



REVIEW ARTICLE

Sustainable forage crop production systems for fodder security: A review

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Received: 29 June 2026; Accepted: 30 July 2026; Available online: Version 1.0: 30 August 2026

Cite this article: Arthi R, Ragavan T, Prabhakaran J, Saravanan S, Rani S, Syed AHH. Sustainable forage crop production systems for fodder security: A review. Plant Science Today. 2026; 13(sp5): 1-16. <https://doi.org/10.14719/pst.16406>

Abstract

Livestock farming significantly contributes to India's agricultural sector by supporting rural livelihoods, food and nutritional security, employment and sustainable farming practices. India supports approximately 536.7 million livestock; however, only about 4 % of its cultivable land is devoted to fodder production, resulting in a persistent shortage of quality feed resources. The fodder demand–supply gap has widened due to limited land available for fodder cultivation, degradation of grazing lands, competition with food crops and limited access to improved fodder technologies. Irregular rainfall, droughts and declining forage productivity and quality have further exacerbated these challenges under changing climatic conditions. Reliance on low-quality crop residues and inadequate feed preservation practices adversely affects animal health, livestock productivity and farmers' income. This review synthesises recent advances in sustainable forage production systems, fodder conservation technologies and climate-resilient strategies to identify approaches for improving fodder security and resilient livestock production. It examines the role of quality fodder in improving the efficiency of current livestock production systems by enhancing milk production, reproductive performance and feed-use efficiency, while identifying key challenges, including weak forage seed systems, inadequate extension services and limited policy support. The review concludes that diversified forage systems, improved fodder conservation practices, rehabilitation of grazing resources and integrated crop–livestock systems are essential for strengthening fodder security and ensuring sustainable livestock production in India.

Keywords: climate-resilient fodder; fodder conservation; fodder security; forage crop production; livestock productivity; sustainable forage systems

Introduction

Sustainable forage crop production is fundamental to resilient livestock farming and plays a crucial role in ensuring continuous availability of quality fodder for supporting animal health, productivity and farm profitability. Besides providing nutritionally balanced feed, sustainable forage production contributes to efficient utilisation of land, water and nutrient resources, enhances soil fertility, promotes biodiversity and strengthens the resilience of agricultural systems under changing climatic conditions (1). In this context, developing sustainable forage production systems has become essential for achieving long-term fodder security and environmentally sustainable livestock production.

Despite the importance of forage crops, fodder availability remains a major constraint to livestock production in many regions. Limited land allocation for forage cultivation, degradation of grazing lands, competition between food and fodder crops, poor adoption of improved forage technologies and inadequate fodder conservation practices continue to restrict the availability of quality feed resources (2).

These challenges are further intensified by climate variability, including erratic rainfall, prolonged droughts, increasing temperatures and frequent extreme weather events, which

adversely affect forage growth, biomass production and nutritional quality (1). Consequently, many livestock production systems continue to depend on low-quality crop residues and seasonal feed resources that fail to meet the nutritional requirements of high-producing animals.

Addressing these challenges requires a transition from conventional fodder production to sustainable forage crop production systems that integrate improved forage species, balanced nutrient and water management, forage legumes, diversified cropping systems, silvopasture, hydroponic fodder production, fodder conservation technologies and integrated crop–livestock systems. These approaches enhance forage productivity and quality, improve resource-use efficiency, strengthen climate resilience and support sustainable livestock production. Although considerable advances have been made in forage breeding, climate-smart agronomy, precision nutrient management and fodder conservation, their adoption remains limited due to inadequate quality seed availability, location-specific production technologies, extension support and policy interventions. Therefore, a comprehensive synthesis of these advances is essential to identify effective strategies for improving fodder security and promoting sustainable livestock production.

Although substantial progress has been made in forage crop improvement, climate-smart agronomic practices, fodder conservation technologies, hydroponic fodder production and digital agriculture, existing research remains fragmented and several important knowledge gaps persist. Most studies have focused on individual technologies or short-term productivity, with limited attention to integrated forage production systems, long-term sustainability, economic feasibility, climate resilience and region-specific management strategies. Furthermore, the application of emerging technologies such as geographic information systems (GIS), remote sensing, artificial intelligence (AI) and precision agriculture in forage production remains insufficiently explored, particularly under smallholder farming conditions. A comprehensive synthesis integrating these advances, identifying current knowledge gaps and highlighting future research priorities is therefore needed to support sustainable fodder production and resilient livestock farming.

Therefore, this review synthesises recent advances in sustainable forage crop production systems and critically evaluates improved forage crops, integrated nutrient and water management, forage-based cropping systems, climate-resilient production practices, fodder conservation technologies, hydroponic fodder production, silvipasture and integrated crop–livestock systems for achieving long-term fodder security. The review further identifies existing knowledge gaps, emerging research priorities and future directions for developing resilient, resource-efficient and environmentally sustainable forage production systems.

Methodology and literature search

This review was conducted using a systematic review methodology and the findings were synthesised narratively to provide a comprehensive overview of sustainable forage crop production systems and their role in ensuring fodder security and resilient livestock farming.

Strategy for collecting appropriate articles

The literature search strategy was designed to identify publications related to sustainable forage systems, fodder security, livestock productivity, climate-resilient forage production and fodder conservation technologies. Relevant articles were retrieved from the Web of Science and ScienceDirect databases using predefined keywords and Boolean operators. The search results obtained from major thematic areas are presented in Table 1.

A comprehensive search strategy was employed using combinations of keywords and Boolean operators such as: “sustainable forage systems”, “fodder security”, “forage crop

production”, “livestock productivity”, “green fodder”, “dry fodder”, “crop residues”, “forage legumes”, “hydroponic fodder”, “silvipasture systems”, “fodder conservation”, “hay making”, “silage production”, “fodder banks”, “genetic improvement of forage crops”, “climate-resilient fodder”, “crop–livestock integration”, “fodder deficit” and “livestock nutrition”.

The values given in Table 1 represent the number of initial search records retrieved for each thematic search strategy before duplicate removal and screening. Because multiple search terms and Boolean operators were used, individual records may have been retrieved under more than one search strategy. Therefore, the values should not be interpreted as independent or cumulative article counts.

Relevant scientific literature was collected from the Web of Science and ScienceDirect databases. Literature published between 2010 and 2025 was considered to capture recent advances in forage production technologies, fodder management, livestock nutrition, climate-resilient agriculture and sustainable livestock systems.

The inclusion criteria comprised peer-reviewed research articles, review papers and relevant book chapters that addressed forage crop production, fodder availability, fodder conservation technologies, forage quality improvement, livestock feeding strategies, climate-smart fodder systems and sustainable livestock production. Only publications published in English between 2010 and 2025 were considered. Publications not directly related to fodder resources, forage management, livestock feeding, or sustainable forage systems were excluded. Duplicate records identified across databases, including duplicate publications reporting the same study, were removed prior to screening. As this review aimed to provide a comprehensive synthesis of the available literature, no formal quality assessment or risk-of-bias tool was applied. Studies were selected based on their relevance to the objectives of the review.

In addition to the peer-reviewed studies included in the qualitative synthesis, official statistical reports and institutional publications issued by the Food and Agriculture Organization (FAO), Department of Animal Husbandry and Dairying (DAHD), Basic Animal Husbandry Statistics, ICAR-IGFRI Newsletter, ICAR-IGFRI Annual Report, the 20th Livestock Census and Government of India publications were consulted to provide updated national and global statistics on livestock population, land use, fodder availability and agricultural production. Unlike the peer-reviewed literature included in the qualitative synthesis, these institutional publications were used only as supporting sources for contextual and statistical information and were not evaluated as part of the systematic review.

Table 1. Initial search records retrieved using major thematic search strategies in web of science and ScienceDirect

Search strategy	Web of Science	ScienceDirect
Fodder security and forage production	780	720
Livestock productivity and fodder resources	650	690
Green fodder and dry fodder production trends	420	390
Climate change impacts on forage systems	510	460
Shrinking grazing lands and fodder deficit	340	310
Hydroponic fodder production systems	350	290
Legume fodders and forage quality	510	460
Silvopastoral systems and fodder trees	280	240
Genetic enhancement of forage crops	390	360
Fodder conservation technologies and silage production	430	410
Sustainable livestock farming	690	620

or included in the final systematic review dataset.

A total of 10300 records were initially identified through database searching and reference cross-checking. Duplicate records were identified and removed manually before screening, resulting in 8150 records for title and abstract screening. The screening and eligibility assessment were conducted by the author using the predefined inclusion and exclusion criteria. When the eligibility of a publication was uncertain, the full text was re-examined against the review objectives before a final inclusion decision was made. Of the screened records, 430 articles were retained for full-text assessment. Following eligibility evaluation, 83 studies that directly addressed the objectives of this review were included in the final qualitative synthesis. The literature screening and study selection process followed the preferred reporting items for systematic reviews and meta-analyses (PRISMA) 2020 guidelines and the complete study selection process is presented in Fig. 1.

Global and Indian livestock sector overview

The livestock sector is one of the most important components of global agriculture, contributing substantially to food and nutritional security, employment generation, rural livelihoods and economic

development. In India, livestock plays a pivotal role in the agricultural economy, serving as a major source of income for millions of rural households. The country possesses one of the world's largest livestock populations and is the leading producer of milk, reflecting the sector's significant contribution to agricultural growth and national development. The key indicators of the global and Indian livestock sector are summarised in Table 2.

Despite its remarkable growth and economic importance, the livestock sector continues to face several challenges that limit productivity and sustainability. Inadequate availability of quality fodder remains one of the major constraints affecting livestock performance and profitability, while high feed costs impose a considerable financial burden on farmers. In addition, climate change further exacerbates these challenges by adversely affecting forage availability, water resources, disease dynamics and animal productivity (3). These constraints underscore the need for sustainable fodder production systems, climate-smart livestock management practices, improved breeding programmes, efficient resource utilisation and enhanced nutrient recycling approaches to strengthen fodder security and ensure resilient livestock production

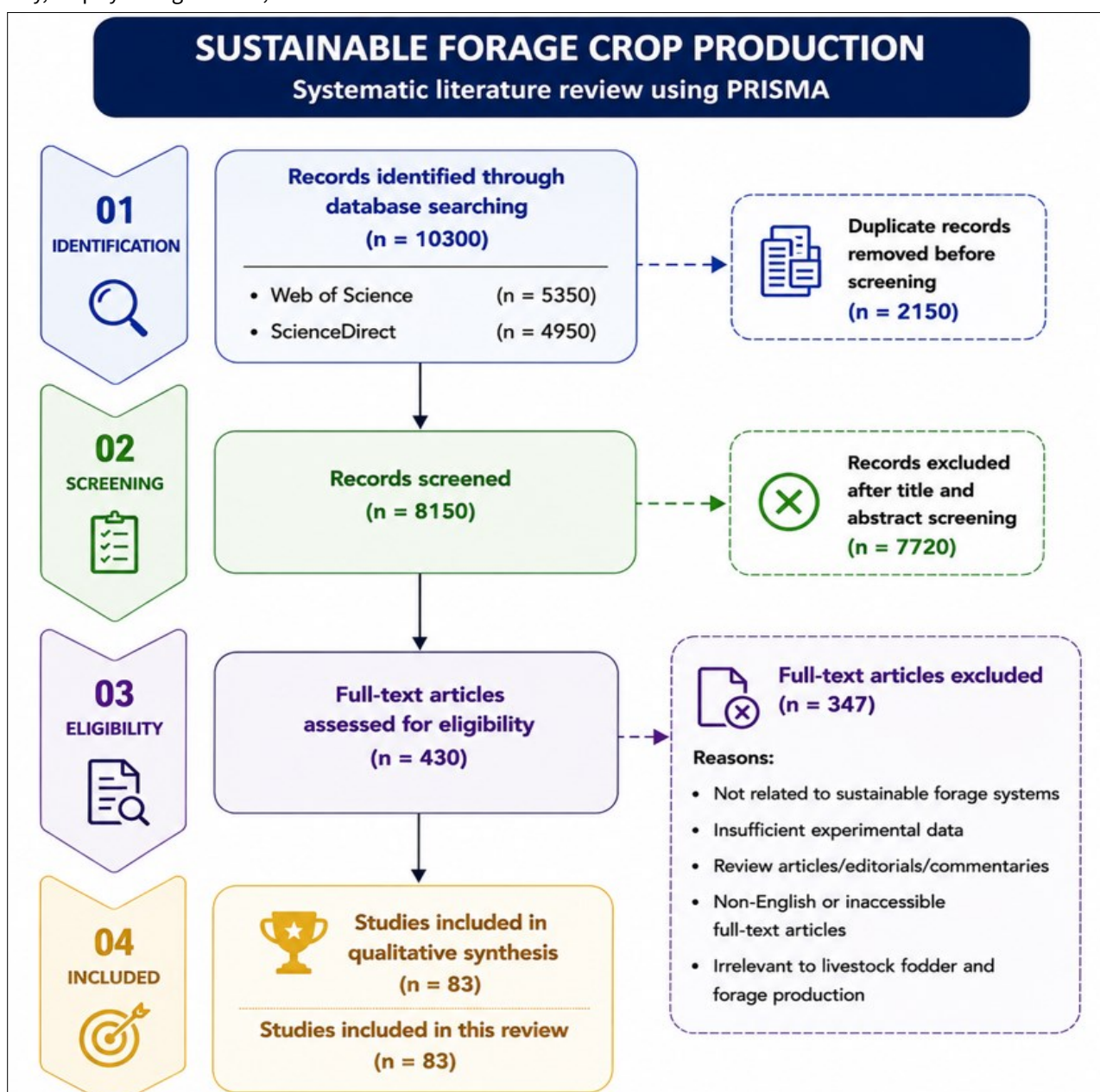


Fig. 1. Search strategy used for literature retrieval from web of science and ScienceDirect databases.

Table 2. Key indicators of the global and Indian livestock sector

Indicator	Global	India	Source
Contribution to agricultural gross domestic product (GDP)	~40 %	~28 %	Food and Agriculture Organization (FAO) (2009); DAHD (2024)
Contribution to national GDP	–	~5 %	DAHD (2024)
Contribution to global protein supply	~34 %	–	FAO (2009)
Contribution to global dietary energy	~18 %	–	FAO (2009)
Rural households dependent on livestock	–	~70 %	DAHD (2024)
Cattle population	–	192.49 million	20 th Livestock Census (2019)
Buffalo population	–	109.85 million	20 th Livestock Census (2019)
Goat population	–	148.88 million	20 th Livestock Census (2019)
Sheep population	–	74.26 million	20 th Livestock Census (2019)
Share of global milk production	–	~24 %	Basic Animal Husbandry Statistics (2024)
Annual milk production growth	–	> 6 %	Basic Animal Husbandry Statistics (2024)

systems (4).

Importance of fodder and forage for livestock productivity

Fodder and forage play a fundamental role in livestock nutrition and directly affect animal health and profitability of the farm. High-quality green fodder enhances rumen microbial activity, nutrient digestion, feed intake and metabolic efficiencies of ruminants. High-protein forage with highly digestible fibre and essential minerals improves milk production, weight gain, reproductive rates and disease resistance. Fodder and forage play a major role in livestock nutrition and directly affect animal health and farm profitability. Good-quality green fodder enhances rumen microbial activity, nutrient digestion, feed intake and metabolic efficiency in ruminants. High-protein, highly digestible fibre and mineral-rich forages improve milk production, weight gain, reproductive performance and disease resistance. Feed constitutes the single largest recurring expenditure in livestock production systems, often accounting for 60–70 % of the total cost of production. Consequently, improving fodder quality and availability is one of the most effective strategies for enhancing farm profitability. A study conducted in southern India reported that feed costs accounted for 63.88 % of the gross production cost in Andhra Pradesh, 72.14 % in Tamil Nadu and 71.62 % in Karnataka. Net profitability varied across the 3 states, ranging from 43 % in Tamil Nadu to 70 % in Andhra Pradesh and 83 % in Karnataka (5).

The use of legume fodders like *Stylosanthes*, *Desmanthus* and *Clitoria* can enhance the crude protein content of livestock diets. Balanced forage systems with grasses, legumes and fodder trees offer a well-rounded diet and beneficial phytochemicals that help maintain the immune system and gut health (6). Additionally, fodder production lowers the expenses of feeding and improves profitability of farms, particularly for smallholder farmers who grow their own forage resources. Fodder banks, silvopastoral systems and community grazing lands are other practices that further improve fodder security and mitigate vulnerability in periods of drought and dry season (7).

Thus, fodder and forage are not merely feed resources but fundamental pillars of livestock productivity, animal health, economic sustainability and environmental resilience. Ensuring their availability, diversity and quality is essential for improving livestock performance, strengthening rural livelihoods and advancing sustainable agriculture in India and across the world.

Current fodder scenario

Despite significant growth in livestock production, India continues to

face substantial fodder deficits that constrain livestock productivity and profitability. This deficit is primarily attributed to the limited area allocated for fodder cultivation, changing cropping patterns, rapid urbanisation, shrinking grazing lands and the combined effects of climate variability on forage production and availability.

India has only 4 % of its cultivable area dedicated to fodder production, which is inadequate to support the country's livestock population of approximately 536.7 million animals (20th Livestock Census, 2019). As the demand for land for food crops is rising, the cultivation of fodder has not been able to match the growing demand for dairy and meat products (8). Consequently, farmers rely heavily on crop residues such as paddy straw, wheat straw and maize stover, which are characterised by low protein and mineral contents, poor energy value and low digestibility. Residues are often the most significant ration component, which can result in ration imbalance, decreased animal productivity and disease vulnerability.

Over the last three decades, India has lost grazing land from 13 million hectares to less than 9 million hectares (DAHD, 2024) and thus, the availability of natural forage resources for small ruminants and pastoral communities has come under threat. Existing pastures have become degraded due to overgrazing and improper management reducing biomass productivity and biodiversity.

Green fodder production trends

Green fodder production is critical for sustaining livestock productivity in India, particularly in dairy-based systems where nutrient-rich roughage directly influences milk yield, reproductive efficiency and animal health. Despite continuous growth in livestock population, green fodder production has increased only marginally over the past two decades, resulting in a widening demand-supply gap. Although research institutions have developed high-yielding fodder varieties such as CO-4, CO-5, hybrid Napier and multicut sorghum, adoption at the farm level (or among smallholders) remains limited due to land scarcity and preference for food crops.

Seasonality strongly affects green fodder availability. The monsoon season ensure temporary abundance, whereas summer and late winter periods experience acute shortages, particularly in rain-fed regions. Arid and semi-arid zones such as Rajasthan and Gujarat are more vulnerable due to erratic rainfall and limited irrigation. Climate variability has further intensified fodder instability through prolonged dry spells and rising temperatures (3).

Fodder production in India continues to face several structural constraints, including fragmented landholdings, labour-intensive cultivation practices and limited access to quality forage seed and planting materials. These challenges restrict the expansion

of dedicated fodder cultivation and contribute to persistent deficits in feed availability. Emerging interventions such as hydroponic fodder production, azolla cultivation, silage making and the cultivation of perennial forage grasses offer promising opportunities for enhancing biomass availability and improving feed security. Nevertheless, fodder supply remains insufficient to meet the growing demands of the livestock sector, highlighting the need for sustained policy support, technological dissemination and strengthened extension services.

Dry fodder and crop residue availability

Dry fodder derived from crop residues forms the backbone of ruminant feeding systems in India, especially during lean periods. The gross crop residue potential generated in India is 696.38 million tonnes/year (9), mainly from rice, wheat, maize and millets. However, effective utilisation is restricted by competing uses such as bioenergy production, industrial applications, domestic fuel and residue burning, leading to regional and seasonal shortages.

The nutritive value of crop residues varies considerably. Wheat straw is preferred because of its higher palatability and digestibility, whereas rice straw has lower feeding value due to its high silica and lignin content. Pulse and oilseed residues contain relatively higher crude protein and serve as valuable supplements to cereal-based dry fodder. Dry fodder is available in various forms, including loose straw, chopped straw (chaff), hay, compressed bales, complete feed blocks and pellets, depending on storage, transportation and feeding requirements.

Efficient storage is essential to minimise quantitative and qualitative losses. Traditional storage methods often expose fodder to moisture, fungal contamination, insect infestation and weather damage, reducing its nutritive value. Scientific storage practices such as covered sheds, raised platforms, ventilated structures and moisture-proof baling help preserve fodder quality and extend shelf life. Densification technologies, including hay baling, complete feed blocks and pelletisation, further improve storage efficiency by reducing storage space, minimising handling losses and facilitating transportation (3). The feeding value of low-quality crop residues can be enhanced through chaffing, urea-ammoniation, alkali treatment and microbial or enzyme-based treatments, which improve fibre digestibility and nutrient availability. Emerging technologies such as mechanised balers, total mixed ration (TMR), precision feeding systems, smart fodder storage, digital fodder inventory management and decentralised fodder banks are improving residue utilisation, reducing post-harvest losses and ensuring year-round availability of quality fodder. Adoption of these technologies, supported by effective extension services and policy interventions, will play a vital role in strengthening fodder security and promoting sustainable livestock production systems (10).

Regional variations in fodder availability

Fodder availability in India varies considerably across regions due to differences in climate, cropping systems, irrigation facilities, land use and livestock density. Northern states such as Punjab and Haryana benefit from extensive irrigation and intensive cultivation of fodder crops such as berseem and maize, resulting in relatively better fodder availability. In contrast, eastern states predominantly depend on rice-based production systems, where paddy straw and seasonal green fodder constitute the major feed resources.

Arid and semi-arid regions, including Rajasthan and Gujarat, experience chronic fodder shortages because of low rainfall,

recurrent droughts and limited irrigation facilities (11). Southern states exhibit mixed patterns, with Tamil Nadu and Karnataka promoting improved fodder cultivation, whereas Kerala depends largely on purchased fodder owing to land constraints. Similarly, hilly regions rely on forest fodder and community grazing lands, often facing seasonal shortages and high transportation costs (12). Higher livestock density in states such as Uttar Pradesh, Bihar and Rajasthan further aggravates the demand-supply imbalance.

Addressing these regional disparities requires location-specific fodder development strategies. These include the promotion of climate-resilient forage species in drought-prone areas, expansion of irrigated fodder cultivation where water resources permit, efficient utilisation of crop residues, establishment of fodder banks, adoption of silvipasture and integrated crop-livestock systems and strengthening fodder conservation through hay, silage and pellet production. Improved seed distribution, region-specific extension programmes and policy support are also essential to ensure year-round fodder availability and enhance the resilience of livestock production systems.

Causes for fodder crisis

Shrinking grazing lands and common property resources

Common property resources (CPRs), particularly village grazing lands, permanent pastures, fallows and revenue wastelands, have historically formed the backbone of India's mixed crop-livestock production systems. Previous studies clearly demonstrated that CPRs functioned not merely as grazing spaces but as risk-buffer systems, supporting livestock survival during droughts and crop failure years, especially for marginal farmers and landless households (13). Subsequent studies reaffirmed that commons provided low-cost fodder, reduced dependence on purchased feeds and stabilised rural livelihoods (14).

However, national-level assessments indicate that there has been a systematic decline in grazing lands, with permanent pastures shrinking from nearly 13–14 % of India's geographical area at Independence to less than 4 % in recent decades (GOI Land Use Statistics, 2023). Decline is accompanied by deterioration in biomass productivity and forage quality, intensifying the national fodder deficit.

Mitigation strategies should focus on restoring degraded grazing lands through reseedling of perennial grasses and legumes, rotational grazing, silvipasture development, watershed management and community-based pasture management. Strengthening village institutions, protecting common property resources from encroachment and integrating grazing land restoration into national programmes such as Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) and watershed development initiatives can substantially improve forage availability and ecosystem resilience.

Land-use competition with food crops

Land-use competition between fodder and food crops has emerged as a major driver of the fodder crisis in India. Increasing population pressure, urbanisation and agricultural intensification have accelerated the conversion of grazing lands, fallows and marginal lands into cropland, settlements and infrastructure. The growing demand for agricultural land has reduced the area available for natural forage production, thereby decreasing biomass availability from grazing resources.

Historically, Indian agriculture followed integrated crop-livestock systems in which food crops, fodder crops and grazing resources coexisted. However, the post-Green Revolution emphasis on high-yielding cereal varieties, irrigation expansion, fertiliser subsidies and assured procurement policies strongly favoured foodgrain production, while fodder crops received limited policy support and were gradually confined to marginal lands. This shift intensified competition for arable land and reduced the area under forage cultivation.

Policy emphasis on foodgrain self-sufficiency has further widened the gap between fodder demand and supply. Addressing this challenge requires integrated land-use planning, promotion of fodder-based crop rotations, intercropping of forage legumes, cultivation of fodder on field bunds and marginal lands, adoption of dual-purpose crop varieties and policy support for forage seed production and fodder cultivation to improve fodder availability without compromising food security (ICAR-IGFRI Newsletter, 2024).

Low adoption of improved forage crops as a cause of the fodder crisis

Despite substantial progress in forage breeding and agronomic research, the adoption of improved forage crops in India remains low, significantly contributing to the national fodder deficit. The fodder crisis is not solely due to land scarcity but also reflects poor adoption of available forage technologies within existing land resources (ICAR-IGFRI Annual Report, 2024).

India has a well-established forage research system led by ICAR-IGFRI, which has released several high-yielding and multicut forage varieties such as CO (BN) 5, CO 4, NB 21 and bajra-napier hybrids suited to different agro-climatic regions. These varieties can yield two to three times more green fodder than local cultivars under proper management. However, adoption remains largely limited to progressive farmers and organised dairy regions, resulting in a widening gap between potential and realised productivity.

Economic and behavioural factors strongly influence adoption decisions. Fodder crops are often perceived as non-remunerative because they lack minimum support prices, assured markets and direct cash returns. Previous studies further noted that small and marginal farmers are reluctant to allocate scarce land to improved forages, as benefits are realised indirectly through livestock productivity rather than immediate income (15). Fragmented landholdings and food security concerns reinforce this preference for food crops.

Limited availability of certified forage seed and weak private sector participation remain major constraints to the widespread adoption of improved fodder varieties. Poor seed multiplication and distribution systems prevent improved varieties from reaching farmers. Forage crops remain largely excluded from formal seed programmes, resulting in continued reliance on low-yielding local planting material.

Knowledge gaps and weak extension services further restrict adoption. Extension systems primarily prioritise food crops and provide limited guidance on forage agronomy, multicut management and fodder conservation practices. Previous researchers reported that inadequate knowledge of cutting intervals, nutrient management and irrigation often leads to poor performance of improved forages and eventual dis-adoption (16).

Policy neglect has also constrained adoption. The Planning Commission (2012) acknowledged that livestock policies have

focused more on breed improvement and health services, while fodder development received limited attention. Fodder crops are rarely integrated into mainstream agricultural schemes, resulting in fragmented support. Separation of crop and livestock policies limits the large-scale diffusion of improved forage technologies (17).

Adoption levels vary regionally, with higher uptake in irrigated dairy belts such as Punjab, Haryana and parts of Tamil Nadu, where market-oriented milk production encourages fodder investment. In contrast, rainfed and arid regions exhibit low adoption due to water scarcity, higher risk and weak extension systems.

Taken together, the available evidence suggests that the low adoption of improved forage crops is driven not by a lack of technological options, but by a combination of economic constraints, weak seed systems, limited extension support and inadequate policy prioritisation. Addressing these barriers will be essential for narrowing the gap between potential and realised fodder productivity. Strengthening certified forage seed production, expanding public-private partnerships in seed multiplication, improving extension services through digital advisory platforms, establishing demonstration farms and providing financial incentives for forage cultivation can significantly enhance adoption of improved forage technologies. Capacity-building programmes and farmer training on multicut forage management and fodder conservation should be prioritised.

Climate change impacts on forage yield as a driver of the fodder crisis

Climate change has emerged as one of the most critical and cross-cutting drivers of the fodder crisis in India, exerting both direct and indirect impacts on forage yield, quality and seasonal availability. Rising temperatures, altered rainfall patterns, increased frequency of droughts and extreme weather events and elevated atmospheric CO₂ levels have fundamentally altered forage production systems across agro-ecological regions. Climate variability disproportionately affects fodder crops and grazing lands because these systems are often rainfed, marginal and weakly supported by institutional mechanisms. Climate-induced stress on forage resources compounds existing land and management constraints, thereby widening the feed-fodder deficit. Increasing mean and maximum temperatures have a direct effect on forage crop physiology, growth duration and biomass accumulation. Heat stress reduces photosynthetic efficiency, accelerates phenological development and shortens the vegetative growth phase in C₃ forage crops such as berseem and lucerne. In the Indian context, rising temperatures during critical growth stages reduce green fodder yield and increase lignification, thereby lowering digestibility.

Multi-cut forage varieties show reduced regrowth potential under prolonged heat stress, particularly in semi-arid regions. Higher temperatures exacerbate evapotranspiration losses, increasing water demand for forage crops and reducing productivity where irrigation access is limited.

Erratic rainfall distribution and increasing drought frequency are among the most significant climate-related constraints to forage production (18). Rainfed grazing lands and fodder crops are highly sensitive to rainfall fluctuations, resulting in large inter-annual variability in biomass production (19).

Under severe drought conditions, forage biomass production in arid and semi-arid regions has been reported to decline by approximately 40–70 %, depending on the forage species,

drought intensity, duration of moisture stress and prevailing agroecological conditions (20). Drought-induced fodder shortages often force distress feeding of crop residues and trigger livestock mortality during severe drought years, as observed in Rajasthan and parts of Maharashtra.

The increasing frequency of extreme events such as floods, cyclones, heat waves and unseasonal rains poses additional risks to forage systems. Extreme precipitation events damage standing fodder crops through lodging, waterlogging and nutrient leaching. In low-lying and coastal regions, saline water intrusion following cyclones further reduces forage productivity and species diversity.

Repeated exposure to extreme weather weakens the resilience of grazing lands, leading to soil erosion, loss of vegetative cover and delayed regeneration (21). Rising atmospheric CO₂ concentrations have complex effects on forage crops. While elevated CO₂ may enhance biomass production in some C₃ species, several studies indicate a decline in nutritional quality. Higher CO₂ levels reduce crude protein concentration and increase fibre content in forage crops, adversely affecting digestibility and animal performance.

Similar trends have also been reported in Indian forage systems, where increased biomass production under favourable environmental conditions did not translate into proportional improvements in forage nutritive value. Such quality dilution could exacerbate nutrient deficiencies in livestock even when fodder quantity appears adequate.

Climate change intensifies the degradation of grazing lands through prolonged droughts, increased erosion and shifts in species composition. Repeated drought cycles reduce palatable grass species and promote invasive and unpalatable weeds (22). Climate stress reduces the regenerative capacity of degraded commons, making restoration efforts more challenging and costly.

Taken together, the available evidence demonstrates that climate change affects fodder systems through multiple interacting pathways, including reduced biomass production, deterioration of forage quality, degradation of grazing resources and increased seasonal variability in feed availability. These combined effects pose significant challenges to livestock productivity and livelihood security, highlighting the urgent need for climate-resilient forage production strategies and adaptive management interventions.

Climate-induced degradation of commons disproportionately affects pastoral and transhumant systems that rely on seasonal grazing mobility. Loss of climate-resilient grazing corridors further constrains adaptation options for these communities. Climate change impacts on forage yield vary significantly across regions. Arid and semi-arid zones face chronic drought stress, while humid and coastal regions experience flood-related fodder losses. Fodder deficits are most severe in regions where climate stress coincides with high livestock density and limited irrigation (23). Climate change could exacerbate existing green fodder deficits by 10–15 % by 2030 if adaptive measures are not implemented (FAO, 2019). Climate-resilient forage production can be strengthened through the development and dissemination of drought-, heat- and flood-tolerant forage varieties, efficient irrigation technologies, conservation agriculture, integrated nutrient management, rainwater harvesting, silvopasture systems and weather-based advisory services. Strengthening climate-resilient fodder banks and promoting diversified forage production systems will further reduce

vulnerability to climate-induced fodder shortages.

Agronomic innovations for enhancing fodder production

Agronomic innovations play a key role in addressing the persistent fodder deficit in Indian livestock production systems. Increasing pressure on land resources, declining common grazing lands and growing demand for livestock products have limited the effectiveness of conventional forage production practices. Improving fodder availability requires a transition from input-intensive approaches to knowledge-based and resource-efficient agronomic interventions. In India, where livestock production is closely integrated with crop farming, agronomic practices that optimise land use, increase biomass production and improve forage quality are important for enhancing livestock productivity and supporting rural livelihoods.

Approaches such as intercropping, border cropping, integration of forage legumes, hydroponic fodder production and genetic improvement of forage crops offer practical options for increasing fodder availability across diverse agroecological conditions. These practices improve forage yield, soil fertility, resource-use efficiency and the resilience of crop-livestock production systems. Together, they strengthen forage production while supporting climate-smart agriculture and environmental sustainability. The flowchart illustrating the agronomic innovations is presented in Fig. 2.

Integration of tree-based fodder species through silvopasture systems

Silvopasture systems, which integrate trees, fodder crops and livestock, represent a promising integrated production system for sustainable fodder production. Silvopasture enhances land productivity by combining perennial woody species with herbaceous fodders, thereby improving biomass production and ecosystem services. In India, fodder trees such as Subabul (*Leucaena leucocephala* (Lam.) de Wit), Sesbania, Gliricidia and Neem play a significant role in supplementing green fodder, particularly during dry seasons.

Tree-based fodder species contribute to improved crude protein supply, mineral nutrition and year-round fodder availability, especially in rainfed and arid regions (24). Silvopasture systems improve soil organic carbon, reduce erosion and enhance moisture retention compared to open grazing systems. Additionally, fodder trees act as carbon sinks, contributing to climate change mitigation.

From a livelihood perspective, silvopasture systems diversify farm income through fuelwood, timber and non-timber forest products, while simultaneously strengthening fodder security. Therefore, promotion of silvopasture through policy support and extension interventions is considered a key future thrust for sustainable livestock farming in India.

Despite their ecological and nutritional benefits, adoption of silvopasture systems remains constrained by long establishment periods, competition for land resources and limited availability of quality planting material. Addressing these constraints through appropriate policy support, quality planting material supply systems and extension interventions will be essential for realising the full potential of silvopasture as a sustainable livestock production strategy in India.

Intercropping and border cropping for maximising land use efficiency in fodder systems

Intercropping and border cropping have emerged as important

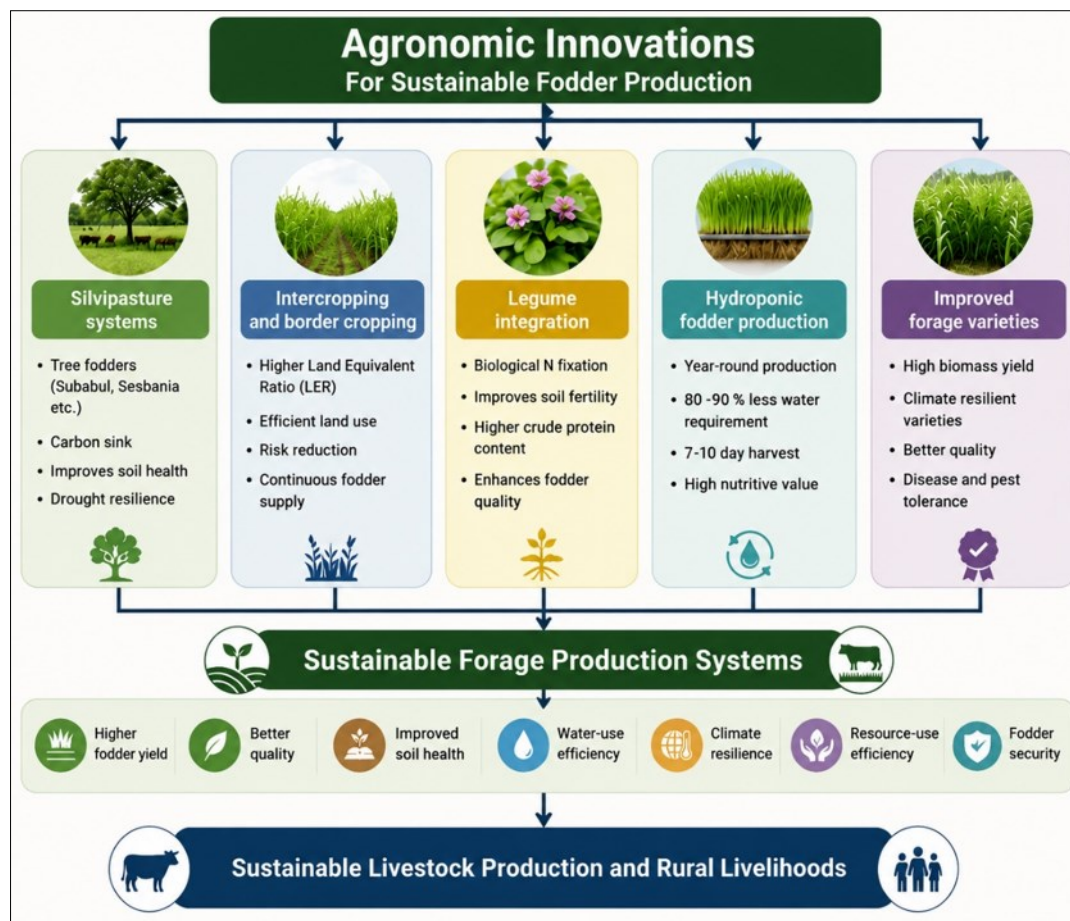


Fig. 2. Agronomic innovations for sustainable fodder production.

agronomic strategies for enhancing fodder production under conditions of land scarcity and fragmented landholdings. Previous researchers defined intercropping as the simultaneous cultivation of two or more crops on the same field, which improves land equivalent ratio (LER) by enabling complementary utilisation of light, nutrients and soil moisture (25). In Indian mixed farming systems, where competition between food and fodder crops is intense, intercropping offers a practical solution to increase fodder availability without reducing food crop area.

Cereal-legume intercropping systems have been widely studied for fodder production due to their synergistic effects on yield and quality. Combinations such as sorghum + cowpea, maize + fodder cowpea and pearl millet + cluster bean consistently recorded higher green fodder yield and superior crude protein content compared to sole cereal fodders. These systems exploit differences in canopy architecture, growth duration and rooting depth, resulting in improved capture of solar radiation and enhanced nutrient uptake. Fodder-based intercropping systems improve economic returns by producing nutritionally balanced fodder within limited land resources.

Border cropping of perennial fodders has gained prominence as an efficient means of utilising otherwise field boundaries and marginal farm spaces. Planting perennial fodders such as CO (BN) 5 Napier, guinea grass and hedge lucerne along field bunds, irrigation channels and farm boundaries substantially enhances total fodder availability per unit farm area. Border cropping is particularly advantageous for small and marginal farmers, as it does not interfere with the main cropping sequence while providing a continuous supply of fodder throughout the year.

Intercropping systems also enhance yield stability under rainfed conditions, where climatic uncertainty often disrupts fodder supply. Diversified cropping systems reduce the probability of complete crop failure by distributing climatic risk across species. Previous researchers noted that fodder-based intercropping systems help stabilise livestock production by ensuring minimum fodder availability during drought years and lean seasons, thereby reducing farmers' vulnerability to feed shortages (26).

From a soil fertility and conservation perspective, intercropping systems improve nutrient cycling and reduce nutrient losses. In earlier reports, higher soil organic carbon levels, improved microbial biomass and enhanced nutrient availability under intercropping compared to monocropping. Border cropping with fodder grasses reduces soil erosion, improves soil aggregation and enhances water infiltration, particularly in sloping and marginal lands (27). These soil health benefits contribute to the long-term sustainability of fodder production systems.

Overall, intercropping and border cropping represent low-cost, scalable and farmer-friendly interventions that align with sustainable intensification objectives. Widespread adoption of these practices could significantly improve fodder availability in fodder-deficit regions while maintaining ecological integrity.

Although intercropping systems generally improve forage productivity and resource-use efficiency, their performance is highly dependent on crop combinations, planting geometry, management practices and local environmental conditions, indicating that location-specific recommendations remain essential for maximising benefits.

Integration of legume fodders for improved biomass production and soil fertility

Integration of legume fodders is a critical component of sustainable fodder production systems due to their unique ability to fix atmospheric nitrogen and enhance forage quality. Biological nitrogen fixation by legumes substantially reduces dependence on synthetic nitrogen fertilisers, thereby lowering production costs and environmental risks. In Indian fodder systems, legumes such as fodder cowpea, lucerne, *Desmanthus* and stylo have been widely promoted for improving both biomass production and nutritional quality.

Integration of legume fodders is a critical component of sustainable fodder production systems due to their unique ability to improve both forage quality and soil fertility. Collectively, the available evidence indicates that cereal-legume fodder mixtures enhance crude protein content, improve rumen microbial activity, increase fibre digestibility and promote better feed conversion efficiency compared to sole cereal fodders (28, 29). Legume inclusion also enhances palatability and voluntary feed intake, resulting in improved milk yield and growth performance in livestock. Comparative information on the production performance of major forage crops, including green fodder yield, dry fodder yield, crude protein content, cutting frequency and their principal agronomic advantages, compiled from published studies (30–35), is summarised in Table 3.

From a soil health perspective, legume fodders contribute significantly to long-term soil fertility through biological nitrogen fixation, improved soil organic carbon, enhanced microbial activity and greater nutrient availability. Under Indian conditions, legume-integrated fodder systems have been associated with improved soil nitrogen balance and reduced dependence on synthetic nitrogen fertilisers, thereby supporting both livestock productivity and environmental sustainability (36).

Thus, integration of legume fodders represents a multifunctional agronomic strategy that improves fodder quantity, quality, soil health and environmental sustainability, making it an important component for sustainable livestock production in India.

Hydroponic green fodder production systems

Hydroponic green fodder production has emerged as an alternative approach for addressing fodder scarcity under conditions of limited land, water and climatic uncertainty. In India, shrinking arable land, competition with food crops, erratic rainfall and seasonal fluctuations in biomass production have constrained conventional forage cultivation, particularly in peri-urban, drought-prone and intensive dairy production systems. Hydroponic technology enables year-round production of fresh green fodder in a controlled

environment using minimal land and water resources.

Hydroponic systems involve the cultivation of cereal grains such as maize, barley, oats, wheat and sorghum without soil using water or nutrient solutions under controlled temperature, humidity and light conditions. Fresh fodder can be harvested within 7–10 days, ensuring a continuous supply irrespective of seasonal limitations (37). In India, hydroponic fodder has gained increasing attention because of its efficient resource use and potential application in commercial dairy farms, smallholder production systems and emergency feeding during droughts and natural calamities. However, widespread adoption is constrained by high establishment costs, energy requirements and uncertainties regarding economic viability (38).

Selection of suitable crop species influences hydroponic fodder performance. The stepwise process of hydroponic fodder cultivation is shown in Fig. 3.

Maize is the most widely used crop in India because of its high germination, rapid growth, palatability and availability, while barley, oats, wheat and sorghum are also suitable depending on climatic conditions (39). Hydroponic maize produces a dense mat of roots, shoots and residual grains that can be fed as a whole unit, reducing feed wastage. Fresh fodder yield generally ranges from six to ten times the initial seed weight within 7–10 days (40). However, biomass accumulation primarily results from water absorption and mobilization of seed reserves rather than net dry matter synthesis. Consequently, hydroponic fodder contains only about 10–15 % dry matter and should therefore be used as a supplementary feed rather than as the sole component of livestock rations (41). Hydroponic fodder is characterised by improved digestibility, enhanced enzymatic activity and higher concentrations of vitamins A, E and B-complex compared with conventionally produced fodder. Germination increases soluble carbohydrates and reduces anti-nutritional factors, thereby improving palatability and feed utilisation. However, crude protein content depends largely on the original seed composition and balanced feeding with dry fodder and concentrates remains necessary to meet livestock nutrient requirements (41).

Several studies have demonstrated improvements in feed intake, rumen fermentation, weight gain, milk yield and milk quality when hydroponic fodder is incorporated into conventional feeding systems (42, 43). Nevertheless, the response varies with crop species, inclusion level, animal category and overall ration composition. Excessive dependence on hydroponic fodder without adequate dry roughage may reduce rumination and fibre intake, highlighting the importance of balanced ration formulation (44). One of the major advantages of hydroponic systems is their high water-use efficiency, requiring approximately 80–90 % less water than conventional

Table 3. Comparative performance of major forage crops in term of production

Forage crop	Dry fodder yield (t ha ⁻¹ yr ⁻¹)	Green Fodder Yield (t ha ⁻¹ yr ⁻¹)	Crude protein (%)	Cutting Frequency	Major advantage	References
Hybrid Napier	35–45	250–350	8–12	7–8 cuts/year	Very high biomass production	(30)
Fodder sorghum	10–16	40–80	8–10	2–3 cuts	Suitable for dry regions	(31)
Maize	12–18	40–60	8–9	Single harvest	Excellent silage crop	(32)
Oat	10–14	50–70	10–12	2–3 cuts	High winter fodder production	(33)
Berseem	12–18	80–120	16–20	5–6 cuts	High-quality dairy fodder	(34)
Cowpea	6–10	25–40	18–24	2–3 cuts	Nitrogen fixation	(35)

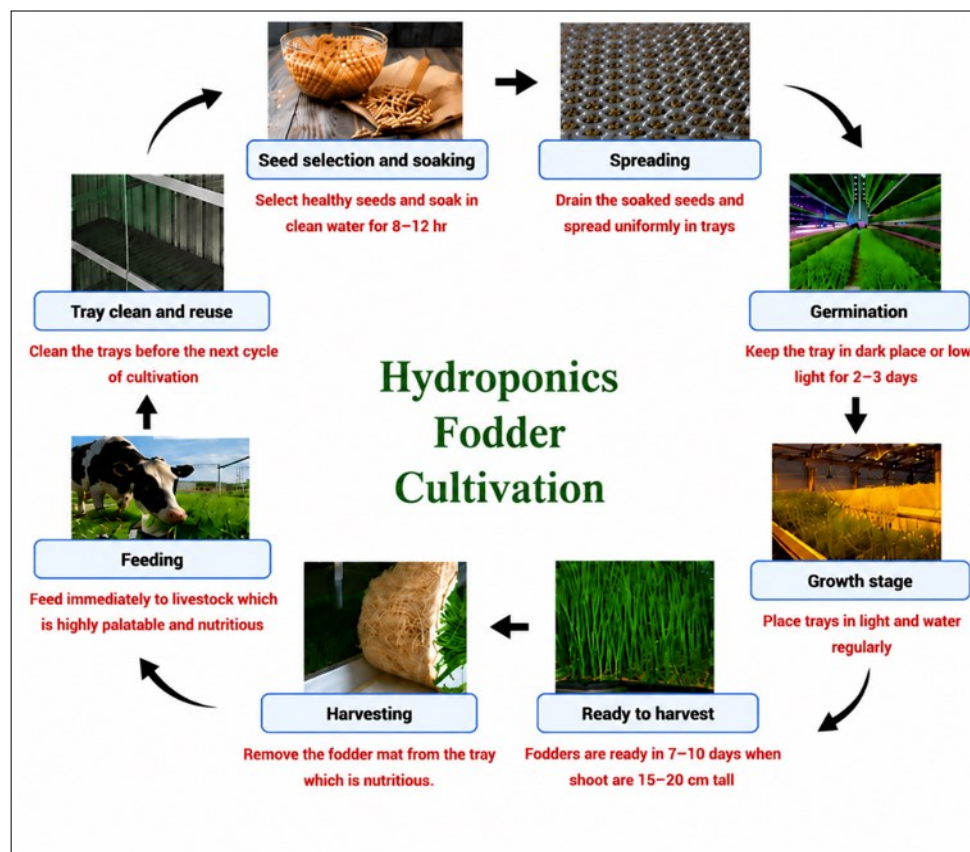


Fig. 3. Process of hydroponic fodder cultivation.

fodder cultivation through recycling of irrigation water (45).

Despite these advantages, economic feasibility remains the principal limitation to large-scale adoption. Initial investment, electricity, labour, seed procurement and maintenance costs are relatively high, although commercial dairy enterprises may achieve favourable returns under efficient management (46, 47). Cost-effectiveness depends on production scale, resource availability and local market conditions, while low-cost hydroponic units and renewable energy integration may improve adoption among smallholder farmers.

Hydroponic fodder also contributes to climate-resilient livestock production by ensuring feed availability during droughts and other extreme weather events. Its rapid production cycle and independence from climatic variability make it a valuable component of climate-adaptive livestock feeding strategies (48).

Overall, hydroponic fodder production offers significant advantages in terms of resource-use efficiency, rapid biomass production and reliable fodder supply under resource-constrained conditions. Although evidence consistently supports improvements in fodder availability and water-use efficiency, the long-term economic viability of hydroponic systems remains context-specific and warrants further investigation. Future research should focus on reducing production costs, optimising nutrient management and evaluating long-term sustainability under diverse farming conditions.

Genetic enhancement for high-yielding and nutritious fodder crops

Genetic enhancement of fodder crops has emerged as a critical long-term strategy for addressing the dual challenge of increasing fodder quantity and improving nutritional quality in livestock production systems. In India, the widening gap between fodder demand and supply, coupled with declining grazing resources and increasing

climatic stress, has made conventional agronomic interventions alone insufficient. Enhancing the intrinsic yield potential and nutritive value of fodder crops through breeding and modern biotechnological approaches is therefore essential for achieving sustainable livestock production and nutritional security. Traditional fodder crops often exhibit limitations such as low biomass yield, poor crude protein content, high fibre and lignin concentration and susceptibility to biotic and abiotic stresses, all of which adversely affect rumen function, feed conversion efficiency and livestock productivity (49). Genetic enhancement aims to overcome these constraints by improving fodder yield, digestibility, protein content, mineral density and stress tolerance.

Modern genetic improvement programmes encompass conventional breeding, marker-assisted selection, molecular breeding, biofortification, transgenic approaches and genome editing. These approaches focus on increasing biomass yield, improving crude protein content, enhancing fibre digestibility, enriching mineral composition and developing climate-resilient forage cultivars (50, 51). Biofortification has emerged as an effective strategy to improve the nutritional quality of fodder crops. Such improvements enhance feed efficiency, reduce dependence on commercial protein supplements and improve livestock productivity, particularly in smallholder production systems where access to concentrate feeds is limited (52). The nutritive values of the major crops are presented in Table 4. Data compiled from published literature (53–59).

Improving biomass yield remains a primary objective of fodder breeding programmes because higher forage productivity is essential under conditions of land scarcity. Selection for rapid early growth, multicut ability, enhanced tillering and tolerance to repeated harvesting has resulted in the development of high-

Table 4. Nutritive parameters of major forage crops in India

Fodder Crop	Neutral detergent fibre-NDF (%)	Acid detergent fibre-ADF (%)	Lignin (%)	In vitro dry matter digestibility (%)	Oxalate content (% DM)	References
Hybrid Napier	65–72	38–45	5–7	55–65	2.0–3.5	(53)
Fodder sorghum	58–68	32–40	4–6	58–68	0.5–1.5	(54)
Maize	45–55	25–32	3–5	65–75	0.1–0.5	(55)
Oat	50–60	28–35	3–5	60–72	0.2–0.8	(56)
Berseem	35–45	22–30	2–4	68–80	0.5–1.2	(57)
Lucerne	38–48	25–35	4–6	65–75	1.5–2.5	(58)
Cowpea	40–50	25–32	3–5	65–75	0.3–1.0	(59)

yielding forage cultivars with improved adaptation to diverse agroecological conditions (60). In addition to increasing fodder availability, improved yield stability under marginal environments contributes to continuous feed supply and strengthens the resilience of livestock production systems.

Genetic approaches aimed at reducing lignin content or altering lignin composition have shown promising results. Earlier studies reported that reduced-lignin fodder varieties exhibit improved dry matter digestibility, higher intake and increased milk yield (61). Previous studies emphasised that lignin modification enhances feed efficiency without compromising plant structural integrity (62). Improved fibre digestibility enhances rumen fermentation, nutrient utilisation and feed efficiency while reducing methane emissions per unit of animal product, thereby contributing to environmentally sustainable livestock production. However, the magnitude of these benefits varies among forage species and production environments, highlighting the need for region-specific evaluation of improved cultivars (63).

Biotechnological interventions have accelerated fodder crop improvement through marker-assisted selection, molecular breeding and genome-editing technologies, enabling precise manipulation of traits associated with yield, forage quality, digestibility, nutrient-use efficiency and stress tolerance (64, 65). Modification of genes involved in lignin biosynthesis has improved fodder digestibility and animal performance, while genome-editing tools such as CRISPR-Cas9 offer targeted genetic improvement without introducing foreign DNA (66, 67). These advanced breeding approaches facilitate the development of climate-resilient, high-quality forage cultivars; however, their successful deployment requires appropriate biosafety assessment and regulatory compliance.

Developing climate-resilient forage cultivars has become a major priority under changing climatic conditions. Improved varieties possessing deep root systems, greater water-use efficiency, heat tolerance and drought resistance provide more stable biomass production under adverse environments (68). These cultivars are expected to play an important role in strengthening long-term fodder security, enhancing livelihood resilience and supporting sustainable livestock production under future climate scenarios (69).

Existing studies consistently demonstrate that genetically improved fodder enhances nutrient utilisation, feed conversion efficiency, milk production, reproductive performance and overall livestock productivity while reducing dependence on concentrate feeds and lowering production costs (70).

Genetic enhancement also contributes to environmental sustainability by improving resource-use efficiency and reducing greenhouse gas emissions. Improved digestibility lowers methane

emissions per unit of animal product, while biofortified fodder crops reduce fertiliser and feed input requirements (71). Consequently, genetic improvement supports sustainable intensification by increasing biomass production, improving nutritional quality and minimising environmental impacts.

Despite significant advances, genetic enhancement of fodder crops faces several challenges, including weak seed systems, limited farmer awareness, slow varietal replacement and regulatory concerns associated with advanced biotechnological approaches. There is a need for stronger linkages between research institutions, seed producers and farmers to enhance the adoption of improved fodder varieties. Capacity building and extension support are critical for realising the full potential of genetic enhancement.

Although significant progress has been made in developing high-yielding and climate-resilient forage cultivars, the evidence indicates that genetic improvement alone cannot address fodder insecurity. The effectiveness of improved varieties depends on complementary agronomic practices, seed availability and farmer adoption. Furthermore, many improved cultivars have been evaluated under experimental conditions, while their performance under diverse farming environments remains insufficiently documented. Future breeding programmes should integrate productivity, nutritional quality, climate resilience and adaptability to local production systems.

Fodder conservation technologies

Fodder conservation technologies constitute an essential component of sustainable forage production systems by enabling the preservation of surplus forage biomass for use during periods of feed scarcity. This temporal imbalance between forage production and demand contributes significantly to the national fodder deficit and reduces the efficiency of forage resource utilisation. Conservation of excess forage through appropriate storage and preservation techniques therefore plays an essential role in stabilising fodder availability, reducing post-harvest losses and enhancing the resilience of forage-based agricultural systems.

The effectiveness of fodder conservation technologies varies according to climatic conditions, forage type, infrastructure availability and farm scale, suggesting that no single conservation approach is universally applicable across all production systems.

Hay making

Hay making is one of the most widely practised methods of fodder conservation and involves reducing the moisture content of harvested forage crops to approximately 15–20 % to prevent microbial deterioration during storage. Properly cured hay can be stored for extended periods while retaining a substantial proportion of its nutritional value. Leguminous forage species such as lucerne, cowpea and *Desmanthus* are particularly suitable for hay production because of their high protein content and favourable drying

characteristics. Beyond serving as an important reserve feed during lean seasons, hay production facilitates efficient utilisation of surplus forage biomass and reduces wastage during periods of peak production. However, improper drying and storage conditions may result in nutrient losses, leaf shattering and reduced forage quality.

Silage production

Silage production is a highly efficient method of conserving high-moisture forage crops through controlled anaerobic fermentation. Crops such as maize, sorghum, pearl millet, oats and hybrid Napier grass are commonly used for silage preparation due to their high biomass production and adequate fermentable carbohydrate content. During ensiling, lactic acid-producing microorganisms lower the pH of the stored material, thereby inhibiting spoilage organisms and preserving nutritional quality (72). Compared with hay, silage generally retains a greater proportion of digestible nutrients and can be stored for prolonged periods with minimal deterioration. The adoption of silage technology has gained increasing attention in India as a strategy for managing seasonal forage surpluses, reducing dependence on external feed resources and improving fodder security under climate-variable conditions. Recent advances, including silage inoculants, silo bags and mechanised harvesting systems, have further enhanced silage quality and storage efficiency. Although silage production is widely recognised as an effective fodder conservation strategy, its success depends on proper harvesting stage, moisture management, fermentation quality and storage infrastructure, which can limit adoption among resource-constrained farmers.

Baled and densified fodder

Baling and densification technologies improve the handling, storage, transportation and utilisation of conserved forage resources. Dry fodder materials such as hay, straw and crop residues can be compressed into compact bales, significantly reducing storage space requirements and transportation costs. Densified fodder blocks provide additional advantages by improving bulk density, minimising storage losses and facilitating long-distance movement of fodder from surplus to deficit regions. These technologies are particularly valuable in regions affected by recurrent droughts and seasonal fodder shortages. Furthermore, mechanised baling of crop residues offers an environmentally sustainable alternative to residue burning, thereby contributing to both fodder security and environmental conservation.

Complete feed blocks and pellet technologies

Complete feed block and pellet technologies represent advanced approaches for efficient utilisation of forage resources and agricultural by-products. These systems combine roughages, crop residues, forage legumes, concentrates and mineral supplements into nutritionally balanced feed products. Pelletisation and block formation improve feed uniformity, reduce selective feeding and wastage, facilitate transportation and extend storage life. Such technologies enable the conversion of low-value biomass resources into high-quality feed products while improving overall resource-use efficiency. Their adoption is increasingly recognised as a sustainable strategy for enhancing fodder availability in regions characterised by limited forage production capacity (73).

Crop residue enrichment technologies

Crop residues constitute a substantial proportion of available fodder resources in India; however, their utilisation is often constrained by

low crude protein content, high fibre concentration and poor digestibility. Various enrichment technologies have been developed to enhance the nutritional quality of these residues (74). Chemical treatments such as urea ammonisation, biological treatments involving microbial inoculants and enzymatic approaches can improve fibre degradation, nutrient availability and overall feeding value. However, the effectiveness of residue enrichment technologies varies across production systems. While controlled experimental studies frequently report substantial improvements in digestibility and feeding value, adoption under field conditions remains limited due to labour requirements, input costs and inadequate farmer awareness. This discrepancy highlights the need for greater emphasis on technology dissemination and economic feasibility assessments. Efficient utilisation of enriched crop residues can significantly contribute to sustainable fodder supply systems while reducing pressure on cultivated fodder resources and promoting circular biomass utilisation within agricultural systems (75).

Community fodder banks

Community fodder banks provide an institutional mechanism for conserving and distributing forage resources during periods of scarcity. These systems involve the organised collection, storage and management of conserved fodder at the village or community level. Fodder banks are particularly important in drought-prone and climate-vulnerable regions where seasonal feed shortages frequently threaten agricultural sustainability (76). By maintaining strategic reserves of conserved forage, community fodder banks enhance local resilience, reduce vulnerability to climatic shocks and support continuity of livestock-based farming systems. Their integration with local forage production programmes can further strengthen regional fodder security.

Collectively, the above conservation technologies provide practical and sustainable options for minimising fodder losses and ensuring year-round feed availability. Their cost-effectiveness, technical feasibility and adaptability across different farming systems make them suitable for widespread adoption, particularly among smallholder farmers.

Future perspectives and emerging opportunities in sustainable fodder production

Breeding of high-protein and climate-resilient forage crops

Despite considerable progress in forage breeding, most commercially available varieties are still selected primarily for biomass yield, with relatively less emphasis on nutritional quality, climate resilience and multiple stress tolerance. Furthermore, many improved cultivars have been evaluated mainly under research station conditions and information on their long-term field performance and farmer adoption across diverse agroecological regions remains limited (77).

High-protein forage crops such as improved lucerne, *Desmanthus*, fodder cowpea and multicut sorghum have been identified as critical components for enhancing livestock nutrition and reducing dependence on costly concentrate feeds (78). Breeding for improved crude protein content, amino acid balance and digestible fibre has shown direct positive impacts on milk yield and feed conversion efficiency. In India, ICAR-led forage improvement programmes have prioritised multicut, drought-tolerant and pest-resistant fodder varieties to ensure yield stability across agro-ecological regions.

Future breeding programmes should prioritise the development of high-protein, climate-resilient forage cultivars with improved digestibility, water-use efficiency, pest and disease resistance and tolerance to drought, salinity and heat stress. Integrating conventional breeding with genomic selection and marker-assisted breeding, along with extensive multi-location testing and farmer-participatory varietal evaluation, will facilitate the development and adoption of region-specific forage varieties capable of ensuring stable fodder production under changing climatic conditions.

Geographic information systems mapping of fodder deficit regions for targeted planning

Geospatial technologies such as GIS and remote sensing offer significant potential for identifying fodder deficit regions and guiding targeted interventions. According to previous researchers, GIS-based spatial analysis enables integration of land use, vegetation cover, rainfall and livestock density to assess regional fodder availability (79). In India, spatial mismatch between fodder demand and supply has been identified as a major contributor to chronic fodder shortages (80).

Although GIS and remote sensing technologies provide valuable information on fodder resources, their application in fodder planning remains limited in many regions due to inadequate spatial databases, fragmented data collection and limited integration into policy and extension programmes. Consequently, fodder development programmes are often implemented without accurate region-specific resource assessment, reducing their effectiveness.

Future efforts should focus on establishing national and state-level GIS-based fodder information systems integrating land use, livestock population, forage resources and climatic data. Real-time satellite monitoring and district-level fodder deficit mapping should be incorporated into planning frameworks to support targeted fodder development programmes, pasture restoration, fodder banks and efficient allocation of resources.

Role of technology, artificial intelligence and internet of things in fodder planning

Digital technologies, including AI, the internet of things (IoT) and decision-support systems, are increasingly being explored to improve fodder planning and livestock management. Digital agriculture enables real-time monitoring and predictive analytics for improved resource efficiency. In fodder systems, AI-driven models can forecast fodder demand, optimise cropping calendars and improve feed ration planning (81).

The IoT-based sensors facilitate real-time monitoring of soil moisture, crop growth and fodder storage conditions, thereby reducing post-harvest losses and improving fodder quality. In India, digital platforms integrated with extension services have shown potential in improving technology adoption among farmers (82).

An AI-enabled livestock nutrition advisory systems support precision feeding by matching fodder quality with animal requirements, leading to improved productivity and reduced methane emissions (83).

Although AI, IoT and precision agriculture offer significant opportunities for improving fodder production and resource-use efficiency, their adoption among farmers remains limited because of

high investment costs, inadequate digital infrastructure, poor internet connectivity and limited technical knowledge. In addition, digital decision-support systems specifically designed for fodder production are still at an early stage of development.

Future research should focus on developing affordable, user-friendly digital platforms that integrate AI, IoT, remote sensing and decision-support tools for fodder production and livestock feeding. Strengthening digital infrastructure, farmer training programmes, extension services and policy incentives will be essential to promote large-scale adoption of precision fodder management technologies and improve sustainable livestock production.

Overall, sustainable fodder production will require the integration of climate-resilient forage breeding, GIS-based resource planning and digital technologies to overcome existing limitations in fodder productivity, resource management and technology adoption. Strengthening research, extension services, policy support and farmer capacity building will be essential for translating these innovations into large-scale adoption and ensuring resilient livestock production under changing climatic conditions.

Conclusion

India's growing livestock sector requires sustainable and resilient fodder production systems to meet increasing feed demand under changing climatic and resource constraints. This review highlights that fodder scarcity remains a major challenge despite advances in forage breeding, climate-smart agronomy, fodder conservation, hydroponic production and digital technologies. An integrated approach combining improved forage crops, sustainable management practices, fodder conservation, efficient crop residue utilisation and region-specific planning is essential to enhance fodder availability, livestock productivity and climate resilience. Strengthening research, extension services, quality seed systems and supportive policies will be crucial for promoting large-scale adoption of these technologies and ensuring long-term fodder security and sustainable livestock production.

Acknowledgements

The authors extend their sincere thanks to Tamil Nadu Agricultural University, Coimbatore and the Agricultural College and Research Institute, Madurai, for providing essential technical assistance and expert guidance.

Authors' contributions

RA collected the literature and drafted the manuscript, while TR provided overall guidance and revised the manuscript. JP, SS, SR and SAHH assisted with literature collection, formatting and manuscript revision. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflicts of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Grammarly to language editing and improvement of grammar, without affecting the scientific content or interpretation of the study. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

- Roy A, Agrawal R, Bhardwaj N, Mishra A, Mahanta SJ. Revisiting national forage demand and availability scenario. *Indian J Forage Sci.* 2019;1–21.
- Solh M, van Ginkel M. Drought preparedness and drought mitigation in the developing world's drylands. *Weather Clim Extrem.* 2014;3:62–6. <https://doi.org/10.1016/j.wace.2014.03.003>
- Tulu D, Gadissa S, Hundessa F, Kebede E. Contribution of climate-smart forage and fodder production for sustainable livestock production and environment: Lessons and challenges from Ethiopia. *Adv Agric.* 2023;2023(1):8067776. <https://doi.org/10.1155/2023/8067776>
- Makkar H. Feed demand landscape and implications of food-not feed strategy for food security and climate change. *Animal.* 2018;12(8):1744–54. <https://doi.org/10.1017/S175173111700324X>
- Patidar A. An economic analysis of dairy enterprise in Indore district of Madhya Pradesh [thesis]. Gwalior: Rajmata Vijayaraje Scindia Krishi Vishwa Vidyalaya; 2016.
- Mahgoub O, Osman NEHI, Lu CD. Nutrient utilization and requirements in sheep and goats raised under different systems and fed low nutritional novel feeds for meat production. *Animals.* 2025;15(18):2658. <https://doi.org/10.3390/ani15182658>
- Hassen A, Ahmed R, Alam MS, Chavula P, Mohammed SS. The effect of feed supplementation on cow milk productivity and quality: A brief study. *Int J Agric Vet Sci.* 2022;4(1):13–25. <https://doi.org/10.34104/ijavs.022.013025>
- Boonkum W, Teawyonyong W, Chankitisakul V, Duangjinda M, Buaban S. Impact of heat stress on milk yield, milk fat-to-protein ratio and conception rate in Thai-Holstein dairy cattle: A phenotypic and genetic perspective. *Animals.* 2024;14(20):3026. <https://doi.org/10.3390/ani14203026>
- Venkatramanan V, Shah S, Prasad S, Singh A, Prasad R. Assessment of bioenergy generation potential of agricultural crop residues in India. *Circular Economy.* 2021;1(4):1335–48. <https://doi.org/10.1007/s43615-021-00072-7>
- Azman NF, Katahira T, Nakanishi Y, Chisyaki N, Uemura S, Yamada M, et al. Sustainable oil palm biomass waste utilization in Southeast Asia: Cascade recycling for mushroom growing, animal feedstock production and composting animal excrement as fertilizer. *Cleaner Circular Bioeconomy.* 2023;6:100058. <https://doi.org/10.1016/j.clcb.2023.100058>
- Ahamad F, Tyagi SK, Singh M, Sharma AK. Groundwater in arid and semi-arid regions of India: A review on the quality, management and challenges. In: *Groundwater in Arid Semi-Arid Areas.* 2023. p. 11–52. https://doi.org/10.1007/978-3-031-43348-1_2
- Puri S, Kumar S. Diversity and use of wild edible plants by migratory shepherds in Himachal Pradesh of the western Himalayas, India. *J Med Plants Res.* 2018;12(30):601–10. <https://doi.org/10.5897/JMPR2018.6682>
- Gaur MK, Goyal R, Kalappurakkal S, Pandey C. Common property resources in drylands of India. *Int J Sustain Dev World Ecol.* 2018;25(6):491–9. <https://doi.org/10.1080/13504509.2018.1423646>
- Speranza CI, Kiteme B, Wiesmann U. Droughts and famines: The underlying factors and the causal links among agro-pastoral households in semi-arid Makueni district, Kenya. *Glob Environ Change.* 2008;18(1):220–33. <https://doi.org/10.1016/j.gloenvcha.2007.05.001>
- Ahmadzai H, Tutundjian S, Elouafi I. Policies for sustainable agriculture and livelihood in marginal lands: A review. *Sustainability.* 2021;13(16):8692. <https://doi.org/10.3390/su13168692>
- Hall A. Pasture measurement technology in Tasmanian dairy farming: Exploring and optimising its role and adoption for improved pasture management [thesis]. Hobart: University of Tasmania; 2019.
- Zhang H, Wang G, Liu J, Hao S, Huang S. The influence of converting food crops to forage crops policy implementation on herbivorous livestock husbandry development: Based on policy pilot counties in Hebei, China. *Agriculture.* 2022;12(11):1872. <https://doi.org/10.3390/agriculture12111872>
- Lamega SA, Komainda M, Hoffmann MP, Ayisi KK, Odhiambo JJO, Isselstein J. It depends on the rain: Smallholder farmers' perceptions on the seasonality of feed gaps and how it affects livestock in semi-arid and arid regions in Southern Africa. *Clim Risk Manag.* 2021;34:100362. <https://doi.org/10.1016/j.crm.2021.100362>
- Pezzopane JRM, Santos PM, da Cruz PG, Bosi C, Sentelhas PC. An integrated agrometeorological model to simulate Marandu palisade grass productivity. *Field Crops Res.* 2018;224:13–21. <https://doi.org/10.1016/j.fcr.2018.04.015>
- Bondaruk VF, Oñatibia GR, Fernández RJ, Agüero W, Blanco L, Bruschetti M, et al. Forage provision is more affected by droughts in arid and semi-arid than in mesic rangelands. *J Appl Ecol.* 2022;59(9):2404–18. <https://doi.org/10.1111/1365-2664.14243>
- Kulkarni S. Climate change, soil erosion risks and nutritional security. In: *Climate Change Resilient Food Systems.* 2021. p. 219–44. https://doi.org/10.1007/978-981-33-4538-6_8
- Farrell HL, Funk J, Law D, Gornish ES. Impacts of drought and native grass competition on buffelgrass (*Pennisetum ciliare*). *Biol Invasions.* 2022;24(3):697–708. <https://doi.org/10.1007/s10530-021-02671-9>
- Tamboli P, Chaurasiya AK, Upadhyay D, Kumar A. Climate change impact on forage characteristics: An appraisal for livestock production. In: *Molecular Interventions for Developing Climate-Smart Crops: A Forage Perspective.* Cham: Springer; 2023. p. 183–96. https://doi.org/10.1007/978-981-99-1858-4_10
- Dogra R, Pant KS, Bishist R, Prakash P, Kumar P. Impact of multipurpose farm trees in subtemperate agroecosystems: Benefits for soil, biomass, fodder and climate resilience. *Agrofor Syst.* 2025;99(5):116. <https://doi.org/10.1007/s10457-025-01217-5>
- Anyoni OG, Susan T, Joseph E, Barnabas M, Alfred O. Effects of intercropping on maize and soybean yield performance, land equivalent ratio and maize leaf area in conservation agriculture. *J Agric Sci.* 2023;16(1):37. <https://doi.org/10.5539/jas.v16n1p37>
- Manoj KN, Shekara BG, Sridhara S, Jha PK, Prasad PV. Biomass quantity and quality from different year-round cereal-legume cropping systems as forage or fodder for livestock. *Sustainability.* 2021;13(16):9414. <https://doi.org/10.3390/su13169414>
- Prommer J, Walker TW, Wanek W, Braun J, Zezula D, Hu Y, et al. Increased microbial growth, biomass and turnover drive soil organic carbon accumulation at higher plant diversity. *Glob Change Biol.* 2020;26(2):669–81. <https://doi.org/10.1111/gcb.14777>
- Sohail S, Ansar M, Skalicky M, Wasaya A, Soufan W, Ahmad Yasir T, et al. Influence of tillage systems and cereals-legume mixture on fodder yield, quality and net returns under rainfed conditions. *Sustainability.* 2021;13(4):2172. <https://doi.org/10.3390/su13042172>

29. Shi F, Guo N, Degen AA, Niu J, Wei H, Jing X, et al. Effects of level of feed intake and season on digestibility of dietary components, efficiency of microbial protein synthesis, rumen fermentation and ruminal microbiota in yaks. *Anim Feed Sci Technol*. 2020;259:114359. <https://doi.org/10.1016/j.anifeedsci.2019.114359>
30. Turano B, Tiwari UP, Jha R. Growth and nutritional evaluation of napier grass hybrids as forage for ruminants. *Trop Grassl-Forrajes Trop*. 2016;4(3):168–78. [https://doi.org/10.17138/TGFT\(4\)168-178](https://doi.org/10.17138/TGFT(4)168-178)
31. Prajapati B, Shrivastava AK, Sarvade S, Agrawal S, Solanki R. Nutrient management for optimizing fodder production of sorghum -A review. *Int J Bio-Resour Stress Manag*. 2023;14(1). <https://doi.org/10.23910/1.2023.3265>
32. Murdia L, Wadhvani R, Wadhawan N, Bajpai P, Shekhawat S. Maize utilization in India: An overview. *Am J Food Nutr*. 2016;4(6):169–76.
33. Dangi S. Oat as green fodder and its intercropping benefits: A review. *Agric Rev*. 2021;42(1). <https://doi.org/10.18805/ag.R-168>
34. Shakil Q, Kanwal A, Asif Z, Humaiyon M, Iqbal J, Hussain K, et al. QS BERSEEM: A breakthrough in high-yield and climate-adapted forage production. *Agric Res*. 2025;63(2):95–104. <https://doi.org/10.58475/2025.63.2.1160>
35. Faye A, Obour AK, Akplo TM, Stewart ZP, Min D, Prasad PV, et al. Dual-purpose cowpea grain and fodder yield response to variety, nitrogen-phosphorus-potassium fertilizer and environment. *Agrosyst Geosci Environ*. 2024;7(1):e20459. <https://doi.org/10.1002/agg2.20459>
36. Rajput A, Panhwar QA, Babar H. Role of leguminous crops by enhancing soil fertility and plant. In: *Legume Crops for Food Security*. 2025. p. 211. <https://doi.org/10.5772/intechopen.1006827>
37. TC S, Kamat VR, TR S, Reddy M. Review on hydroponics green fodder production: Enhancement of nutrient and water use efficiency. *Int J Chem Stud*. 2020;8:2096–102. <https://doi.org/10.22271/chemi.2020.v8.i2af.9060>
38. Elmulthum NA, Zeineldin FI, Al-Khateeb SA, Al-Barrak KM, Mohammed TA, Sattar MN, et al. Water use efficiency and economic evaluation of the hydroponic versus conventional cultivation systems for green fodder production in Saudi Arabia. *Sustainability*. 2023;15(1):822. <https://doi.org/10.3390/su15010822>
39. Murthy AK, Dhanalakshmi G, Chakravarthy K. Study on performance of different fodder crops under low cost green house hydroponic fodder production system. *Int J Environ Agric Biotechnol*. 2017;2(2):238752. <https://doi.org/10.22161/ijeab/2.2.50>
40. Abdula AH. Contribution of hydroponic feed for livestock production and productivity. *Sci Front*. 2022;3(1):1–7. <https://doi.org/10.61186/gppj.1.3.1>
41. Vastolo A, Cutrignelli MI. Hydroponic forage in ruminant nutrition: A systematic review of nutritional value, performance outcomes and sustainability. *Animals (Basel)*. 2025;15(24):3544. <https://doi.org/10.3390/ani15243544>
42. Raeisi Z, Tahmasbi R, Dayani O, Ayatollahi Mehrgardi A, Tavassolian I. Digestibility, microbial protein synthesis, rumen and blood parameters in sheep fed diets containing hydroponic barley fodder. *J Livest Sci*. 2018;6(1):9–17.
43. Yahyaei M, Talebi B. Hydroponic fodder for livestock production and productivity: A review. *Greenhouse Plant Prod J*. 2024;1(3):1–12. <https://doi.org/10.61186/gppj.1.3.1>
44. Benu I, Jelantik IGN, Penu C, Laut MM. Effect of replacing grass silage with hydroponic maize fodder on nutrient intake and digestibility, rumen parameters and blood metabolites of weaned Ongole × Brahman calves. *Jurnal Ilmu Ternak Veteriner*. 2024;29:36–44. <https://doi.org/10.14334/jitv.v29i1.3331>
45. Baghdadi A, Golzardi F, Hashemi M. The use of alternative irrigation and cropping systems in forage production may alleviate the water scarcity in semi-arid regions. *J Sci Food Agric*. 2023;103(10):5050–60. <https://doi.org/10.1002/jsfa.12574>
46. Kazimierczuk K, Barrows SE, Olarte MV, Qafoku NP. Decarbonization of agriculture: The greenhouse gas impacts and economics of existing and emerging climate-smart practices. *ACS Eng Au*. 2023;3(6):426–42. <https://doi.org/10.1021/acsengineeringau.3c00031>
47. Naresh R, Jadav SK, Singh M, Patel A, Singh B, Beese S, et al. Role of hydroponics in improving water-use efficiency and food security. *Int J Environ Clim Change*. 2024;14(2):608–33. <https://doi.org/10.9734/ijecc/2024/v14i23976>
48. Bilal A, Hassan S, Sardar A, ul Abideen Z, Naeem M. Economic viability of cucumber farming: Hydroponic systems VS traditional soil methods. *J Asian Dev Stud*. 2024;13(4):561–75. <https://doi.org/10.62345/jads.2024.13.4.46>
49. Amole T, Augustine A, Balehegn M, Adesogoan AT. Livestock feed resources in the West African Sahel. *Agron J*. 2022;114(1):26–45. <https://doi.org/10.1002/agg2.20955>
50. Dash PK, Ganesan K, Manivannan N, Kumar SV, Senthil N, Pushpam R. Revolutionizing livestock sustainability: Pioneering breeding strategies for superior forage biomass and quality. *HORIZON*. 2024;11(4):1093–107.
51. Bhardwaj AK, Chejara S, Malik K, Kumar R, Kumar A, Yadav RK. Agronomic biofortification of food crops: An emerging opportunity for global food and nutritional security. *Front Plant Sci*. 2022;13:1055278. <https://doi.org/10.3389/fpls.2022.1055278>
52. Maleko D, Msalya G, Mwilawa A, Pasape L, Mtei K. Smallholder dairy cattle feeding technologies and practices in Tanzania: Failures, successes, challenges and prospects for sustainability. *Int J Agric Sustain*. 2018;16(2):201–13. <https://doi.org/10.1080/14735903.2018.1440474>
53. Meel M, Gautam L, Garg S. Growth-stage dependent nutritional dynamics of super Napier grass. *Int J Agric Food Sci*. 2025;7(5):262–6. <https://doi.org/10.33545/2664844X.2025.v7.i5d.406>
54. Somegowda VK, Vemula A, Naravula J, Prasad G, Rayaprolu L, Rathore A, et al. Evaluation of fodder yield and fodder quality in sorghum and its interaction with grain yield under different water availability regimes. *Curr Plant Biol*. 2021;25:100191. <https://doi.org/10.1016/j.cpb.2020.100191>
55. Subrahmanya D, Kumar R, Tyagi N, Ram H, Singh M, Meena R, et al. Yield of fodder maize (*Zea mays*) and its chemical composition under varying plant densities and nutrient management. *Indian J Anim Nutr*. 2017;34(4):425–9. <https://doi.org/10.5958/2231-6744.2017.00068.8>
56. Gazal A, Dar Z, Zaffar G, Lone A, Abidi I, Shabir A, et al. Trends in breeding oat for nutritional grain quality: An overview. *J Appl Nat Sci*. 2014;6(2):904. <https://doi.org/10.31018/jans.v6i2.552>
57. Adnan M, Tahir MHN, Shehzad MA, Raza K, Shabir N, Ameen T, et al. Characterization of exotic berseem (*Trifolium alexandrinum* L.) germplasm for forage yield and quality. *Pak J Biochem Biotechnol*. 2025;6(1):18–28. <https://doi.org/10.52700/pjbb.v6i1.259>
58. Homolka P, Koukolova V, Podsedníček M, Hlaváčková A. Nutritive value of red clover and lucerne forages for ruminants estimated by in vitro and in vivo digestibility methods. *Czech J Anim Sci*. 2012. <https://doi.org/10.17221/6346-CJAS>
59. Jayathilake C, Visvanathan R, Deen A, Bangamuwage R, Jayawardana BC, Nammi S, et al. Cowpea: an overview on its nutritional facts and health benefits. *J Sci Food Agric*. 2018;98(13):4793–806. <https://doi.org/10.1002/jsfa.9074>
60. Michalk DL, Kemp DR, Badgery WB, Wu J, Zhang Y, Thomassin PJ. Sustainability and future food security—a global perspective for livestock production. *Land Degrad Dev*. 2019;30(5):561–73. <https://doi.org/10.1002/ldr.3217>
61. Buse K, Carroll A, Bradford B, Min D, Jagadish K, Kononoff P. The effect of replacing conventional alfalfa hay with lower-lignin alfalfa hay on feed intake, nutrient digestibility and energy utilization in

- lactating Jersey cows. *J Dairy Sci.* 2024;107(11):9379–89. <https://doi.org/10.3168/jds.2024-24882>
62. Xu X, Min D. Harvesting schedule effects on forage yield and nutritive values in low-lignin alfalfa. *J Anim Sci Technol.* 2022;64(2):262–73. <https://doi.org/10.5187/jast.2022.e10>
 63. Kamal M, Aldhalmi AK, Abd El-Hack ME, Elsherbeni AI, Youssef IM, Hussein S, et al. Enhancing the feed efficiency of crop residues in ruminants—a comprehensive review. *Ann Anim Sci.* 2025;25(2):529–45. <https://doi.org/10.2478/aoas-2024-0081>
 64. Kumari M, Dubey AK, Kumar R, Kumar A. Marker-assisted selection in plant breeding for stress tolerance. In: *Improving Stress Resilience in Plants*. Elsevier; 2024. p. 371–87.
 65. Noor T, Zia MA, Shauket S, Ahmed H, Alvi ZA, Muhmmad A, et al. Integrating marker-assisted selection in breeding programs for abiotic stress resilience. *Plant Stress Responses.* 2025;47. https://doi.org/10.1007/978-3-031-24619-1_14
 66. Bryan G, Winichayakul S, Roberts N. Nutritional enhancement of animal feed and forage crops via genetic modification. *J R Soc N Z.* 2025;55(2):327–42. <https://doi.org/10.1080/03036758.2024.2387136>
 67. Sami A, Xue Z, Tazein S, Arshad A, He Zhu Z, Ping Chen Y, et al. CRISPR-Cas9-based genetic engineering for crop improvement under drought stress. *Bioengineered.* 2021;12(1):5814–29. <https://doi.org/10.1080/21655979.2021.1969831>
 68. Hart EH, Christofides SR, Davies TE, Rees Stevens P, Creevey CJ, Müller CT, et al. Forage grass growth under future climate change scenarios affects fermentation and ruminant efficiency. *Sci Rep.* 2022;12(1):4454. <https://doi.org/10.1038/s41598-022-08309-7>
 69. Melese M, Getachew B, Woldemeskel E, Gunnabo AH. Legume integration in smallholder farming systems for food security and resilience to climate change. *PLoS One.* 2025;20(8):e0327727. <https://doi.org/10.1371/journal.pone.0327727>
 70. Hawkins J, Yesuf G, Zijlstra M, Schoneveld GC, Rufino MC. Feeding efficiency gains can increase the greenhouse gas mitigation potential of the Tanzanian dairy sector. *Sci Rep.* 2021;11(1):4190. <https://doi.org/10.1038/s41598-021-83475-8>
 71. Sanchez-Palacios JT, Henry D, Penrose B, Bell R. Formulation of zinc foliar sprays for wheat grain biofortification: a review of current applications and future perspectives. *Front Plant Sci.* 2023;14:1247600. <https://doi.org/10.3389/fpls.2023.1247600>
 72. Muck R, Kung Jr L. Silage production. In: *Forages: The Science of Grassland Agriculture.* 2007;2:617–33. <https://doi.org/10.1002/9781119436669.ch42>
 73. Paulk CB, Stark CR, Dunmire KM. Feed processing technology and quality of feed. In: *Sustainable Swine Nutrition.* 2022. p. 429–44. <https://doi.org/10.1002/9781119583998.ch16>
 74. Sarkar S, Skalicky M, Hossain A, Brestic M, Saha S, Garai S, et al. Management of crop residues for improving input use efficiency and agricultural sustainability. *Sustainability.* 2020;12(23):9808. <https://doi.org/10.3390/su12239808>
 75. Kamusoko R, Jingura RM, Parawira W, Chikwambi Z. Strategies for valorization of crop residues into biofuels and other value-added products. *Biofuels Bioprod Biorefin.* 2021;15(6):1950–64. <https://doi.org/10.1002/bbb.2282>
 76. Fungo B, Buyinza J, Sekatuba J, Nansereko S, Ongodia G, Kwaga P, et al. Forage biomass and soil aggregate carbon under fodder banks with contrasting management regimes. *Agrofor Syst.* 2020;94(3):1023–35. <https://doi.org/10.1007/s10457-019-00473-6>
 77. Jha UC, Nayyar H, Parida SK, Siddique KH. Horse gram, an underutilized climate-resilient legume: breeding and genomic approach for improving future genetic gain. In: *Developing Climate Resilient Grain and Forage Legumes.* Springer; 2022. p. 167–78.
 78. Kebede G, Assefa G, Feyissa F, Mengistu A. Forage legumes in crop-livestock mixed farming systems: A review. *Int J Livest Res.* 2016;6(4):1–18. <https://doi.org/10.5455/ijlr.20160317124049>
 79. Qamara C, Yuzaria D, Madarisa F, Budiarsa A. GIS-based multi-criteria land suitability analysis for five tropical forage legumes in highland agroecosystems. *Jurnal Ilmu Ternak Univ Padjadjaran.* 2025;25(3):5. <https://doi.org/10.24198/jit.v25i3.66009>
 80. Long M, Xiong X, Lin H. Spatiotemporal analysis of food production–demand mismatch in China and implications for agricultural structural adjustment. *Foods.* 2024;13(13):1990. <https://doi.org/10.3390/foods13131990>
 81. Melak A, Aseged T, Shitaw T. The influence of artificial intelligence technology on the management of livestock farms. *Int J Distrib Sens Netw.* 2024;2024(1):8929748. <https://doi.org/10.1155/2024/8929748>
 82. Shahab H, Naeem M, Iqbal M, Aqeel M, Ullah SS. IoT-driven smart agricultural technology for real-time soil and crop optimization. *Smart Agric Technol.* 2025;10:100847. <https://doi.org/10.1007/s42979-024-03258-0>
 83. Islam MR, Oliullah K, Kabir MM, Alom M, Mridha M. Machine learning enabled IoT system for soil nutrients monitoring and crop recommendation. *J Agric Food Res.* 2023;14:100880. <https://doi.org/10.1016/j.jafr.2023.100880>

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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