Sustainable fodder production in South Asia through silvopastoral systems

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Silvopasture is a farming practice involving the integration of tree and livestock grazing operations on the same land. Intensive management of these systems enables them to generate short and long-term economic returns from forest products and forage. Silvopastoral systems have been considered to increase efficiency while reducing the environmental burden and extreme ranching/animal husbandry systems. Over the past few years, there has been a rapid accumulation of scientific evidence supporting the role of silvopasture in meeting the fundamental needs of not only humans but also the animal population in the era of climate change. In South Asian countries like India, the silvopastoral system can be a viable option to provide balanced food as well as shelter for the livestock. This review aims to provide a critical and systematic evaluation of the scientific literature about the effect of different silvopasture systems on the fodder production, environment and performance of livestock, especially in the context of South Asia. We conducted a search using PubMed, Scopus, Science Direct, Web of Science and Google Scholar to identify the key literature on the theme. A total of 98 manuscripts underwent a four-step PRISMA appraisal process, resulting in the final selection. This process resulted in a final sample of 56 articles, which were used to explore the potential for long-term improvement in fodder quality through expanding the silvopastoral system. One of the key conclusions is that by improving the social acceptability of these silvopastoral systems and also addressing the challenges, their economic and environmental sustainability can be further enhanced.

Keywords: Climate change, environmental sustainability, fodder, livestock, silvopastoral system.

SMALL and marginal farmers in Asian countries such as India, Pakistan, Bangladesh, Nepal, Sri Lanka and Bhutan rely heavily on the livestock sector to maintain nutritional security. It contributed about 4.4% to the total gross value added (GVA) of India in 2019–20 (ref. 1). The scarcity of land, uncertain rainfall and requirement of manure and fertilizer for fodder production is increasing day by day, and as a result, farmers are using crop residues to feed the livestock[2,3]. A silvopastoral system can be a viable solution to this problem. In conventional monoculture pastures (CP), sustainable intensification solutions are required to boost biomass output and input use efficiency besides promoting environmental benefits. This will enhance productivity and reduce adverse environmental effects[4].

Whereas the term ‘silvi’ stands for ‘tree’, ‘pasture’ denotes ‘grasses’ or a combination of grass and legume crops. The silvopasture system is a tree-based livestock-raising strategy that entails planting trees, shrubs, and annual grasses on pastures, farms and backyards to supply nutrient-rich green feed all year[5]. According to Sharrow[6], the most frequent kind of agroforestry in industrialized countries is silvopastoral systems. These systems are known as ‘Dehesa’ in Spain, ‘Montado’ in Portugal and ‘Streuobst’ in other European nations[7]. Tree leaves and pods are traditional sources of not only feed but also fodder for household animals. It serves as a protein source to complement crop or grass residues, particularly during summer. In order to supply animals with healthy green feed throughout the year, silvopastoral systems should be established on natural pastures and degraded areas[8–10]. A silvopastoral system provides protein, energy, and other nutrients to animals[11]. During crucial grass scarcity seasons, they may also be the only source of feed[12]. At present, we are facing deficits in feeds, green fodder, and dry crop residues of 64%, 61% and 22% respectively (Table 1). Thus, the emergence of silvopastoral systems could offer a promising opportunity to meet this demand while addressing environmental concerns and promoting livelihood resilience.

Methodology

This review adhered to the guidelines outlined in the preferred reporting items for systematic review[13].

Search strategy

Systematic review encompassed peer-reviewed articles published in English before November 2023. Systematic

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Table 1. Supply and demand scenario of forage and roughage in India until 2030 (in million Mg)

	Supply		Demand		Deficit as % of demand	
Year	Green fodder	Dry fodder	Green fodder	Dry fodder	Green fodder	Dry fodder
1995	379	421	947	526	60	20
2000	385	428	988	549	61	22
2005	390	443	1025	569	62	22
2010	395	451	1061	589	63	23
2015	401	466	1097	609	64	24
2020	406	473	1134	630	64	25
2025	411	488	1170	650	65	25
2030	417	503	1207	671	65	25

Source: Based on 10th and 11th Five-Year Plan Document Vision 2030 (http://www.igfri.ernet.in).

searches were systematically carried out using PubMed, Scopus, Science Direct, Web of Science and Google Scholar databases. Boolean operators (i.e. AND, OR, NOT) were integrated to combine words or phrases, and wildcard truncations (denoted as ‘ ’) were employed to account for a range of possible word forms. All the search terms are ‘silvopastoral’ OR ‘silvopasture’ OR ‘crop-livestock-system’, ‘fodder’ OR ‘sustainable fodder production’, ‘climate change’ OR ‘thermal stress’ AND ‘performance of livestock’.

Study inclusion criteria and screening

We conducted a systematic review focusing on experimental studies elucidating the impacts of various silvopasture systems on fodder quality and productivity. The inclusion and exclusion criteria were predetermined and unanimously agreed upon by all authors. A total of 98 results from diverse sources were collated in a Mendeley® account, with the initial exclusion of duplicates. The screening and appraisal process comprised four steps: Step 1 involved excluding publications in languages other than English to ensure a critical assessment of methods and results. Step 2 consisted of evaluating titles and abstracts to eliminate articles irrelevant to the topic (e.g. housed livestock, artificial shade, crop production under silvopasture and pasture production). Step 3 entailed a second screening of titles and abstracts to remove articles not related to the silvopastoral system of South Asia, excluding those conducted in different agroecological regions. In Step 4, thesis and conference proceedings were excluded, and full texts of the remaining articles were meticulously examined. Experimental studies were excluded if they did not directly address the relationship between fodder crop production and the silvopasture system. The articles retained at this stage ($n = 56$) were categorized into sections (components of the silvopastoral system, silvopasture model for resilience to climate change, forage production through silvopastoral system, challenges) if they described multiple relevant effects. Despite variations in methodology among the selected studies, a meta-analysis approach was deemed unsuitable and, consequently, discarded. To ensure a comprehensive overview of the literature, no additional restrictions were imposed based on publication year, study type, sample size, journal or overall quality.

Strengths and limitations

We conducted a comprehensive literature search to identify studies that elucidate the specific aspects of silvopastoral systems, including their design, management practices, economic viability and ecological benefits, providing a comprehensive overview of their potential for sustainable fodder production in South Asia.

Components of the silvopastoral system

Grasses-legumes-crops: Legumes, fodder grasses and crops should be chosen based on agro-ecological parameters such as biotic, edaphic, climatic and topographic characteristics, as well as the farmer’s needs. The most productive green fodder crop is Napier grass (250–300 tonnes per hectare), followed by lucerne (140–150 tonnes ha^{-1}) and berseem (70–100 tonnes ha^{-1})[14,15]. Table 2 shows detailed information on various kinds, seed rates, sowing periods and production potential of fodder crops, legumes and grasses.

Fodder tree species: The inter-tree spacing varies depending on the availability of moisture and nutrients. Trees or shrubs should be cultivated on bunds to limit competition amongst main and companion crops, but grasses/legumes should be permitted to grow freely in the field[16]. Several fodder trees are accessible, all of which can provide high-quality, nutritious fodder (Table 3). Tree spacing varies according to moisture and nutrient availability, as well as species. For fodder production, however, spacing can be lowered to 1 m for several species.

Results and discussion

Silvopasture model for resilience to climate change

Due to the diversity of plant types integrated into a dynamic shrub-grassland mosaic, silvopastoral systems have high

Table 2. Fodder producing grasses/legumes/crops cultivated in agri-silviculture system

Common name	Varieties	Seed rate	Sowing time	Yield ($t ha^{-1}$)		Reference
				Green	Dry	
Berseem	Berseem Ludhiana-1 (BL-1); Jawahar Berseem-1 (JB-1)	25–30 kg ha^{-1}	Last week of September to first week of December	70–100	15–18	15
Lucerne/Alfalfa	Chetak (S-244)	25–30 kg ha^{-1}	September–December	140–150	8–9	15
Jowar (sorghum)	MP Chari, Jawahar Chari-6, Jawahar Chari-69	30 kg ha^{-1}	At onset of monsoon	53	15	15
Stylosanthes	Stylosanthes Phule Kranti (RSS-2000-95)	5–6 kg ha^{-1}	June–July to September–October	25–30	10–12	15
Guinea grass	Bundel Guinea-1 (JHGG-96-5); Bundel Guinea-2 (JHGG 04-01)	3–6 kg ha^{-1}	June–September/ October–November	50–60	15–18	14
Anjan grass	Bundel Anjan-1; Bundel Anjan-3 (IGFRI-727)	5 kg ha^{-1}	At onset of monsoon	35–40	6–12	14
Saen grass	Bundel sain Ghas-1 (IGS 9901)	33,000–35,000 seedlings ha^{-1}	Before on set of monsoon	18.3	4.7	14
Dharaf grass	Bundel Dhawalu Ghas-1 (IGC 9903)	4 to 5 kg ha^{-1}	In June–July (on set of monsoon)	25–30	6–7	14
Napier grass	Pusa Giant Napier, IGFRI-10, CO-1; JP-1, JP-13	10,000 stem cutting or rooted slips for one hectare	Pre-monsoon in the month of June–July	250–300	14–15	14
Dinanath grass	Jawahar Pennisetum-12; Bundel-1; Bundel-2	2.5–5 kg ha^{-1}	Onset of monsoon	55–60	14	15

Table 3. Fodder yielding perennial tree species cultivated in silvopasture system

Common name	Planting time	Yield		Reference
		Green	Dry	
Subabul	July–August	55–85 t ha^{-1}	20 t ha^{-1}	15, 47, 48
Sirish	After monsoon rain sets in	40–70 t ha^{-1}	11–15 kg $tree^{-1}$	30, 47, 48
Shisham	After monsoon rain sets in	40–70 t ha^{-1}	5–6 kg $tree^{-1}$	47, 49
Mulberry	July–August	40–120 t ha^{-1}	43 t ha^{-1}	47, 50
Kachnar	Onset of monsoon	7.7 kg $tree^{-1}$	6.7 kg $tree^{-1}$	47, 49
Agastya	June–July	80 t ha^{-1}	20 t ha^{-1}	47, 51
Gliricidia	After onset of monsoon	43 t ha^{-1}	5-6 t ha^{-1}	47
Ber	July–August	46 t ha^{-1}	3.5 t ha^{-1}	47, 52
Anjan	After onset of monsoon	24–26 t ha^{-1}	4–10 t ha^{-1}	8
Neem	Onset of monsoon	40–70 t ha^{-1}	40–60 kg ha $tree^{-1}$	47, 48

conservation importance. Silvopastoral systems are among the most promising techniques for sustainably managing tropical environments. Climate change and land use are continuously changing, which makes it necessary to measure resilience and adaptability at a wide range of temporal and spatial scales (Figure 1)[17]. Silvopastoral systems, as proposed by Solorio *et al.*[18], employ trees to supply high-quality animal feed and versatile legumes, especially *Leucaena leucocephala*, which is a shrubby legume that thrives in a wide range of agro-climatic conditions. Its leaf, which includes 20–25% protein, promotes a remarkable weight increase in cattle.

The resilience to drought and longevity of *Leucaena* are key benefits. Due to its deep root system, it can continue to produce high-quality forage even during dry spells, helping graziers cope with drought and lessen their reliance on protein or urea supplements. The silvopastoral system successfully combines grasses and leguminous species that coexist in the same area simultaneously. Together with other multipurpose tree species, these two species can utilize the soil and atmospheric resources more effectively, positively impacting the systems' productivity and viability. Additionally, the silvopastoral system encourages reforestation, improves soil fertility, particularly nitrogen content, and sequesters carbon to prevent the emission of methane and carbon dioxide[19].

Four major factors contribute to the successful management of the silvopastoral system model: (i) As part of their metabolism, plants utilize clay minerals and recycle them either back into the soil litter or through root senescence, resulting in a constant state of dynamic nutrient transfer. (ii) Silvopastoral systems are highly capable of sequestering carbon, thereby restoring degraded areas and generating revenue for farmers. Combining shrubs and trees with grasses enhanced net carbon flow and primary production considerably[20]. There is higher biological

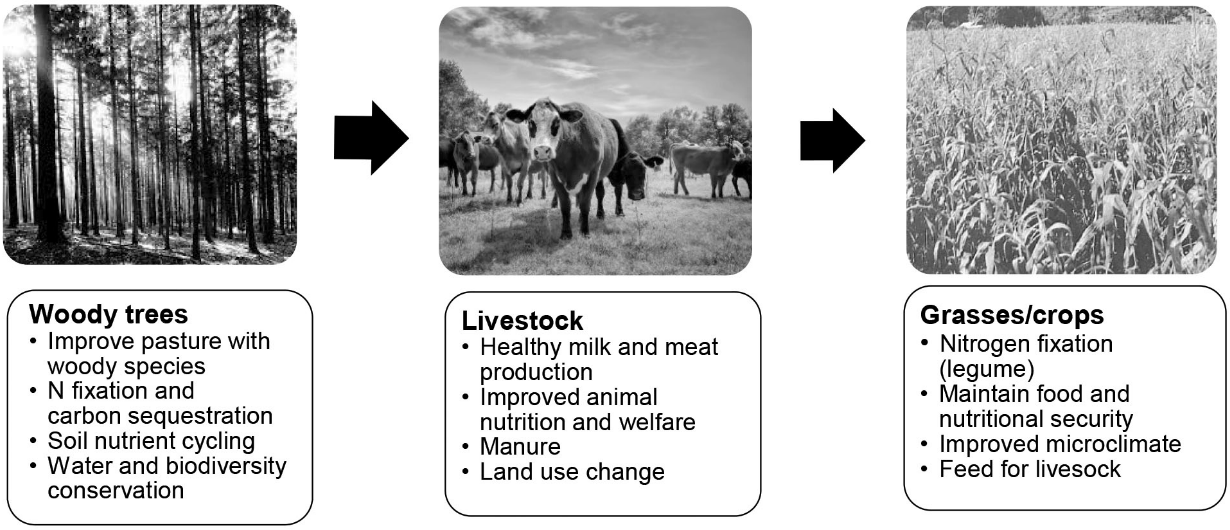

Figure 1. Model of silvopastoral system for resilience to climate change.

productivity, a greater percentage of soil organic matter, and greater carbon storage in silvopastoral systems than grass-only systems[21]. Adding strong forage legumes to pasture is a more cost-effective and sustainable solution to pasture degradation[22,23]. (iii) Greenhouse gas mitigation, ruminant methane emissions are among the highest in the industry in terms of greenhouse gas emissions. (iv) Microclimatic conditions created by shade inside silvopastoral systems improve the ecosystem, reduce the temperature, and boost animal performance. Shading has increased dairy cow milk yields and live weight gains in cattle feedlots in hot climates[24].

Silvopastoral systems are beneficial in tropical livestock systems because they reduce vulnerabilities while increasing adaptive capacity[19]. These systems increase resilience in various ways, viz. increase fodder yield and quality, thereby increasing carrying capacity; improve animal comfort by increasing adaptive capacity and providing better microclimatic conditions; develop effective local protein and energy feed sources; protect soil from erosion and maintain soil fertility through nutrient cycling. Additionally, they develop environmentally friendly livestock systems that are suitable for sustainable agriculture, as well as improving soil fertility by fixing atmospheric nitrogen, increasing organic matter and enhancing the cycle of nutrients. Furthermore, Greene *et al.*[25] discovered that silvopasture in the eastern US has the potential to expand by 5.6–25.3 million hectares under the base case, capturing up to 4.9 or 25.6 Tg CO_2e yr^{-1} respectively. The envisioned expansion of silvopasture in these scenarios would primarily result from the demand for fodder as a supplemental feed, along with the cultivation of speciality timber products. The mitigation potential per hectare exhibited significant variability, ranging from 0.5 to 6.5 t CO_2e ha^{-1} yr^{-1}, attributed to differences in C accumulation rates among various species.

Forage production through silvopastoral system

The amount and quality of forages generated in silvopasture impact paddock productivity and the potential of the system to generate profit. Trees influence the availability of light and water, as well as the possibility of nutrient competition. Therefore, trees may significantly impact forage productivity and nutritional content, depending on forage availability and system design. Using 43 species of forage, Pang *et al.*[26] examined the effects of non-shadow (100% full sunlight), moderate shadow (45% sunlight) and deep shadow (20% sunlight). To ensure adequate water and nutrient availability, the forages were grown in containers to prevent root competition from other species. All 43 species produced less annual forage in full sun than in moderate shadow, whereas 31 of them produced even more in deep shadow. C_3 grasses were able to tolerate greater shade than C_4 grasses. Moreover, legumes and grasses can perform as well under agroforestry systems as they do in open pastures, provided root competition with other species is maintained to a minimum[27].

The nutritional composition and quality of 22 forages growing under moderate to intense shadow, which included 16 grass types and 6 legumes, were evaluated by Pang *et al.*[28]. The crude protein levels of forages grown under moderate shade and full sunlight were similar, and 18 of 22 forages under dense shade showed the same level. Under moderate and dense shade, 14 and 15 forages respectively, maintained relative feed value equal to that in the control. As a result, they established that most legume and grass forages cultivated under silvopasture would be equivalent to, or even better than, those cultivated under open pasture.

As a result of changing pedo-climatic conditions, in New York, Orefice *et al.*[29] analysed the forage production quantity, quality and financial benefits of converting an early successional northern hardwood forest to silvopasture,

Table 4. Performance of tree species under different silvopastoral systems

Treatment	60 months of planting		84 months of planting	
	Survival (%)	Looped biomass (q ha^{-1})	Survival (%)	Looped biomass (q ha^{-1})
Prosopis (sole)	100	13	93	29
Acacia (sole)	85	25	81	32
Prosopis + fodder grass	95	17	95	34
Acacia + fodder grass	90	19	90	26
CD ($P = 0.05$)	NS	2.78	NS	2.20

Source: Singh *et al.*[53].

Table 5. Green fodder yields under different silvopastoral systems at different growth stages

Treatments	48 months of planting	60 months of planting	72 months of planting	84 months of planting
Grasses (sole)	103	175	207	219
Prosopis (sole)	35	55	79	47
Acacia (sole)	42	72	85	88
Prosopis + Karnal grass – Berseem	75	158	50	222
Acacia + Karnal grass – Rhodes grass	61	57	113	162

Source: Singh *et al.*[53].

thinned forest and open-pasture systems. In the first year of the study, the authors noted that the silvopasture system generated less fodder biomass than an open-pasture system, but the two systems had equivalent fodder in the second year. Furthermore, fodder quality research found that silvopasture forage had more crude protein than open-pasture forage, although acid and neutral detergent fibre contents were comparable. The presence of trees, according to the scientists, boosted the nutritional content of forage while keeping it digestible. There was no difference in the net present value or internal rate of return of silvopasture and open pasture, regardless of the initial cost of harvesting the timber.

Acacia nilotica cultivated as a solo crop generated much more lopped biomass (25.10 q ha^{-1}) than *A. nilotica* and *Prosopis juliflora* grown in conjunction with other grass species (Table 4).

Nonetheless, at the 84-month growth stage, the *Prosopis* + berseem intercrop generated considerably higher lopped biomass (33.55 q ha^{-1}). Tree lopping in extremely alkaline soils enhanced *P. juliflora* plant height substantially. During the dormant season, cutting off tree-side branches promotes better tree development and boosts the fodder productivity of surrounding grasses (Table 5). *P. juliflora* and *A. nilotica* were planted as single plants, and fodder yields from these plants, as well as other planted grass species such as *Chloris gayqna*, *Trifolium alexendrium*, *Leptochloa fusca* and *Panicum maximum*, were monitored at regular intervals. It was revealed that fodder yields in both the solitary plantation and the intercrop grew with each shortening of the period. Compared to intercrop yields, *L. fusca* generated the most fodder 48 months after planting. Similar patterns were seen up to 72 months following planting when *P. juliflora* outperformed other silvopastoral systems in terms of fodder output. As the tree and grass combination system promoted soil health more, the improvements in fodder biomass yields between 48 and 84 months after planting were greater in the tree and grass cropping system than in the single tree plantation and sole grass cropping systems.

Nutritional importance

Soil composition, irrigation, manure and fertilizer application, growth stage, and feed resource diversity all significantly affect the nutritional content of fodder crops. Mimosine is a poisonous, non-protein chemical found in Subabul leaves and seeds[30]. To reduce the harmful impact, sheep, goats, and cattle may be fed 30% of the recommended quantity of subabul fodder[31]. Table 6 shows the nutritional value of several fodder tree species in terms of crude protein, total digestible crude nutrients, digestible crude protein, crude fibre, phosphorus and calcium content.

Environmental benefits

The silvopastoral system is adaptable to climate change and helps to reduce greenhouse gases by directly storing carbon from the atmosphere and decreasing the production of enteric methane[32]. It helps boost land productivity by improving soil fertility and maintaining environmental potentialities[33]. It can significantly contribute to both above- and below-ground carbon sequestration[34]. Diversifying pastures, particularly with legumes, increases not only forage but also animal production besides improving soil quality by enhancing its chemical, biological, and physical properties[21]. Plant diversity promotes cation exchange capacity and the accumulation of soil organic matter, which contribute to ecosystem services such as carbon sequestration,

Table 6. Nutritive values of fodder trees cultivated under silvopastoral system

Tree species	Crude protein (%)	Digestible crude protein (%)	Total digestible nutrients (%)	Crude fibre (%)	Ca (%)	P (%)
Sirish	14.9–29.2	11.6	49.3	25.3–37.5	1.1–2.7	0.1–0.3
Neem	12.4–18.3	8.4–9.3	42.8–53.3	11.4–23.1	0.9–4.0	0.1–0.3
Kachnar	10.7–15.9	5.0–9.2	47.9–55.5	20.7–33.0	1.4–4.1	0.2–0.4
Shisham	2.7–24.1	3.7–9.1	20.9–52.2	12.5–32	2–2.3	0.2
Bamboo	14.2–15.1	9.3	48.9	15.6–23.5	1.1–1.6	0.2–0.3
Jamun	8.8–10.2	0.1	43.8	19.8	1.3	0.1–0.2
Dhamni	13.2	–	–	–	1.5	0.1
Anjan	9.0	–	–	30.4	2.3–3.3	0.1
Subabul	15.2–27.6	12.6–16.4	57.1–70.2	10.2–17.2	2.7–3.1	0.2
Mulberry	15–27.6	10.7	59.6	9.1–15.3	2.4–4.7	0.1–0.2
Khejri	13.9–15.3	–	–	17.5–22.1	1.9–3.6	0.2–0.5
Jharber	11.5	5.5	51.1	33.8	1.9	0.3
Agastya	25–30	–	75	18.4	1.48	0.34
Gliricidia	14.7	–	–	19.9	1.58	0.29
Acacia	15.1	–	–	22.6	1.21	0.26

Source: Dwivedi[54], Devendra[55].

nitrogen cycling, and water and soil conservation[35,36]. Moreover, the deep root system of trees reduces erosion and extracts moisture from deeper strata of the soil. Therefore, the adoption of a silvopastoral system can foster spatial heterogeneity, hence creating a 'fertility island' around trees[37].

According to Singh[32], forage-based feeding methods exhibit great production and cost efficiency in ruminants. This system also has the potential to produce employment for rural residents by including animal husbandry tasks such as the gathering, processing, and selling of value-added products from grasses and trees[38]. The silvopastoral system can support biodiversity protection as well as landscape aesthetics[39] by providing a habitat for fauna and flora species[40]. Silvopasture systems have the potential to improve animal health and well-being, leading to healthier food for humans[41].

Challenges in developing silvopastoral system

The growth of trees in livestock-grazed paddocks is one of the most challenging difficulties in silvopasture. Both browsing and debarking, in actuality, threaten the survival and growth of newly planted seedlings[42]. According to Karki *et al.*[43], Kiko goats spend roughly 2% of their awake time debarking trees when grazing in well-established pine silvopastoral systems based in Alabama, USA. According to Zhang *et al.*[44], grazing height and time affect the rejuvenation capacity of 12 oak species. To imitate grazing, acorns were planted in separate pots, and seedlings were trimmed at varied stages, heights, and times. As a result of being cut 5 days after germination, seedlings resprouted faster and produced larger dry masses of regenerated shoots than those cut 10 days after germination. Although the 12 oak species were clipped at two developmental stages, the regeneration success remained the same. Seedlings trimmed to a higher stubble height of about 3 cm recovered more quickly and successfully than seedlings trimmed to a lesser stubble height. These studies revealed that, whereas grazing height influenced establishment success, the grazing schedule did not affect regeneration success. It might be challenging to establish and sustain productive silvopastoral systems that are tailored to each particular environment.

To maximize the utilization of geographical, temporal, and physical resources, Jose *et al.*[45] and Nasar *et al.*[46] advocated minimizing negative (competition) and maximizing positive (facilitation) interactions among system components. Under such complex systems, the ecological principles that govern interactions between forages, trees, and cattle are conserved. As a result, the authors aimed to demonstrate how to build and run long-term silvopastoral systems using broad ecological principles shared by complex natural systems[46]. They spoke about how (i) geographical and temporal heterogeneity may boost system performance, (ii) perennialism can boost complementarity, (iii) structural and functional variety can boost resource utilization, and (iv) disturbance ecology concepts can be utilized to make effective management decisions. They resolved that analysing silvopastoral systems based on these ecological principles would aid in the improvement of design and management strategies. Most aspects of the silvopasture system have been thoroughly studied, but from a climate change and social point of view, additional research efforts are needed to address emerging challenges.

Conclusion

Due to a decrease in per capita availability, land under fodder cultivation remains stagnant, with little scope for development. The silvopastoral system diversifies agricultural operations, promotes tree development, increases animal output, improves nutrient cycling and improves wildlife habitat. The tree components of this system alter the microenvironment, increasing green fodder production under the canopy. The silvopastoral system promotes animal output while lowering greenhouse gas emissions. The efficiency of nitrogen cycling processes is improved by legume trees. It restores damaged land, sequesters CO_2, and increases soil carbon and nitrogen stocks. The silvopastoral system increases adaptation capacity while decreasing vulnerability to climate change. Hence, fodder production through the silvopastoral system not only improves the livelihood of farmers by ensuring food security but also increases productivity along with sustainability.

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