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FORAGE CROPS AS CLIMATE-RESILIENT CROPS UNDER CLIMATE CHANGE AND POTENTIAL EL NIÑO CONDITIONS: A REVIEW

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SUMMARY

Climate change threatens agricultural productivity, food security, and livestock sustainability through rising temperatures, irregular rainfall, droughts, and extreme weather events. El Niño conditions intensify these challenges by reducing rainfall, increasing moisture stress, and causing fodder shortages. Climate-resilient forage crops, especially C_4 grasses, offer solutions through high photosynthetic efficiency, water-use efficiency, deep roots, and rapid regrowth. Species such as *Cenchrus ciliaris*, *Dichanthium annulatum*, *Chloris gayana*, and *Megathyrsus maximus* support fodder security and sustainable livestock production. Forage legumes improve soil fertility, nutrition, and ecosystem resilience. Integrating drought-tolerant forages, improved varieties, and climate-smart management practices strengthens livestock systems against future climate uncertainties.

Key words: Climate change, El Niño; forage crops, C_4 plants, forage grasses, forage legumes

Agriculture is strongly influenced by climatic conditions, and even small changes in temperature and rainfall patterns can significantly affect agricultural productivity. During recent decades, global warming, unpredictable precipitation patterns, increased frequency of droughts, floods, and heat waves have created serious challenges for agricultural sustainability. Climate change is not only affecting food grain production but is also creating major constraints for livestock production through reduced availability of green fodder and grazing resources (Dheeravathu *et al.*, 2025). Livestock production plays a crucial role in rural economies by providing milk, meat, fiber, manure, income security, and draft power. Millions of small and marginal farmers depend on livestock as an important component of mixed farming systems. However, livestock productivity is directly related to the quantity and nutritional quality of available feed resources. In many developing regions, natural grasslands, pastures, and crop residues remain the primary sources of animal feed. Climate-related degradation of these resources has become a major threat to sustainable livestock production. Rising temperatures accelerate evapotranspiration, increase soil moisture loss, and create unfavorable conditions for forage establishment and growth. Changes in rainfall distribution influence pasture regeneration, seed germination, and seasonal biomass production. Extended drought periods reduce plant growth, decrease forage quality, and increase pressure on grazing lands. Heat stress also affects livestock directly by reducing feed intake, growth rate, reproductive efficiency, and milk production. The El Niño Southern Oscillation (ENSO) is one of the most important climatic phenomena influencing agricultural systems worldwide. El Niño phases are commonly associated with abnormal warming of tropical Pacific Ocean waters, resulting in altered atmospheric circulation patterns. In many tropical and subtropical regions, El Niño events are linked with below-normal rainfall, delayed monsoon arrival, longer dry spells, and higher-than-normal temperatures. These conditions create severe challenges for forage production and livestock feed security. Under these changing climatic scenarios, the development and adoption of climate-resilient forage crops have become essential. Forage crops capable of maintaining productivity under heat, drought, and moisture stress conditions can provide reliable fodder resources and reduce vulnerability of livestock systems. Among forage crops, C4 grasses are particularly important because they possess unique adaptations that enable efficient growth in warm environments (Dheeravathu et al., 2024). Most tropical pasture grasses belong to the C4 photosynthetic group and are naturally adapted to high temperature, intense solar radiation, and seasonal drought conditions. Their ability to efficiently utilize water and nutrients makes them valuable crops for climate-smart livestock production. However, sustainable forage systems cannot rely only on grasses. Forage legumes also contribute significantly to resilient pasture ecosystems. Legumes improve forage nutritional quality through higher crude protein content, enhance soil fertility through biological nitrogen fixation, and increase biodiversity within grazing systems. Species such as *Stylosanthes*, *Desmanthus*, *Clitoria*, *Leucaena*, and *Lablab* have demonstrated considerable adaptation to tropical drought-prone environments.

Therefore, integrating climate-resilient grasses and legumes offers a promising approach for maintaining fodder availability, improving livestock productivity, restoring degraded ecosystems, and developing sustainable agricultural systems capable of withstanding future climate variability.

Climate Change and Its Impact on Forage Production

Climate change affects forage crops through several interconnected environmental stresses. The major impacts include increasing temperature, drought stress, irregular rainfall, heat waves, and declining soil moisture availability.

Rising temperature

Global temperatures have increased significantly during the last century, and further warming is projected under future climate scenarios. Temperature directly influences plant physiological processes including: Photosynthesis, Respiration, Enzyme activity, Cell division, Flowering and seed production and Biomass accumulation Moderate increases in temperature may stimulate growth in some tropical C4 forage species. However, excessive temperatures negatively affect plant metabolism and reduce productivity. High temperature increases respiratory losses, accelerates plant maturity, and decreases forage quality by increasing fiber concentration. Heat stress can result in: Reduced leaf expansion, Lower tiller production Decline in photosynthetic efficiency, Reduced carbohydrate accumulation Poor seed development

Although many C_3 forage species experience rapid decline under high temperature, C_4 grasses maintain comparatively better photosynthetic activity because of their carbon-concentrating mechanism.

Climate Change Impacts on Forage Production (Continued)

Drought stress: Water scarcity is becoming one of the most important limitations for forage production under climate change. Increased temperature enhances evapotranspiration, causing rapid depletion of soil moisture. Prolonged drought reduces plant growth, pasture productivity, and forage quality. Major effects of drought stress include: Reduced seed germination and poor crop establishment, Limited root and shoot development, Reduced leaf expansion, Decline in tillering ability, Early leaf senescence, Reduction in green biomass production, Lower crude protein content and digestibility, Drought conditions also alter plant nutrient uptake and microbial activity in soils. In grazing ecosystems, repeated drought periods reduce pasture recovery after grazing and accelerate land degradation. Climate-resilient forage species overcome drought conditions through deep rooting, efficient water utilization, osmotic adjustment, and rapid recovery after rainfall.

Erratic rainfall patterns: Climate change has altered rainfall distribution in many agricultural regions. Instead of predictable seasonal rainfall, farmers increasingly experience delayed rains, short intense rainfall events, and prolonged dry intervals. Irregular rainfall affects forage production through: Delayed sowing and establishment, Uneven pasture growth, Reduced seedling survival, Poor regeneration of natural grasslands, Increased soil erosion Reduced availability of seasonal fodder.Rainwater conservation and drought-tolerant forage varieties are therefore essential components of climate adaptation strategies.

Heat waves: Heat waves are becoming more frequent and intense due to global warming. Extreme heat reduces plant photosynthetic efficiency and increases respiration losses. During heat stress: Photosynthetic enzymes become less active, Stomatal regulation becomes impaired, Water loss increases, Biomass production declines, Forage quality decreases, Tropical C4 grasses show better adaptation to heat waves because their photosynthetic systems function efficiently at higher temperatures.

Influence of El Niño Conditions on Forage Availability

The El Niño Southern Oscillation (ENSO) is a major climatic phenomenon affecting rainfall and temperature patterns globally. El Niño events often create unfavorable agricultural conditions, particularly in tropical and subtropical regions. Potential El Niño conditions may result in: Reduced monsoon rainfall, Delayed onset of rainy season, Increased atmospheric temperature, Extended drought periods, Reduced groundwater recharge, Declining pasture productivity. During El Niño years, natural grazing lands experience reduced vegetation growth, resulting in severe fodder shortages. Livestock farmers often depend on stored fodder and crop residues, which may not provide sufficient nutritional requirements.

Climate-resilient forage crops provide an important adaptation strategy by maintaining biomass production under unfavorable weather conditions.

Why C_4 Forage Grasses Are Climate Resilient: Most tropical forage grasses belong to the C4 photosynthetic category. The C4 pathway provides several advantages that enable plants to survive and produce biomass under high temperature and limited water availability (Table 1 and 2).

Efficient Photosynthetic Mechanism:

In C_4 plants, carbon dioxide is initially fixed by the enzyme phosphoenolpyruvate (PEP) carboxylase into four-carbon compounds. These compounds are transported to specialized bundle sheath cells where carbon dioxide is released and enters the Calvin cycle.

This carbon concentrating mechanism: Increases photosynthetic efficiency, reduces oxygen interference with RuBisCO, minimizes photorespiration, improves carbon assimilation. As a result, C_4 grasses produce greater biomass under warm environments.

Reduced Photorespiration

Photorespiration reduces carbon gain in C_3 plants, especially under high temperature conditions. C_4 plants minimize photorespiration by concentrating carbon dioxide around RuBisCO. Advantages include: Greater carbohydrate production, Higher biomass accumulation, Improved productivity under heat stress, Better adaptation to tropical environments.

High Water-Use Efficiency: Water-use efficiency refers to biomass produced per unit of water consumed.C4 forage grasses possess:Lower stomatal opening requirements, Reduced transpiration losses, Efficient carbon fixation, Better performance under moisture stress, Therefore, they are highly suitable for rainfed and drought-prone regions.

Physiological and Morphological Adaptations of Forage Grasses

Deep Root Systems: Many perennial forage grasses develop extensive root systems that penetrate deep soil layers. Benefits include: Extraction of stored soil moisture, Improved nutrient, absorption, Increased drought tolerance, Soil stabilization, Reduced erosion Narrow Leaves, Many drought-adapted grasses possess narrow leaves that reduce water loss. Advantages: Lower transpiration rate, Reduced heat load, Better survival during dry periods (Table 2).

High Tillering Capacity: Tillering ability enables grasses to maintain productivity after grazing. Benefits: Rapid canopy recovery, Continuous fodder production, Better grazing toleranc**e**

Rapid Regrowth Ability: Perennial forage grasses regenerate quickly after grazing or harvesting due to: Stored carbohydrates in roots, Active growing points, Strong regenerative capacity. This ensures continuous fodder supply throughout the year.

Temperature Adaptation of C4 Forage Crops

C_4 grasses generally show optimum photosynthesis between 30°C and 40°C. Many tropical forage grasses continue functioning efficiently even at temperatures above 40°C when sufficient soil moisture is available. However, extreme temperatures beyond optimum limits cause: Reduced photosynthesis, Increased respiration, Reduced net carbon gain, Lower biomass production, Some forage grasses exhibit respiratory acclimation, allowing them to maintain productivity under prolonged heat exposure. Drought Adaptation Mechanisms: Stomatal Regulation-During drought, plants partially close stomata to reduce water loss while maintaining carbon fixation. Osmotic Adjustment-Plants accumulate compatible compounds such as: Proline, Soluble sugars, Glycine betaine, These compounds maintain cell water balance. Root Development-Deep roots allow plants to access moisture from deeper soil horizons. Leaf Rolling-Leaf rolling reduces exposed leaf area and minimizes transpiration. Delayed Senescence-Some grasses maintain green leaves longer during drought conditions, helping sustain photosynthesis.

TABLE 1
Comparison between C_3 and C_4 forage species

Characteristic	C_3 Species	C_4 Species
Photosynthesis	Moderate	High
Photorespiration	High	Very low
Heat tolerance	Moderate	High
Drought tolerance	Moderate	High
Water-use efficiency	Low	High
Nitrogen-use efficiency	Lower	Higher
Biomass production	Moderate	High
Climate resilience	Moderate	High

Importance of Climate-Resilient Forages in Livestock Production

Climate-resilient forage crops contribute to livestock systems by: Ensuring continuous fodder availability, improving milk production, Supporting animal growth, Enhancing reproductive performance, Reducing feed costs, Improving farm profitability, Reliable forage production reduces dependence on purchased feed resources and strengthens livestock-based livelihoods.

Role of Forage Legumes Under Climate Change

Although most forage legumes are C_3 plants, many tropical legumes possess excellent adaptation mechanisms against drought and heat stress (Table 3).

TABLE 3
Important climate-resilient legumes

Legume Species	Varieties
Clitoria ternatea	JGCT2013-3
Desmanthus virgatus	TNDV-1, TSHL-1 (Telangana dasharath)
Fieldbean	Bundel Sem-1 (JLP-4)
Guar	Bundel Guar-1,Bundel Guar-2,Bundel Guar-3
Stylosanthes	Phule kranti,stylosanthas scabra, Stylosanthes hamata
Lucerne	chetak

Source: Modified from Database of forage crop varieties (updated edition)

Advantages of Grass–Legume Mixtures

Grass–legume pastures provide greater stability than monoculture systems. Major benefits include: Higher crude protein content, Improved forage digestibility, Biological nitrogen fixation, Reduced fertilizer requirement, Improved soil fertility, Increased soil carbon storage, Better drought resilience, Greater pasture biodiversity, Improved livestock performance. Legumes improve the quality of mature grass forage by increasing protein availability and supporting rumen microbial activity.

Management Strategies for Climate-Resilient Forage Production: Soil Moisture Conservation-Recommended practices: Contour bunding, Mulching, Farm ponds, Rainwater harvesting ,Conservation tillage, Integrated Nutrient Management:

TABLE 2
Major Climate-Resilient Range Grasses and Improved Varieties

S. No.	Grass Species	Improved Varieties
1	*Cenchrus ciliaris*	Bundel Anjan-1, Bundel Anjan-3, Bundel Anjan-4, Marwar Anjan
2	*Brachiaria*	DBRS-1
3	*Cenchrus setigerus*	Marwar Dhaman, Bundel Dhaman-1
4	*Lasiurus scindicus*	Jaisalmeri Sewan
5	*Dichanthium annulatum*	Gujarat Marvel Grass-1, Marvel-7, Marvel-8
6	*Chloris gayana*	Rhodes-10
7	*Setaria sphacelata*	Setaria-92, Nandi, PSS-1
8	*Megathyrsus maximus*	Bundel Guinea-1, Bundel Guinea-2, CO-1, CO-2, CO-3
9	*Pennisetum pedicellatum*	Bundel Dinanath-1, Bundel Dinanath-2

Use of Farmyard manure, Compost, Biofertilizers, Balanced chemical fertilizers improves soil fertility and forage productivity. Improved Grazing Management: Rotational grazing prevents overgrazing and improves pasture recovery. Adoption of Improved Varieties-Drought-resistant varieties improve fodder availability under climate stress. Mixed Farming -Systems-Integration of:Crops, Livestock, Trees, Forage crops, enhances overall farm resilience.

CLIMATE RESILIENT CROPS: FORAGE AND MILLETS

Several millets and forage and other crops have been identified as climate-resilient due to their capacity to tolerate abiotic stresses, including forage cereals and millets, including pearl millet, kodo millet, and sorghum, have also been reported to possess adaptive traits that confer resilience under variable climatic conditions (Singh *et al*., 2010; Malathi *et al*., 2022; Amrutha *et al*., 2023; Dheeravathu *et al.* (2024a and b), Sravanthi *et al.*, 2024, 2025; Dheeravathu *et al.*, 2026). Legumes species such as cowpea (Vigna unguiculata), berseem (*Trifolium alexandrinum*), *Clitoria ternatea*, *Centrosema* spp., and Siratro (*Macroptilium atropurpureum*) have shown tolerance to multiple stresses, including excess soil moisture (Dheeravathu *et al*., 2017a, 2017b, 2021a, 2021c, 2022c, 2023). Among grasses, Guinea grass (*Megathyrsus maximus*), Bajra–Napier hybrids, trispecific hybrids, and Dinanath grass (*Pennisetum pedicellatum*) have demonstrated adaptability under adverse moisture conditions (Singh *et al*., 2020, Singh et al. (2021), Dheeravathu *et al*., 2021a, 2021b, 2022a, 2022b).

CONCLUSION

Climate change and increasing El Niño frequency represent major challenges for livestock production systems worldwide. Reduced rainfall, rising temperature, drought events, and pasture degradation directly threaten fodder security and animal productivity. C_4 forage grasses represent some of the most climate-resilient agricultural crops because of their superior photosynthetic efficiency, high water-use efficiency, deep root systems, rapid regeneration ability, and tolerance to heat and drought. Their integration into farming systems can ensure sustainable fodder production and improve livestock resilience under changing climatic conditions. Forage legumes further strengthen climate adaptation by improving forage quality, fixing atmospheric nitrogen, enhancing soil fertility, and supporting sustainable pasture ecosystems. Grass–legume combinations provide balanced nutrition, improve soil health, and maintain stable forage production during climatic uncertainties. Future livestock systems must focus on climate-smart forage management, improved varieties, conservation practices, and integrated crop–livestock approaches. Investment in forage research, seed production, and farmer awareness will be essential for developing resilient livestock production systems capable of facing future climate challenges.

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