector.

The Intergovernmental Panel on Climate Change (IPCC) report predicts global temperatures could rise by 1.1 to 6.4°C by 2090–2099, compared to 1980-1999 levels, with the most likely increase ranging between 1.8 and 4.0°C (IPCC, 2007). India is especially vulnerable to climate change due to its large population dependent on agriculture and the increasing pressure on natural resources for livelihoods. Farmers are already witnessing significant shifts in agro-ecological conditions (Palsaniya *et al*., 2012c).

Since 1901, India has experienced a warming trend of 0.51°C, with the rate accelerating to 0.21°C per decade since 1970. The effects of global warming are evident in the growing frequency and intensity of hydro-meteorological disasters such as droughts, cyclones, and floods. Furthermore, climate change is expected to disrupt global precipitation patterns, influencing both the quantity and seasonal distribution of rainfall in many regions (IPCC, 2007).

Climate change is expected to have a profound impact on key agricultural processes, such as soil and water dynamics, carbon and nitrogen cycles, crop growth and development, and the prevalence of weeds, pests, and diseases. These changes are likely to result in increased heat stress, higher evapotranspiration, shorter growing seasons, enhanced photosynthesis, and reduced water usage due to elevated atmospheric CO2 levels. The projected effects are expected to heighten crop yield variability, creating challenges for both food and fodder security. This paper explores the impact of climate change on forage and livestock production and discusses potential adaptation and mitigation strategies to improve and sustain forage production in the changing climate.

Impact of Climate on Forage Crops

The agro-ecosystem is a complex interaction of atmospheric and climatic factors, soil nutrients, and biological processes. Climate change is expected to affect the quantity and quality of fodder and feed, primarily due to rising atmospheric CO2 levels and temperatures (Chapman *et al*., 2012). These impacts will vary depending on location, livestock system components, species involved, and management practices (IFAD, 2010).

Climatic changes may alter the geographical suitability of crops, leading to shifts in the types and extent of crops grown in specific areas. Increased CO2 levels could enhance herbage growth, particularly for C3 species (Chapman *et al*., 2012; Thornton *et al*., 2015), by causing partial stomatal closure, reducing transpiration, and improving water-use efficiency (Wand *et al*., 1999). Similarly, temperatures rising to 30-35°C may accelerate herbage growth, particularly for C4 species. Changes in temperature and CO2 levels could also influence pasture composition by altering species competition and growth dynamics (IFAD, 2010; Thornton *et al*., 2015). In areas where dryland crop yields are limited by soil moisture, a reduction in moisture availability would further lower yields. Seasonal changes in water availability could affect plant competition dynamics (Polley *et al*., 2013). Fodder crops, often grown on marginal lands with limited resources, are especially vulnerable. Variations in climate factors may affect competition dynamics, the composition of mixed cropping systems, weed growth, and crop productivity to varying degrees (Rai *et al*., 2014). In pastures, primary productivity could increase with changes in species composition if factors such as temperature, precipitation, and nitrogen deposition rise together (IPCC, 2007). However, extreme climatic events such as floods and droughts may damage root systems, disrupt leaf growth, and reduce overall yields (Baruch and Merida, 1995).

A warmer climate, combined with unpredictable rainfall patterns, accelerated evapotranspiration rates (Rai *et al*., 2017), and rapid depletion of soil nutrients, necessitates more efficient water and nutrient usage to sustain crop productivity. Rising temperatures and drought conditions can negatively impact forage quality by reducing water-soluble carbohydrates and nitrogen levels. Higher temperatures also increase the concentration of lignin and cell wall components (cellulose and hemicellulose) in plants (Polley *et al*., 2013), which lowers digestibility and degradation rates (IFAD, 2010; Polley *et al*., 2013), limiting nutrient availability for livestock (Thornton *et al*., 2009). In contrast, elevated CO2 levels improve forage quality, with a more significant effect on C3 plants compared to C4 plants (Polley *et al*., 2013; Thornton *et al*., 2009; Wand *et al*., 1999). The impact of climate change on forage quality differs by region and is largely influenced by the length of the growing season (Polley *et al*., 2013; Thornton *et al*., 2009). A 2°C increase in temperature is expected to have negative effects on pasture and livestock production in arid and semi-arid regions, while benefiting humid temperate regions.

In addition to shifting species distributions, rising temperatures may affect reproduction, migration, and mortality rates of various species (Steinfeld *et al*., 2006). Climate change also threatens pasture biodiversity, with projections suggesting that a 2 to 3°C rise above pre-industrial levels could result in a 20–30% loss of plant and animal biodiversity (IPCC, 2014). These changes are likely to impact agricultural practices, requiring adjustments in sowing times and growing season durations. Adaptation strategies may include changes in sowing and harvesting schedules, modifications to the genetic traits of cultivars, and adjustments in cropping systems by replacing certain crops to better align with the new conditions.

Approaches for Enhancing Forage Production

Sustainable forage production can be achieved through the implementation of suitable adaptation and mitigation strategies, leveraging various technologies and practices. Adaptation strategies involve adjustments in production and management systems, breeding methods, advancements in science and technology, and improving farmers' awareness and adaptive capacity (IFAD, 2010; Rowlinson *et al*., 2008; USDA, 2013). Mitigation options include carbon sequestration, dietary management to reduce enteric fermentation, improved manure management, and optimizing fertilizer use (Steinfeld *et al*., 2006; Thornton and Gerber, 2010; UNFCCC, 2008). For these strategies to succeed, strong institutional and policy support is essential (Dickie *et al*., 2014).

Fodder-based agricultural systems have significant potential for adapting to climate change due to their flexibility in terms of sowing time, duration, and management. By implementing appropriate adaptation strategies, yield losses due to climate change can be minimized, or yields can even increase in regions where climate change is beneficial. These strategies can also improve the resilience of both crop and livestock production systems to climate change (USDA, 2013). Adaptation efforts can take place at different levels, from individual farms to entire societies, villages, watersheds, or national scales. At the farm level, adaptation options might include changes in tillage practices, planting and harvest dates, crop rotations, choosing suitable crops and varieties, managing irrigation water, optimizing fertilizer use, and adding nitrogen to counteract climate impacts on forage crops. Improved crop management and risk management strategies, such as early warning systems and crop insurance, can also help reduce farmers' vulnerability. As a result, research is crucial to evaluate and implement these adaptation measures, customizing them for specific locations and livestock systems.

Forage and livestock breeding strategies

Forage production per unit area is shaped by the interactions between plant genotypes and environmental factors. A notable increase in productivity can be achieved primarily through integrated crop management practices, which include the use of improved seeds, fertilizers, and efficient agricultural techniques (Kumar *et al*., 2016).

Forage varieties that grow rapidly and are suited to specific weather patterns, enabling higher dry matter accumulation and extended leaf duration, will be critical for adapting to changing climates. Traits such as fast regeneration, the ability to withstand defoliation, and strong persistence under challenging conditions will also be valuable. To enhance forage and livestock production, breeding strategies should focus on improving tolerance to environmental stresses while boosting growth, productivity, and reproduction (Henry *et al*., 2012; Ghosh *et al*., 2016). Furthermore, policy measures that assist farmers in adapting to climate change will play a crucial role. For instance, establishing international gene banks like those operated by CGIAR could support breeding programs and serve as a safeguard against future challenges (Thornton *et al*., 2008). However, such initiatives would require significant investment and global collaboration to succeed.

Forage production system modifications and management

Forage-based production systems can be more effectively adapted to climate change through diversification strategies, such as incorporating perennial grasses, legumes, and trees, integrating livestock within an integrated farming system, and adjusting the timing and locations of farming activities. This diversification can enhance resilience to droughts and heatwaves and may improve production when crops and livestock face challenges due to temperature and precipitation changes. Moreover, diversified systems are more resilient in managing climate change-related diseases and pest outbreaks (Batima *et al*., 2005; IFAD, 2010; Kurukulasuriya and Rosenthal, 2003).

Adaptation to climate change can also be achieved by modifying crop rotations, cropping patterns, and altering the timing and methods of management practices, such as sowing, irrigation, spraying, cutting, and grazing. These adjustments can help cope with changes in growing season length, heatwaves, and shifts in precipitation patterns (Batima *et al*., 2005; IFAD, 2010; Kurukulasuriya and Rosenthal, 2003). In forage crop management, timely sowing is crucial, as these crops have a short growth cycle. Adjustments in seed rates and spacing may be required to address unusual weather conditions. Since moisture is often a limiting factor, efficient water management will be essential for optimizing productivity and resource use in the future. Effective agro-advisories can help conserve natural resources and mitigate the impacts of climate change (Palsaniya *et al*., 2016a). Irrigation scheduling, which aligns irrigation with weather conditions, is a key water conservation practice for optimal crop use.

Improved feeding practices, such as adjusting diet compositions, modifying feeding times or frequencies (Renaudeau *et al*., 2012), integrating agroforestry species into animal diets (Thornton *et al*., 2015), and training producers on feed production and conservation for different agro-ecological zones (IFAD, 2010), can help mitigate climate change risks. These practices can promote higher feed intake, compensate for lower feed consumption, reduce heat stress, address feed shortages during dry periods, and prevent malnutrition and livestock mortality. Resource-conserving technologies like conservation tillage, crop rotations, increased use of crop residues, mulching (Ghosh *et al*., 2017), reducing soil erosion, managing soil acidity, and double-cropping can also aid in restoring soil organic carbon in cultivated soils (Steinfeld *et al*., 2006).

Grassland and grazing management

Grasslands not only store more carbon than croplands but also sequester it at a faster rate. Tropical savannas and temperate pastures together sequester 27% of global carbon, compared to just 6% from croplands (IPCC, 2000). However, the rate of greenhouse gas (GHG) emissions can vary based on grazing management, grazing history, climate, and the specific ecosystem (IFAD, 2010; Henderson *et al*., 2015). Carbon sequestration rates can be improved by integrating trees, legumes, enhancing plant species, introducing earthworms, and using fertilizers (Conant *et al*., 2001). Additionally, increasing grassland productivity and soil carbon sequestration has been observed by boosting grazing pressure in areas with fewer animals than the land's livestock carrying capacity (Holland *et al*., 1992), implementing rotational grazing, and excluding overgrazed pastures from livestock grazing (IFAD, 2010). The quality and quantity of natural grassland production can be enhanced by introducing range of legumes such as *Stylosanthus hamata*, *S. seabrana, Atylosia scarabaeoids, Clitoria ternatea, Desmodium tortosum, Glycine javanica, Lablab purpureus, Macroptilium atropurpureum, Mimosa invisa*, and others. Using perennial forage species can provide higher forage yields under changing climatic conditions and help mitigate the adverse effects of climate change through carbon sequestration (Kaul *et al*., 2010). These perennial forage crops are also beneficial because they can be easily established and grown under rainfed conditions with minimal agricultural inputs.

Nutrient management

Manure and fertilizer management play a crucial role in influencing greenhouse gas (GHG) emissions in forage production. Effective manure management practices should involve covering storage pits, minimizing storage time, enhancing waste and housing systems, utilizing solids separators to remove bedding, and optimizing manure application timing and methods for crops (ICF International, 2013; Dickie *et al*., 2014). However, implementing mitigation measures in grazing systems is challenging due to the widespread distribution of manure across grasslands (Dickie *et al*., 2014). GHG emissions can also be minimized by balancing dietary proteins and adding feed supplements like tannins (Hess *et al*., 2006). Other strategies for nutrient management include improving nutrient use efficiency (Ghosh *et al*., 2015), employing plant genetic modifications (Dickie *et al*., 2014), applying organic fertilizers (Denef *et al*., 2011), adopting integrated nutrient management practices, conducting regular soil tests, using advanced fertilizers (such as slow-release and coated fertilizers), and ensuring proper fertilizer placement (Kumar *et al*., 2014). Integrating legumes with grasses in pastures can also help reduce GHG emissions in feed and fodder production (Dickie *et al*., 2014). Dixit *et al*., (2014) found that the productivity and profitability of the fodder sorghum + cowpea-chickpea cropping system in semi-arid central India improved with the combined use of organic manure, phosphorus, and sulfur. Similarly, participatory balanced nutrient management strategies implemented by farmers have led to increased productivity and resilience in agricultural production systems in central India (Palsaniya *et al*., 2016b).

Agroforestry-based forage production systems

Agroforestry practices offer a balance between agricultural production and environmental conservation while capturing carbon to reduce greenhouse gas emissions, even in wasteland systems like silvipasture (Palsaniya *et al*., 2011a; Palsaniya and Ghosh, 2016). These practices are known for enhancing productivity and environmental quality, including improvements in air, soil, and water conditions, as well as biodiversity. Additionally, agroforestry promotes better nutrient recycling and contributes to the sustainability of production systems (Dhyani *et al*., 2010; Palsaniya *et al*., 2010b; Palsaniya *et al*., 2012a). These self-sustaining tree-crop-livestock systems improve efficiency by generating more output with less land and fewer resources (Kumar *et al*., 2017).

Various agroforestry systems provide important resources such as fodder, fuel, food, and fruits, including agri-silviculture (crops + trees/animals), silvi-pasture (trees + pasture/animals), agri-horti (crops + fruit trees), horti-pasture (fruit trees + pasture/animals), and agri-horti-silvipasture (crops + fruit trees + MPTS + pasture). Many multipurpose tree species (MPTS) cultivated in these systems supply leaf fodder for livestock, in addition to wood. These leaves can be either browsed directly by free-roaming animals or collected and fed to animals in stalls. Livestock grazing alongside MPTS trees benefits from both nutritious fodder and shade on hot, sunny days. The pruned biomass from these trees can be used as feed during lean periods, preserved as leaf meal, or applied as mulch (Palsaniya *et al*., 2012b). In India, tree leaves from agroforestry systems are primarily used as fodder for small ruminants, and for large ruminants during fodder shortages. More than 60% of the fodder needs of goats are typically met with tree and shrub fodders. Popular trees and shrubs for goats include peepal (*Ficus religiosa*), bargad (*Ficus benghalensis*), gular (*Ficus recemosa* or *Ficus glomerata*), neem (*Azadirachta indica*), jamun (*Engenia jambolans*), mahua (*Bassia latifolia)*, jackfruit (*Artocarpus heterophylus*), bhimal (*Grewia oppositifolia*), kachnar (*Bauhinia variegata*), ber (*Zizyphus jujuba*), jharberi (*Zizyphus numularia*), mulberry (*Morus alba*), cassava (*Manihot esculenta*), gliricidia (*Gliricidia maculata*, *G. sepium*), babul (*Acacia nilotica*), and khejri (*Prosopis cineraria*). A socio-economic and livelihood analysis in the drought-prone Bundelkhand region showed that grazing and agroforestry play a significant role in domestic livestock production, boosting milk and meat supply and providing a steady income source for households (Palsaniya *et al*., 2008; Palsaniya *et al*., 2009).

Watershed based approach

Integrated watershed management is widely regarded as a climate-resilient strategy due to its beneficial effects on natural resource conservation (Palsaniya *et al*., 2011b; Palsaniya *et al*., 2012d), farm productivity, profitability, and livelihoods (Palsaniya *et al*., 2012e). It also enhances grass and animal productivity while maintaining ecosystems (Palsaniya *et al*., 2010a). Studies assessing the impact of integrated watershed management have demonstrated increased fodder productivity and availability, improved forage quality, and reduced grazing pressure on natural forests and grazing lands, as well as a boost in milk productivity in the areas studied (Palsaniya *et al*., 2010a). Additionally, involving local communities in the planning, implementation, and management of watershed projects ensures the effective and sustainable achievement of goals (Palsaniya *et al*., 2016b).

Livestock based integrated farming system approach

In contemporary agriculture, diversification, particularly through an integrated farming system approach, is a key strategy for enhancing farm viability and climate resilience (Kumar *et al*., 2017). Studies have indicated that while income from crop production is decreasing, income from other sectors, especially animal husbandry, is increasing. Factors such as labor shortages, water scarcity, and rising demand for dairy products are encouraging farm households to diversify into sectors like animal husbandry. In this regard, integrated farming systems are essential for ensuring livelihood security, resource recycling, climate change resilience, and long-term sustainability. Various livestock-based integrated farming system models are being developed and tested for different groups, such as dairy farmers, peri-urban farmers, intensive agricultural practitioners, and rainfed farmers, both at research farms and on farmers' fields.

Post-harvest forage processing and value addition

Efficient post-harvest management of surplus fodder is a crucial strategy to tackle seasonal and regional forage shortages, especially during natural disasters like droughts and floods. Given livestock's heavy dependence on crop residues, it is essential to implement effective post-harvest processing, value addition, densification, storage, and transportation methods. Techniques such as baling and enriching crop residues, particularly paddy straw and leguminous crop residues, ensure proper storage, provide balanced feeding alongside green fodder, and help reduce wastage and storage losses. Leaf meals made from leguminous fodder, pulses (like lentil, gram, grass pea, and stylo), and tree leaves (such as subabool, gliricidia, and khejri) offer cost-effective alternatives to expensive concentrates. To ensure a steady supply of forage throughout the year, the establishment of fodder banks is vital. These banks would store feed blocks, leaf meals, and region-specific mineral supplements. Transporting bales of different forage products (such as grasses, wheat straw, and paddy straw) can result in a 1.5 to 4.0% reduction in weight and a 15.5 to 43.9% reduction in volume. Additionally, technologies have been developed to preserve surplus green fodder as hay or silage for use during periods of scarcity.

Forages from new niches

In India, farmers with small or marginal land holdings, as well as livestock keepers with limited forage requirements, can effectively grow forages on bunds. These areas do not compete with existing crops or farming systems, utilizing land that would otherwise remain unused for agriculture. Cultivable land along irrigation channels, farm boundaries, backyards, threshing areas, animal complexes, and community lands can all be used for forage production. Forage cultivated on bunds or farm boundaries can yield 7.0–11.0 quintals of green fodder per 100 meters of bund length. This approach not only boosts farm productivity but also serves as a protective barrier for main crops, reduces water runoff, and helps prevent soil erosion. By dedicating just 10% of bunds to forage production, approximately 17.9 tonnes of green fodder can be produced annually. This method has shown positive outcomes under the National Initiative on Fodder Technology Demonstration (NIFTD) program, which is implemented at 100 Krishi Vigyan Kendras (KVKs) across the country (Ghosh *et al*., 2016).

Non-conventional forages

There is an opportunity to diversify feed resources by incorporating nontraditional or underutilized options such as cactus, lathyrus, sugar beet, and moringa. These can be grown on unused lands, marginal soils, and degraded areas, in combination with other available forages and grasses (Sunil Kumar *et al*., 2017). Spineless cactus, in particular, is well-suited for arid and semi-arid regions, thriving on degraded lands, pasture areas, nalla bunds, and field boundaries, especially in drought-prone and low rainfall zones. Moringa and sugar beet are excellent for providing energy and protein-rich feed supplements in milk-producing areas. Furthermore, involving farmers and local extension services in the development, assessment, and promotion of nonconventional fodder resource (NCFR)-based technologies is essential.

Policy Support

Several essential policy measures are required to foster the rapid development of forage resources in India. These include creating a comprehensive database on fodder production and usage, increasing investment in forage development, providing credit facilities for forage production, setting support prices for forage, and improving the marketing of seeds. Additionally, policies should prevent the diversion of edible crop residues for purposes like packaging, address grazing and common property resource management, and offer legal protection for grasslands. A Mission Mode Approach can be adopted to address the forage shortage. Technologies such as urea-ammoniation of straws, total mixed rations, and feed blocks are available to improve feed utilization and enhance animal productivity, although their adoption is still limited. To encourage the use of these technologies, strong extension services are crucial. The National Seed Corporation (NSC) and State Seed Corporations (SSCs) should establish fodder seed production targets, and reserves should be created to ensure the security of fodder crops.

Future R&D Thrust

- Formulating a national policy for the management of grazing, fodder, and pasturelands.
- Restoring grazing lands, communal pastures, and forest areas.
- Tackling challenges in fodder seed production through initiatives such as seed hubs, seed villages, participatory seed production, and involvement of NGOs.
- Enhancing forage production by adopting climate-resilient integrated crop management practices.
- Implementing an integrated watershed management strategy with a focus on forage and livestock activities.
- Increasing agricultural income through precision farming techniques and resource conservation technologies.
- Establishing a Green Research Fund to strengthen research on climate adaptation, mitigation, and impact evaluation.
- Encouraging collaborative management of natural resources involving multiple stakeholders, such as farmers, pastoralists, and herders.
- Enhancing community participation in adaptation and mitigation strategies, including utilizing traditional knowledge from local communities and indigenous groups.
- Promoting reforestation, restoring degraded grazing lands, and establishing fodder banks.
- Strengthening infrastructure for post-harvest management and value addition in forages, such as hay, silage, leaf meals, bales, and fodder blocks.
- Improving risk management through early warning systems and policies that support crop insurance.
- Expanding the use of modern technologies like biotechnology, information technology, and GIS in forage production and management.

Summary

Agriculture in semi-arid and arid regions faces challenges due to its rainfed nature, complexity, limited funding, and high vulnerability. Water scarcity, poor soil quality, and low productivity further contribute to food security issues in these areas. In this context, fodder and livestock play a crucial role in the economic stability of small and marginal farmers. Climate change poses a significant threat to species, ecosystems, and the financial health of fodder-livestock systems. To build resilience, livestock-based production systems should integrate techniques like soil moisture conservation, double cropping (combining food and fodder), live mulch application, and conservation tillage (minimal tillage). Ex-situ water harvesting methods such as building check dams and small ponds, along with growing fodder along farm boundaries, are essential for intensifying and diversifying crop production. Degraded lands can be used for silvipasture and boundary plantations of Multipurpose Tree Species (MPTS), as well as adopting non-traditional fodder species like cactus and moringa. A comprehensive approach that includes drought-resistant forages, livestock breeds, soil and water conservation, the restoration of grazing lands, surplus fodder management, value addition, and strong stakeholder collaboration can promote sustainable forage production, higher farm income, improved livelihoods, and reduced rural youth migration. Ongoing research and development in fodder and livestock, combined with grazing and pasture management policies, government scheme integration, and fodder banks in drought-prone regions, will help mitigate the impacts of climate change on the fodder and livestock sectors.

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