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CLIMATE-RESILIENT FODDER AND LIVESTOCK PRODUCTION THROUGH AGROFORESTRY IN INDIA: A REVIEW

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SUMMARY

The livestock sector constitutes the socio-economic backbone of the Indian agrarian landscape, supporting the livelihoods of over 70 million farm families. However, this critical sector faces an existential threat from a chronic forage deficit – currently estimated at 35.6% for green fodder and 10.95% for dry residues –now compounded by the escalating volatility of climate change. This review synthesizes the transformative potential of agroforestry as a multifaceted land-use strategy designed to bridge the forage demand-supply gap while bolstering the climate-adaptive capacity of livestock systems. By integrating woody perennials into crop and pasture lands, agroforestry functions as a "green shield," providing essential ecosystem services: moderating microclimatic extremes, sequestering atmospheric carbon, and enhancing soil nutrient cycling. Empirical evidence from diverse agro-climatic zones, particularly the semi-arid regions of India, underscores that silvopastoral and hortipastoral models significantly expand carrying capacities and provide nutrient-dense fodder during critical lean periods. The strategic incorporation of multipurpose trees, including *Prosopis cineraria*, *Ailanthus excelsa*, *Moringa oleifera*, and *Grewia optiva*, offers a biological intervention to mitigate heat stress, thereby optimizing milk yields and weight gain in dairy animals. Despite its documented efficacy, widespread adoption is stalled by systemic hurdles, including restrictive regulatory frameworks, a scarcity of high-quality germplasm, and socio-economic constraints. This article concludes by advocating for a paradigm shift toward integrated tree-livestock landscapes, supported by robust policy interventions and decentralized nursery networks, to ensure long-term national fodder and nutritional security.

Key words: Climate resilient, agroforestry, fodder, livestock, climate change, mitigation

Agriculture employs roughly 54.3% of India's workforce, with the livestock sector accounting for 4.11% of national GDP (Yadav *et al.*, 2026). The major economy in livestock sector revolves around milk and its byproducts, which is highly dependent on livestock nutrition through fodder, roughages and concentrates. Amongst them, fodder remains one of the cornerstones for providing sufficient nutrition to livestock (Halli *et al.*, 2018; Dushyant *et al.*, 2025). Despite its importance, fodder production is limited due to focused cultivation of cash crops, growing in marginal lands, limited resource and increasing impacts of climate change. Frequent weather anomalies such as erratic rainfall, drought frequency, temperature extravagance and rapid increase in greenhouse gases impairs whole value chain of fodder supply, quality and seasonal availability, which results in risk to productivity of livestock and farmers income. The contribution of livestock in total agriculture and allied sector Gross Value Added (GVA) has increased from 24.38% in 2014-15 to 30.87% in 2023-24. Livestock sector contributed 5.49% of total GVA in 2023-24 (Surisetti, 2025). India is ranked first in milk production contributing 25% of global milk production. As the world's largest producer and consumer of milk, India hosts a staggering livestock population of 536.76 million animals, yet the land allocated for fodder cultivation has remained stagnant at approximately 4.9% of the gross cropped area for the past three decades (Singh *et al.*, 2022). This structural imbalance has led to a chronic fodder crisis that is particularly acute during the summer and winter lean periods (Halli *et al.*, 2018). The Intergovernmental Panel on Climate Change (IPCC) report predicts global temperatures could rise by 1.1 to 6.4°C by the end of 21^{st} century (2090–2099), relative to 1980-1999 levels, with the most likely increases ranged between 1.8 and 4.0°C depending on the socioeconomic and emission scenarios (IPCC, 2007). Climate change acts as alarming stress multiplier in this context. Unfavorable weather conditions, including extreme temperatures and prolonged dry spells, directly hinder the morphological development and nutritional quality of conventional forage crops (Kumari *et al*., 2023). In rainfed regions, which constitute 51% of India's net sown area, the capricious nature of the monsoon often results in total crop failure, forcing farmers to rely on nutritionally poor crop residues or expensive commercial concentrates (Sharda *et al*., 2010).

Bridging fodder gaps with agroforestry

Estimate on demand-supply gap in fodder availability shows a net deficiency of 11.23% green fodder, 23.40% dry fodder and 28.90% concentrate feed materials in the country (Roy *et al*., 2019). By 2050, the demand for green and dry feed will be 1012 and 631 million tonnes, respectively. In the year 2050, with the current rate of expansion in forage supplies, there will be an 18.4% deficit in green fodder and a 13.2% shortfall in dry fodder (Dhamodharan *et al*., 2024). Green forage supply must rise at a rate of 1.69% per annum to satisfy the deficit; however, the area under cultivated fodder accounts for only 4% of the total cultivated land (8.4 million ha) in the country, and has remained unchanged over last few decades. (Dagar, 2017), which is not adequate to meet the fodder demand. The escalating risk of heat stress further compounds the problem, as high ambient temperatures disrupt the physiological and metabolic homeostasis of high-yielding dairy breeds, leading to substantial economic losses (Bagath *et al*., 2019). Agroforestry emerges as a transformative solution to these intersecting challenges. By deliberately integrating woody perennials with agricultural crops and livestock, agroforestry systems create a more stable and resilient production environment (Diaz, 2016). These systems represent a sophisticated ecological engineering approach that optimizes resource use efficiency across different temporal and spatial scales. The "green shield" effect provided by trees buffers the understory vegetation and grazing animals against climatic extremes, while simultaneously providing a secondary source of high-quality forage through tree loppings (Jose and Dollinger 2019). Agroforestry provides 62% of the fodder, fuelwood and timber requirement of the rural people in arid regions (Mathukia *et al*., 2016)

Agroforestry for climate resilient fodder production

Over the last fifty years, agroforestry has progressed from being a traditional, farmer-driven practice to a science-backed and policy-supported solution for sustainable agriculture and climate resilience. The resilience of agroforestry is achieved through synergistic mechanisms including microclimate moderation and soil enhancement. Agroforestry has an important role in reducing vulnerability, increasing resilience of farming systems and buffering households against climate-related risks (Parthiban *et al*., 2022). It also provides for ecosystem services - water, soil health, and biodiversity. Therefore, agroforestry will be required to contribute substantially to meet the demands of rising population for food, fruits, fuelwood, timber, fodder, biofuel, and bio-energy as well as for its perceived ecological services (Mathukia *et al*., 2016). Agroforestry practices offer a balance between agricultural production and environmental conservation while capturing carbon to reduce greenhouse gas emissions, even in wasteland systems like silvipasture (Ghosh, 2016). These practices are known for enhancing productivity and environmental quality, including improvements in air, soil, and water conditions, as well as biodiversity. Additionally, agroforestry promotes better nutrient recycling and contributes to the sustainability of production systems (Dhyani *et al*., 2010). These self-sustaining tree-crop-livestock systems improve efficiency by generating more output with less land and fewer resources (Kumar *et al*., 2017). Various agroforestry systems provide important resources such as fodder, fuel, food, and fruits, including agri-silviculture (crops + trees/animals), silvi-pasture (trees + pasture/animals), agri-horti (crops + fruit trees), horti-pasture (fruit trees + pasture/animals), and agri-horti-silvipasture (crops + fruit trees + MPTS + pasture). Many multipurpose tree species (MPTS) cultivated in these systems supply leaf fodder for livestock, in addition to wood. These leaves can be either browsed directly by free-roaming animals or collected and fed to animals in stalls. Livestock grazing alongside MPTS trees benefits from both nutritious fodder and shade on hot, sunny days. The pruned biomass from these trees can be used as feed during lean periods, preserved as leaf meal, or applied as mulch (Palsaniya *et al*., 2012). In India, tree leaves from agroforestry systems are primarily used as fodder for small ruminants, and for large ruminants during fodder shortages. More than 60% of the fodder needs of goats are typically met with tree and shrub fodders. Popular trees and shrubs for goats include khejri (*Prosopis cineraria*), mahaneem (*Ailanthus excelsa*), moringa (*Moringa oleiofera*), rohida (*Tecomella undulata*), jaal (*Salvadora oleoides*), bargad (*Ficus benghalensis*), gular (*Ficus glomerata*), neem (*Azadirachta indica*), jamun (*Syzygium cumini*), mahua (*Madhuca latifolia*), kachnar (*Bauhinia variegata*), ber (*Zizyphus jujuba*), jharberi (*Zizyphus numularia*), mulberry (*Morus alba*), cassava (*Manihot esculenta*), gliricidia (*Gliricidia sepium*), babul (*Acacia nilotica*) and Israeli kikar (*Acacia tortilis*). The greatest value of fodder trees lies in their role as diet supplements rich in protein, energy, minerals and vitamins. Fodder trees have almost double the amount of protein (18 to 25%) and high levels of essential elements such as calcium, sodium and sulphur as well as critical micronutrients such as iron and zinc when compared to fodder grass species, which can save farmers expenses on purchased concentrate feeds (Moleele, 1998). Tree leaves are a rich source of supplementary protein, vitamins and minerals and their use in ruminants helps to enhance microbial growth and digestion (Cheema *et al.*, 2011). Jamala *et al.* (2013) claimed that leguminous species contain 25 to 50% more crude protein than non-leguminous plants.

Carbon Sequestration, ecosystem restoration and resilience via agroforestry

Agroforestry plays vital roles in mitigation of atmospheric accumulation of greenhouse gases. Agroforestry land use increases livelihood security and reduces vulnerability to climate and environmental change. There are ample evidences to show that the overall (biomass) productivity, soil fertility improvement, soil conservation, nutrient cycling, micro-climate improvement, and carbon sequestration potential of an agroforestry system is generally greater than that of an annual system (Dhillon and Wuehlisch, 2013, Chavan *et al.*, 2023). Carbon sequestration rates are very encouraging for complex agroforestry, boundary planting, hedgerow intercropping, and ‘home gardens’ (Calfapietra *et al.*, 2010). Nevertheless, highest carbon storage results are found in “multistory/ compex” agroforestry systems (Sajwaj *et al.*, 2008) that have many diverse species using ecological “niches” from the high canopy to bottom story shade-tolerant crops. The silvipastoral system in a natural grassland in the semi-arid state of Uttar Pradesh, where introduced species of *Albizia procera*, *Eucalyptus tereticornis*, *Albizia lebbeck*, *Emblica officinalis* and *Dalbergia sissoo* accumulated 8.6, 6.92, 6.52, 6.25 and 5.41 t/ha/yr of biomass (Rai *et al.*, 2009). The carbon storage in the system was 1.89-3.45 t C/ha in silvipasture and 3.94 tC/ha in pure pasture. Kaur *et al.* (2002) observed that an increase in organic carbon of 1.7 to 2.3 times in a silvipastoral system connecting *Leuceana leucocephala*, *Cenchrus ciliaris* and *Stylosanthes hamata* as compared to a control.

Agroforestry profoundly improves soil quality through natural means using tree litter, root symbiosis, and microbial processes. Root associations also enhance soil aeration and water permeability, allowing for greater water retention and microbial populations (Singh *et al.*, 2013; Bhardwaj *et al.*, 2023). This, subsequently, minimizes soil erosion, maximizes fertility, and maximizes sustainable fodder productivity. Agroforestry systems increase water holding capacity by promoting soil structure, organic matter levels, and decreasing surface runoff. Tree roots assist in soil stabilization, erosion minimization, and groundwater recharge. Agroforestry enhances the water holding capacity of the soil, providing a sustainable water supply for fodder crops and livestock, and improving climate resilience (Kaushal *et al.*, 2021; Kumar *et al.*, 2025). Mixed farming systems sustain varied plant and animal species, promoting ecosystem stability through habitat creation, increasing genetic diversity, and encouraging ecological interactions. The co-culture of trees, crops, and animals in agroforestry enhances biodiversity conservation by providing shelters for various plant and animal species (Kumar *et al.*, 2023). The agroforestry systems of mixed farming foster genetic diversity, intensify ecological processes, and limit pest infestation (Dissanayaka *et al.*, 2024). Through conservation of biodiversity, the systems support sustainable agriculture as well as long-term ecological equilibrium.

Future outlook

Climate change is no longer a distant threat; it already becomes a current reality that affects fodder availability, nutritional quality and seasonal distribution throughout agro-ecological zones. In response, our future scientific strategy should be based on innovation, local adaptability, and resilience. The first and foremost priority is the development and promotion of climate resilient fodder varieties and tree based fodder system. Future breeding programs must focus on traits such as drought tolerance, high biomass, fast maturity, and nutritional stability under stress. Integrating agro-ecological methods such as crop rotation, intercropping, and multiple systems, along with agroforestry, offers a promising pathway toward ensuring both productivity and resilience of fodder systems. These strategies not only improve soil fertility and structure through biological nitrogen fixation and enhanced organic carbon, but also promote biodiversity and ecosystem services, such as carbon sequestration and improved water use efficiency. Agroforestry, in particular, stands out as a holistic solution, combining tree species with fodder crops to create systems that not only increase fodder yield but also contribute significantly to soil health, erosion control, and carbon capture, there by mitigating the adverse effects of climate change. Shifting from chemical fertilizers to integrated practices, combining organic amendments like farmyard manure with biofertilizers, provides a sustainable way to enhance fodder yields while combating soil degradation and nutrient depletion. Water management strategies, including efficient irrigation techniques and the use of rain water harvesting, further complement these efforts by mitigating the impacts of water scarcity in arid and semi-arid regions. The use of salt-tolerant tree and fodder species and amendments such as gypsum and biochar mitigate soil salinity and acidity, while improving soil structure and nutrient availability. Selection of new genotypes and varieties of food crops having high forage value without reduction in food grain yield needs to be developed on a continuous basis. There is need to promote fodder production through improved agronomic practices and use of improved seed. Ongoing research and development in fodder and livestock, combined with grazing and pasture management policies, government scheme integration, and fodder banks in drought-prone regions, will help mitigate the impacts of climate change on the fodder and livestock sectors.

CONCLUSION

Agroforestry is a resilient and adaptive method of coping with climate change while maintaining the long-term sustainability of fodder production in India. Agroforestry land use increases livelihood security and reduces vulnerability to climate and environmental change. There are ample evidences to show that the overall (biomass) productivity, soil fertility improvement, soil conservation, nutrient cycling, micro-climate improvement, and carbon sequestration potential of an agroforestry system is generally greater than that of an annual system. Agroforestry has an important role in reducing vulnerability, increasing resilience of farming systems and buffering households against climate-related risks. It also provides for ecosystem services - water, soil health, and biodiversity. In order to realize the full potential of agroforestry, there is a need to strengthen favorable policies, invest in research and development, and directly involve farmers through awareness generation programs, incentives, and capacity-building. An organized and inclusive agroforestry approach will help ensure ecological sustainability, economic stability, and climate resilience for generations to come.

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