**Silvopastoral Systems in India for Fodder Production and Livestock Sustainability: A Review**

**Abstract**

Silvopastoral systems combine trees, forage crops, and livestock to maximize land productivity, conservation of biodiversity, and sustainable rearing of livestock. Silvopastoral systems are very important in increasing the ecological and economic sustainability of livestock production, particularly in developing nations such as India. Livestock farming is a key component of rural livelihoods, providing food security, employment, and farm diversification. But its sustainability is under threat from challenges like fodder shortage, land degradation, and climate change. Silvopastoral systems offer a suitable alternative by combining multipurpose tree species, nutrient-rich forage crops, and resilient livestock species in a synergistic way. Silvopastoral systems enhance soil fertility, enhance carbon sequestration, reduce heat stress in animals, and provide fodder throughout the year. This review examines the importance, structure, advantages, disadvantages, and future scope of silvopastoral systems in India with a focus on their utility to enhance fodder productivity and provide livestock sustainability under an altered climatic situation.

**Introduction**

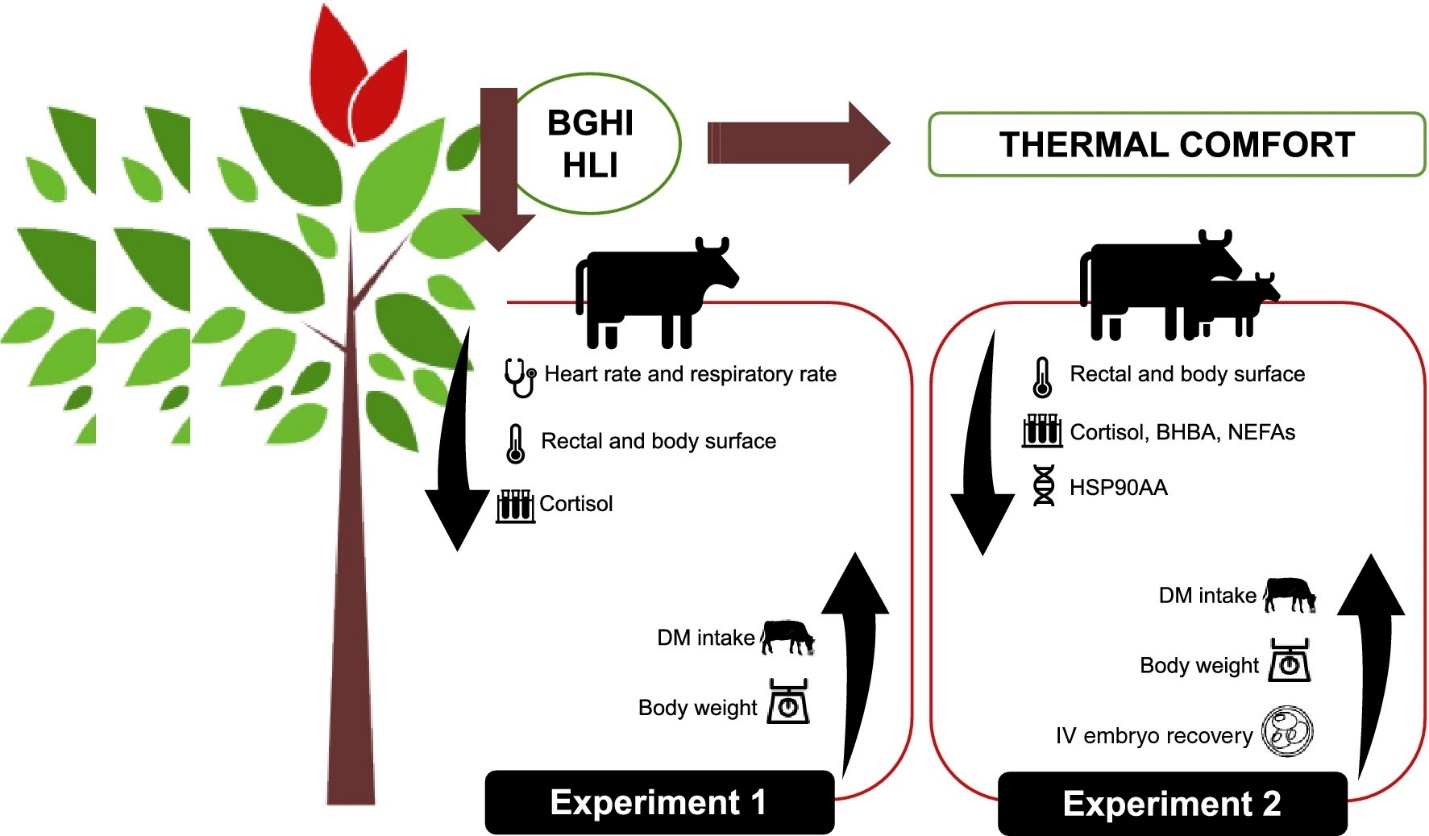
Livestock rearing in India is an essential sector of the farm economy that delivers milk, meat, draught power, and employment to countless rural families (Phand, S., and Das, S. 2022). The livestock sector plays an important role in providing food security as well as contributing to national GDP (Metaferia et al., 2011). But it is confronted with severe challenges such as fodder shortages, decreasing pasturelands, land degradation, and the negative impacts of global climate change (Thornton et al., 2007). Historical pasturelands are also being converted to other uses like urbanization, intensive monoculture agriculture, and forest clearing, resulting in greater pressure on animal production systems (Mueller et al., 2021).

**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 |

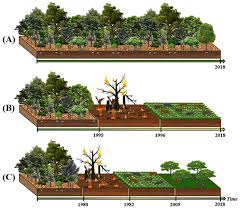
Source, Source: Based on 10th and 11th Five-Year Plan Document Vision 2030 [(http://www.igfri.ernet.in](http://www.igfri.ernet.in/)).

Silvopastoral systems involve tree crops in combination with grazing pastures or fodder cultivation, while agrosilvopastoral systems involve livestock in combination with crops, multifunctional hedgerows, woodlots, or fodder trees (Moreno, and Rolo, 2019). The systems have a great deal of diversity in their structural elements (e.g., choice of trees and shrubs), productive roles (e.g., food, fodder, fiber, and crop production), and ecological benefits (e.g., soil conservation and wind protection) (Vandermeulen et al., 2018). Common practices involve the creation of high-density tree and shrub plantations in pastures, cut-and-carry systems where the livestock are fed with leaves from specific plantings, and growing fast-growing shrubs and trees to be used in fencing and windbreak systems (Nair et al., 2021).



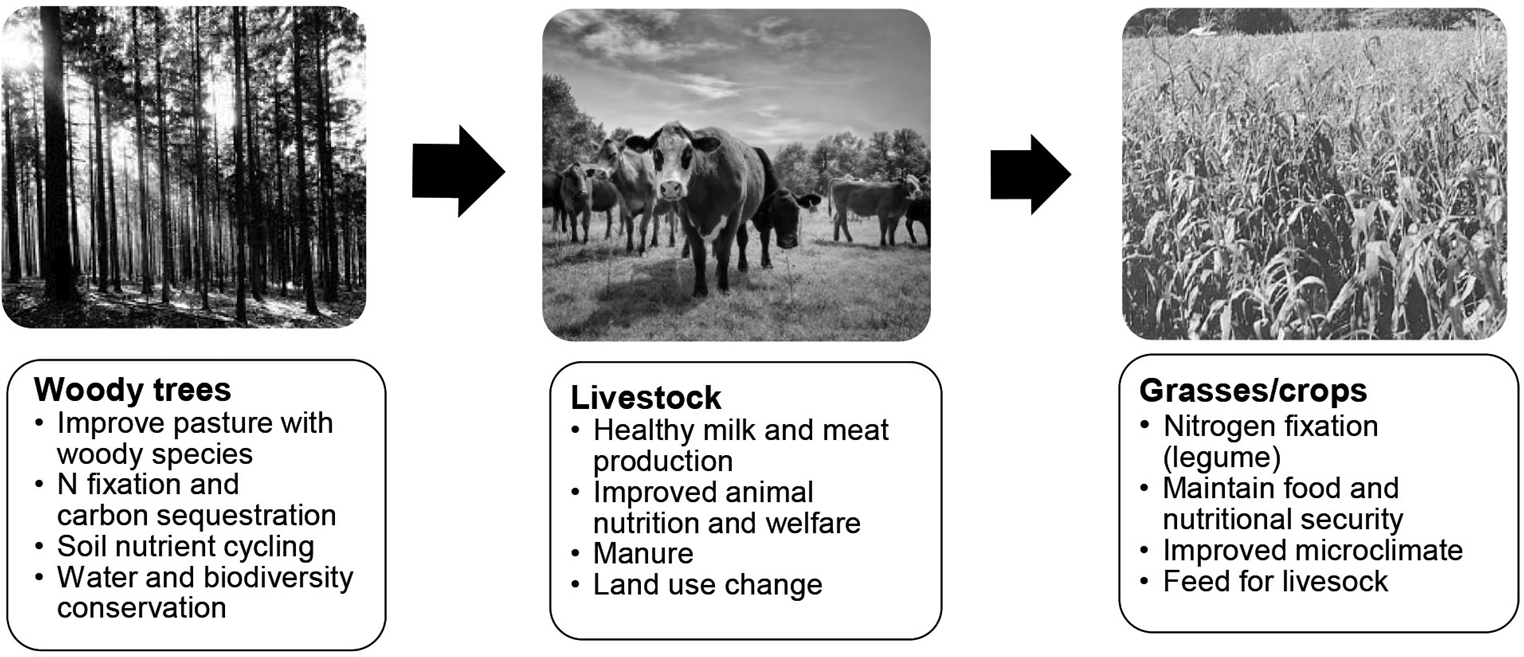
(Source, Lemes et al., 2021)

Figure-1: A hypothetical model suggests that natural shade in pasture areas enhances the thermal comfort of beef heifers and cows by lowering the black globe humidity index (BGHI) and heat load index (HLI). As a result, it leads to a decrease in heart rate, respiratory rate, rectal and body surface temperatures, cortisol levels, and heat shock protein expression (HSP90AA), while promoting an increase in dry matter intake (DMI), body weight, and in vitro embryo recovery. **BHBA** refers to β-hydroxybutyrate, and **NEFAs** denote non-esterified fatty acids.



(Source, Silva-Olaya et al., 2021)

**Figure 2.** image show that, where (**A**) Native vegetation; (**B**) Pasture; (**C**) Silvopastoral system.



(Source, Som et al., 2024)

Figure-3: Silvopastoral system and their uses

Silvopastoral systems may be managed intensively or extensively. Intensive systems entail growing fodder shrubs at high densities (4,000–40,000 plants per hectare) with enhanced tropical grasses and trees or palms, which are planted at 100–600 trees per hectare (Dagar, and Gupta, 2020). The systems tend to adopt rotational grazing methods, which are marked by high stocking rates, short grazing periods, and long recovery periods (Donaghy et al., 2021). In contrast, semi-intensive silvopastoral systems have three levels of vegetation—shrubs with edible leaves, trees that can also bear edible leaves, and pasture (Vega Quintero, 2024). These systems produce more plant biomass and animal products than the usual pasture-based systems, while offering the possibility of harvesting tree and shrub foliage and using it as livestock feed in times of drought (Gabriel, 2018).

Silvopastoral systems are practiced globally, either through farmers' intentional adoption or through the natural evolution of ecosystems to offer protection and ecological services (Moreno, and Rolo, 2019). Prominent examples include the *Iberian Peninsula's* Dehesa and Montado ecosystems, the South American El Chaco region, and many landscapes in Africa and Asia (Verdade et al., 2011). Argentina has seen considerable expansion of forest-pasture systems covering more than 34 million hectares, both communal and indigenous lands. In North America and Europe, there is growing interest in using trees and shrubs in integrated farming systems, either for wood, fruit, or nut production, as windbreaks, or to complement livestock diets through direct browsing or following pruning or coppicing. Australian farmers too have set up high-density *Leucaena* *plantations* with grasses (Adegbeye et al., 2024).

Silvopastoral systems ensure sustainable land management by enhancing cattle production using natural ecological processes (Pezo et al., 2018). Silvopastoral systems increase efficiency in the use of resources and have numerous environmental advantages, such as minimizing deforestation and land degradation, improving soil fertility through nutrient uptake from lower soil layers, and maximizing water retention and infiltration capacity (Sileshi, et al., 2020). They also regulate the hydrological cycle by reducing runoff, sequestering carbon in above- and below-ground biomass, and promoting biodiversity (Lal, 2019).

**Table 2.** Different fodder forest tree used for silvopasture system

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Common name | Planting time | Yield | | Reference |
| Green | Dry |
| Subabul | July–August | 55–85 t ha–1 | 20 t ha–1 | (Panday and  Roy 2011, Khanna 2013, Reddy  et al., 2016) |
| Sirish | After monsoon rain sets in | 40–70 t ha–1 | 11–15 kg tree–1 | Newaj et al., 2005), Khanna  2013, Reddy et al., 2016) |
| Shisham | After monsoon rain sets in | 40–70 t ha–1 | 5–6 kg tree–1 | Khanna 2013, Singh et al.,  2013) |
| Mulberry | July–August | 40–120 t ha–1 | 43 t ha–1 | Khanna 2013, Datt et al.,  2008) |
| Kachnar | Onset of monsoon | 7.7 kg tree–1 | 6.7 kg tree–1 | Khanna 2013, Singh et al.,  2013) |
| Agastya | June–July | 80 t ha–1 | 20 t ha–1 | Khanna 2013, Mariswamy et  al., 2017) |
| Gliricidia | After onset of monsoon | 43 t ha–1 | 5-6 t ha–1 | (Khanna 2013) |
| Ber | July–August | 46 t ha–1 | 3.5 t ha–1 | Khanna 2013, Verma, 2016) |
| Anjan | After onset of monsoon | 24–26 t ha–1 | 4–10 t ha–1 | (Tewari, 2007 |
| Neem | Onset of monsoon | 40–70 t ha–1 | 40–60 kg ha tree–1 | (Khanna 2013, Reddy 2016) |

(Source, Sow, S 2024)

In addition, silvopastoral systems enhance animal well-being by providing more nutritional access than conventional pasture systems, alleviating heat stress through natural shading, and shelter that reduces fear and anxiety and lowers the risk of ectoparasites (Broom et al., 2013). Through the use of well-suited livestock breeds for tropical conditions, intensive silvopastoral systems can attain high levels of productivity through the use of high-quality, locally produced feed resources (Kumar et al., 2024). Further, incorporation of nitrogen-fixing crops eliminates the need for manmade fertilizers, while enhanced forage quality lessens the necessity for external nutritional additives (Abdel-Raouf et al., 2012).

Given that India hosts the world's largest livestock population, it is critical to provide sufficient and sustainable fodder resources (Singh et al., 2022). The existing fodder shortage, at an estimated 30-40% per annum, has a major bearing on livestock productivity and rural livelihoods (Dhamodharan et al., 2024). Climate change, overgrazing, and the declining size of traditional grazing areas further aggravate this shortage. There is an urgent need to provide a sustainable and resilient fodder supply (Tulu et al., 2023).

**Fodder Species Used in Silvopastoral Systems and Their Nutritional Value**

The silvopastoral system integrates trees, shrubs, and grasses to provide sustainable forage, improve soil fertility, and enhance livestock productivity (Jose, and Dollinger, 2019). The following fodder species are commonly used in silvopastoral systems along with their nutritional attributes.

**Table-3. Tree Species Used in Silvopastoral Systems**

These trees provide high-protein foliage, shade, and contribute to soil improvement.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Tree Species** | **Crude Protein (%)** | **Digestibility (%)** | **Key Nutrients** | **References** |
| *Leucaena leucocephala* (Subabul) | 20-25 | 70-80 | High protein, rich in calcium and phosphorus | (Shelton & Dalzell, 2007) |
| *Albizia lebbeck* (Siris) | 18-22 | 65-75 | Rich in fiber, good for ruminants | (Mandal et al., 2005) |
| *Morus alba* (Mulberry) | 15-22 | 75-85 | High-energy, rich in vitamins and minerals | (Singh & Makkar, 2002) |
| *Gliricidia sepium* | 18-25 | 60-75 | Nitrogen-fixing tree, high in crude protein | (Kaitho et al., 1998) |
| *Acacia nilotica* (Babul) | 12-18 | 55-65 | Provides tannins and crude fiber | (Bhatta et al., 2012) |

**2. Shrub Species Used in Silvopastoral Systems**

These shrubs are nutrient-rich and enhance fodder quality.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Shrub Species** | **Crude Protein (%)** | **Digestibility (%)** | **Key Nutrients** | **References** |
| *Sesbania sesban* | 20-28 | 70-85 | High digestibility, rich in protein | (Paterson et al., 1998) |
| *Cajanus cajan* (Pigeon pea) | 18-24 | 65-80 | Provides protein and fiber | (Norton, 2003) |
| *Calliandra calothyrsus* | 15-22 | 55-70 | Good for ruminants, rich in minerals | (Palmer & Schlink, 1992) |
| *Desmanthus virgatus* | 17-22 | 60-75 | Highly palatable, good for nitrogen fixation | (Cook et al., 2005) |

**Table-4. Grass Species Used in Silvopastoral Systems**

Grasses ensure continuous forage supply and enhance soil cover.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Grass Species** | **Crude Protein (%)** | **Digestibility (%)** | **Key Nutrients** | **References** |
| *Cenchrus ciliaris* (Buffel grass) | 8-14 | 55-65 | Drought-tolerant, rich in fiber | (Bogdan, 1977) |
| *Pennisetum purpureum* (Napier grass) | 10-16 | 60-70 | High biomass, good for silage | (Boonman, 1993) |
| *Brachiaria* spp. | 12-16 | 65-75 | High digestibility, good for grazing | (Miles et al., 1996) |
| *Dichanthium annulatum* (Marvel grass) | 10-14 | 60-70 | Provides energy and protein | (Hacker, 1992) |
| *Panicum maximum* (Guinea grass) | 12-18 | 65-75 | High protein, good for dairy cattle | (Skerman & Riveros, 1990) |

In this regard, silvopastoral systems, being a type of agroforestry, present a viable and sustainable option (Vandermeulen et al., 20180. Through the combination of multipurpose trees, high-yielding pasture grasses, and livestock in a mutually beneficial relationship, these systems maximize land use efficiency, increase biodiversity, and promote soil health (Machebe et al., 2023). Silvopastoral practices also sequester carbon, enhance microclimatic conditions, and yield economic gains through the diversification of farmers' income sources (Chappa et al., 2024). Consequently, these systems have become an essential approach to providing long-term sustainability in India's livestock industry.

**Table-5.** Different plants with fodder potential used in the silvopastoral system and their nutritional value.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| 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, 1992, Devendra, 1992, and Som, et al., 2024)

**Elements of Silvopastoral Systems**

Silvopastoral systems are a sustainable livestock production strategy that combines productivity with environmental stewardship (Jose, and Dollinger, 2019). Integrating trees, forages, and livestock into a well-organized system can enhance soil fertility, biodiversity, and economic resilience for farmers (Haddad et al., 2021). Silvopastoral systems are a practical solution for sustainable agriculture in any climatic region with proper planning and management (Louhaichi et al., 2022).

**Table 6.** Fodder producing grasses/legumes/crops cultivated in agri-silviculture system

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Yield (t ha–1) | | | | | | |
| Common name | Varieties | Seed rate | Sowing time | Green | Dry | Reference |
| 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 | (Pandey, K. C. and Roy 2011) |
| Lucerne/Alfalfa | Chetak (S-244) | 25–30 kg ha–1 | September–December | 140–150 | 8–9 | (Pandey, K. C. and Roy 2011) |
| Jowar (sorghum) | MP Chari, Jawahar Chari-6, Jawahar Chari-69 | 30 kg ha–1 | At onset of monsoon | 53 | 15 | (Pandey, K. C. and Roy 2011) |
| Stylosanthes | Stylosanthes Phule Kranti (RSS-2000-95) | 5–6 kg ha–1 | June–July to September– October | 25–30 | 10–12 | (Pandey, K. C. and Roy 2011) |
| 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 | (Vaghela et al., 2014) |
| Anjan grass | Bundel Anjan-1; Bundel Anjan-3 (IGFRI-727) | 5 kg ha–1 | At onset of monsoon | 35–40 | 6–12 | (Vaghela et al., 2014) |
| Saen grass | Bundel sain Ghas-1 (IGS 9901) | 33,000–35,000  seedlings ha–1 | Before on set of monsoon | 18.3 | 4.7 | (Vaghela et al., 2014) |
| 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 | (Vaghela et al., 2014) |
| 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 | (Vaghela et al., 2014) |
| Dinanath grass | Jawahar Pennisetum-12; Bundel-1; Bundel-2 | 2.5–5 kg ha–1 | Onset of monsoon | 55–60 | 14 | (Pandey, K. C. and Roy 2011) |

(Source, Som et al., 2024)

**Tree Component:** Multipurpose tree species like *Leucaena leucocephala*, *Acacia nilotica, Albizia lebbeck*, and *Prosopis cineraria* supply quality fodder, shade, and improve soil enrichment through nitrogen fixation and organic matter contribution (Rao, 2002). These trees help sequester carbon, enhance microclimate regulation through temperature and humidity control, and serve as windbreaks, which lessens soil loss and water loss (Raj, 2017). They are also a source of firewood, timber, and medicinal outputs, providing varied benefits to the farmer and the rural community. Trees contribute significantly to silvopastoral systems by shading, enhancing soil fertility, and providing other fodder resources. Fruit and timber trees can also be added to give more economic returns (Dagar, and Gupta, 2020).

**Forage Component:** Legumes (e.g., *Stylosanthes* spp., *Medicago sativa*) and perennial grasses (e.g., *Cenchrus ciliaris*, *Panicum maximum*) are important for increasing fodder supplies and soil fertility through nitrogen fixation and organic matter accumulation (Jank et al., 2019). They improve livestock nutrition, leading to increased milk production, quality meat, and general animal health. Their deep roots improve soil water retention and structure, thus their resistance to drought (Ponnampalam et al., 2022). By incorporating diverse and high-yielding forage species, silvopastoral systems can significantly reduce the dependency on costly commercial feed, ensuring economic sustainability for farmers (Pezo et al., 2018).

**Table 7.** Different green fodder spp. 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., 2015, and Som, et al., 2024)

The forage cover is composed of grasses, legumes, and shrubs that form the main source of feed for animals (Tarawali, 1995). Drought-resistant, high-yielding species like Guinea grass, Buffel grass, and leguminous forages) are widely grown. Forage species are chosen based on climate, soil, and animal requirements (Oscar, and Kibet, 2011).

**Livestock Component:** Cattle, buffaloes, sheep, and goats benefit from diversified feed resources, improved nutrition, and stress mitigation under tree canopies(Devendra, 2011 ). The availability of high-quality forage enhances animal health, boosting reproductive efficiency and reducing mortality rates (Capstaff, and Miller, 2018). Good grazing management provides for the sustainable use of fodder, whereas rotational grazing practices can avoid overgrazing and encourage pasture re-growth. Silvopastoral systems also enhance livestock well-being through shade provision, alleviation of heat stress, and reduced exposure to adverse climatic conditions, thus contributing to improved productivity and profitability for the farmer. Livestock species like goats, sheep, and cattle are part of silvopastoral systems (Cuartas Cardona et al., 2014). They influence vegetation management as well as nutrient cycling through grazing. Stocking rates and rotational grazing practice maintain the health of pasture and avoid overgrazing (de Faccio Carvalho et al., 2010).

**Table 8. Different tree species under different silvopastoral systems**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | | | | |
|  | 60 months of planting | | 84 months of planting | |
| Treatment | 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., 2015, and Som, et al., 2024)

**Soil and Water Management**

Efficient soil and water conservation methods are essential for sustaining productivity. Mulching, contour planting, and agroforestry trenches minimize soil erosion and increase water retention (Xing, and Wang, 2024). Trees in the system enhance the structure of the soil and its organic matter, resulting in efficient moisture conservation and fertility (Fahad et al., 2022).

**Biodiversity and Ecosystem Services**

Silvopastoral systems enhance biodiversity by providing wildlife and favorable microorganisms with diverse habitats (Yadav et al., 2019). They support ecological balance through the presence of several species of plants, lowering the prevalence of pests and diseases. Silvopastoral systems are also important for carbon sequestration through capturing atmospheric carbon in biomass and soil, thereby counteracting the effects of climate change (Alonso, 2011).

**Nutrient Cycling and Waste Management**

Livestock manure, tree litter, and plant residues contribute organic matter to the soil, which enriches it by restoring vital nutrients (Ayamba 2021). Composting and controlled grazing are proper manure management practices that maximize nutrient availability and minimize environmental pollution (Ayilara, et al., 2020).

**Economic and Social Benefits**

The diversified production system of silvopasture adds economic resilience to farmers through varied sources of income from livestock, timber, fruits, and fodder sales. The systems also provide jobs in tree planting, forage management, and raising livestock that advance rural livelihoods (Vijay Kumar et al., 2014). the Requirement for Alternative Farming Systems

**The Role of Silvopastoral Systems in Sustainable Agriculture**

Traditional farming systems have led to extensive environmental degradation, where soil nutrients have been depleted and natural resources exhausted (Lal, 2009). Decline in soil fertility reduces farm productivity, prompting farmers to expand agricultural land, a process that accelerates deforestation and environmental pollution (Hossain et al., 2020). Moreover, global warming, combined with a rapidly growing human population, has placed a tremendous burden on food security across the world. In light of these constraints, it is now imperative to create new, sustainable production systems that can improve the production of food while maintaining natural resources and reducing deforestation (Newton et al., 2013).

**Silvopastoral Research in Mexico**

A five-year Mexican research project, adapted from a national one, has investigated silvopastoral systems (SPS) as an alternative to traditional livestock agriculture in the tropics (Erales Villamil et al., 2017). Conducted in the Tepalcatepec Valley of Michoacán, this study was aimed at assessing the benefits and constraints of using SPS compared to traditional ranching practices (Villamil, 2017). The project involved the survey of 115 farmers to analyze farm characteristics, population, cattle breeds, farming systems, feeding systems, animal performance, commercialization strategies, and health management practices.

It also examined the evolution of various national SPS programs to establish research gaps, collaboration needs, education requirements of stakeholders, as well as issues of implementation in Mexico (Nigenda et al., 2015). System analysis was conducted comprehensively covering aspects such as sequestration of carbon, biodiversity, health of the soil, nutrient cycling, and large-scale ecological processes involving the water cycle. (Feng et al., 2024) Precise measurement of the economic and environmental impacts of SPS agriculture was a top research priority. Additionally, the research highlighted the necessity of improving the communication and coordination among scientists, government agencies, and stakeholders in order to better make research work and facilitate successful implementation of SPS practices (Abera, 2016).

**Animal Health Component of the Study**

One of the main areas of interest in this research was the examination of livestock health in SPS farms. The study outlined traditional animal health practices and enumerated common cattle diseases in the region (Mahato, 2004). To enhance disease surveillance, there was an establishment and execution of a community-based livestock syndromic surveillance system for two years in five farms (Kijazi, 2023). Farmers' information were cross-checked for consistency with veterinarians' findings to verify validity. Incidence rates of disease were calculated monthly among different cattle categories (adults, growers, and calves), and the most frequent and economically relevant syndromes were identified (Renault et al., 2028). The high degree of correlation between farmer and veterinarian observations testified to the validity of this community-based approach.

In addition, the research analyzed the risk of introduction of bovine tuberculosis into the silvopastoral epidemiological compartment (Erales Villamil et al., 2017). Using the @Risk™ software, six different scenarios were simulated in an attempt to estimate the probability of introduction of the disease through replacement heifers and sires (Villamil, 2017). In consideration were the national bovine tuberculosis control and eradication program, disease prevalence at the regional level, and contemporary cattle management practice within Tepalcatepec Valley. The findings found that the smallest probability of introduction of tuberculosis occurred when replacement cattle were subjected to both the tuberculin caudal fold test and the cervical comparative test simultaneously.

**Economic and Social Barriers to Adoption**

Despite the obvious benefits of silvopastoral systems—more environmental sustainability, higher productivity, and economic profitability—there are several barriers to their adoption (Lee et al., 2020). The significant initial capital required for SPS implementation is one of the greatest challenges, since the majority of small-scale farmers lack sufficient financial resources. Low-interest loans, credit programs, and government subsidies should be among the measures used to encourage SPS uptake (Alam, and Tomossy, 2017). Improved estimation of the cost of establishing SPS is also required. The first three years of production are the costliest in terms of investment, and therefore financial inputs from timber and fruit production should be considered, which would be able to offset initial costs (Dawson et al., 2014).

**Scaling Up Silvopastoral Systems in the Future**

To better utilize the potential of silvopastoral agriculture, further research needs to be done to maximize economic models, identify ecological benefits, and examine its role in animal and human health (Smith et al., 2022). The acquisition of knowledge on a greater diversity of tree, forage, and livestock species combinations will enable the development of optimized SPS configurations tailored to different ecological zones (Lecegui et al., 2022). In addition, research funding remains limited; however, growing consumer demand for environmentally friendly livestock products can drive market-driven reforms. Greater public awareness and support for sustainable agriculture can also result in greater government agency, industry, and non-governmental organization investment in the sector for improving agricultural resilience to climate change (Ignaciuk, 2015).

With a combination of ecologic sustainability and farm productivity, silvopastoral systems offer a valuable path to sustainable and resilient farming systems (Haddad et al., 2021). With studies and policy actions gaining strength, larger-scale deployment can have a monumental impact on constructing global food security, carbon sequestration, and wildlife protection (Solorio, 2017).

**Environmental Benefits of Silvopastoral Systems**

Silvopastoral systems deliver numerous environmental benefits compared to other livestock production on open pasture (Huertas et al., 2021). These benefits include better soil quality, increased biodiversity, improved water holding capacity, and most significantly, enhanced carbon sequestration (Paciullo et al., 2021). By integrating trees, shrubs, and forage crops into pasture lands, silvopastoral systems develop a more secure agro-landscape that can help reduce the negative impacts of climate change (Haaland et al., 2021).

Among the most important environmental advantages of silvopastoral systems is their carbon sequestration potential in various ecosystem compartments such as the soil, trees, and forage crops (Moreno et al., 2014). The capacity of the systems to sequester and store atmospheric CO₂ is essential in mitigating greenhouse gas emissions and supporting climate-resilient agriculture. A number of scientific studies have examined the carbon sequestration capacity of silvopastoral systems, with the focus on their long-term environmental sustainability (Peri et al., 2027).

Silvopastoral systems offer numerous environmental advantages over conventional open-pasture livestock farming (Huertas et al., 2021). Among these are better soil health, biodiversity, water retention, and most significantly, carbon sequestration. Through the cultivation of trees, shrubs, and forage plants within pasturelands, silvopastoral systems produce a more climate-resilient farming landscape that counters the negative impacts of global warming (Vaishnav et al., 2021).

One of the chief environmental advantages of silvopastoral systems is their capability to sequester carbon within various ecosystem compartments, such as the soil, trees, and forage species. The potential of these systems to capture and store atmospheric CO₂ is the key to controlling greenhouse gas emissions and supporting climate-resilient agriculture (Singh, and Mishra, 2023). Research has estimated carbon sequestration capacity in silvopastoral systems with a focus on their significance towards long-term environmental sustainability.

**Research on Fodder Production and Carbon Stock in India**

**Varsha et al. (2019)** analyzed the three fodder species in terms of their forage productivity, nutritional quality, and ability to sequester carbon, which were hybrid Napier grass (*Pennisetum purpureum*), Mulberry (*Morus alba*), and Stylosanthus (*Stylosanthes* sp.), a nitrogen-fixing leguminous plant. The research investigated these species as monoculture as well as in mixed cropping using two or all three of the fodder types.

The study found that the hybrid Napier monoculture, which is most widely adopted among southern Indian farmers, yielded the highest forage dry matter. But in spite of being highly productive, it had the poorest fodder quality and carbon storage potential (Raj et al., 2023). On the other hand, the Mulberry monoculture system had the highest potential for carbon sequestration but much lower forage yields. In comparing crude protein yield and carbon sequestration, the best system was a mixed silvopastoral system with hybrid Napier and Mulberry trees (Gupta et al., 2020). This blend provided a balanced strategy, optimizing forage production for animals while also promoting environmental sustainability through improved carbon sequestration and soil enrichment (Adegbeye et al., 2024).

The combination of several plant species in silvopastoral systems guarantees a more stable and diversified ecosystem. The incorporation of nitrogen-fixing plants such as Stylosanthus improves soil fertility, thereby minimizing the application of chemical fertilizers (Epifanio et al., 2020). The incorporation of deep-rooted plants such as Mulberry also increases soil structure and water retention, thus making the systems drought-resistant (Rahman, and Hoque,2007).

**Carbon Sequestration in Mexican Silvopastoral Systems**

In a contrasting climatic and edaphic setting, López-Santiago et al. (2019) implemented a study in Mexico comparing the carbon sequestration potential of various land-use systems. The scientists estimated the biomass and soil carbon stock of a silvopastoral system made up of *Leucaena leucocephala*, a nitrogen-fixing fodder tree, and *Panicum maximum* (Guinea grass). They compared the results with a natural deciduous tropical forest and a traditional grass monoculture.

Aboveground and root biomass was estimated in this study utilizing allometric models and measuring down to the third deepest level at a 30-cm depth. Results confirmed that silvopastoral as well as the natural forest both retained substantially greater amounts of aboveground biomass than that found on monoculture pasture (Moreno, and Rolo, 2019). Highest accumulation of belowground biomass occurred within the silvastopal system further elucidating that carbon would be sequestered here below ground (Morales Ruiz et al., 2021).

While the natural forest had the highest SOC levels at all depths, the silvopastoral system had higher total carbon sequestration potential than the monoculture pasture (Amézquita et al., 2004). This result highlights the ecological advantages of planting trees among pasturelands, as they aid in enhanced carbon capture without reducing agricultural productivity (Aryal et al., 2022). Moreover, trees' deep-root systems, such as those of *Leucaena leucocephala*, assist in stabilizing the soil, avoiding erosion, and enhancing nutrient cycling.

**Comparative Analysis of Multi-Tree Silvopastoral and Open-Pasture Systems**

The collective findings from these studies underscore the immense environmental benefits of silvopastoral systems. By enhancing carbon sequestration, improving soil health, and promoting biodiversity, silvopastoral practices provide a viable strategy for sustainable livestock production while mitigating climate change impacts (Ortiz et al., 2023).

While the world's agricultural systems strive to meet food production needs while preserving the environment, silvopastoral systems present a hopeful solution. Promoting the practice can result in more sustainable farming systems that contribute to economic and environmental sustainability. Investing in research, farmer training, and policy promotion of silvopastoral practices will be critical to furthering climate-smart agriculture and ensuring a sustainable future for livestock

**Aryal et al. (2019)** also compared the carbon storage potential of silvopastoral systems in Mexico between a multi-tree-based silvopastoral system and a traditional open-pasture system. In their study, they estimated tree and root biomass from allometric models as well as grass biomass and SOC concentration up to 15 cm depth.

It was discovered in the study that carbon storage in the herbaceous vegetation layer was greater in the silvopastoral system than in the open pasture. The same trend was evident in SOC content, further supporting the higher sequestration potential of silvopastoral systems for carbon (Aryal, 2022). These findings further establish that combining trees and plant species with biodiversity into grazing areas for livestock could notably increase sequestration of carbon, supporting long-term climate change mitigation (Witt, 2011).

**Other Environmental Benefits of Silvopastoral Systems**

Besides sequestering carbon, silvopastoral systems offer other environmental benefits that enhance ecological balance and sustainability.

**Increased Biodiversity:** With the inclusion of multiple plant species, silvopastoral systems harbor a variety of flora and fauna (Perez-Alvarez et al., 2023). Biodiversity increases ecosystem stability, enhances pollination, and maintains pest populations in check naturally without the use of chemical pesticides.

**Soil Health Enhancement:** Having deep-rooted trees in silvopastoral systems increases soil aeration and porosity and minimizes erosion (Sharrow et al., 2009). Furthermore, the organic contribution of tree litter and root exudates enriches the microbial populations of the soil, promoting healthier and more fertile soils.

**Effective Water Management:** Silvopastoral systems' multi-layered vegetation improves water retention as it minimizes runoff and maximizes soil infiltration (Vinodhini, 2023). This is especially useful in drought areas, as it keeps moisture levels high for extended periods, minimizing reliance on irrigation.

**Mitigation of Livestock Heat Stress:** Trees offer natural shade, and a more favorable microclimate is created for the grazing animals (Masters et al., 2023). Decreased heat stress enhances the productivity of livestock, resulting in improved weight gain, milk yields, and overall animal health.

**Greenhouse Gas Emissions Reduction:** Silvopastoral systems reduce methane and nitrous oxide emissions by enhancing forage quality and ruminant digestion efficiency (Vargas et al., 2022). High-quality forage minimizes enteric fermentation, a key source of methane emissions in animal husbandry.

**Forage Production in Silvopastoral Systems**

The quality and yield of forage grown in silvopastoral systems are important factors that determine paddock productivity and system profitability (Sarvade et al., 2019). Trees affect the availability of key environmental resources like light, water access, and the possibility of nutrient competition. Therefore, tree presence can impact the growth and nutritional content of forage depending on forage choice and system planning.

**Pang et al. (2019)** tested the influence of different levels of light intensity—full sunlight (100%), moderate shade (45%), and dense shade (20%)—on the yields of 43 forage plants. To account for root competition and provide water and nutrients freely, the forages were planted in pots. Their results showed that all 43 species had lower yields in full sunlight than in moderate shade, and 31 of these species even yielded more in dense shade. In addition, C3 grasses were more shade tolerant than C4 grasses. The investigation also emphasized that both legumes and grasses might grow equally well in agroforestry systems and open pastures, as long as root competition with other plants is reduced to a minimum.

In addition, **Ford et al. (2019)** studied forage yield, quality, and animal performance under open-pasture, silvopasture, and woodland systems on three Central Minnesota farms with different soil types. Calf pairs were rotationally grazed using 2-hectare paddocks, and forage was assessed prior to grazing cycles. Open pastures supported the largest forage yields, followed by silvopasture systems, and the least in woodland systems. Nonetheless, under drought conditions, silvopastoral systems performed better than both woodland and open-pasture systems. Though forage quality was affected by season and site, the general impact of the production system on forage quality was small, and livestock productivity was comparable among all systems.

**Fannon et al. (2019)** also did a similar study in Appalachia, comparing open pasture to 8-year-old honey locust and black walnut silvopastoral systems. Pre-grazing forage biomass was always higher in open pasture than in honey locust or black walnut silvopastures, although honey locust silvopastures produced more summer forage than black walnut systems. Post-grazing biomass showed the same trend, while forage quality was the same in all systems, with no influence on hair sheep carcass attributes.

**Clavijo et al. (2019)** investigated a different silvopastoral model through the inclusion of perennial cool-season grasses in commercial poplar plantations in Argentina's Paraná River delta. Comparisons between plots that were sown and not sown indicated small differences in summer yield of forage, although production grew gradually through autumn and reached a maximum during winter. The research concluded that incorporating grass into poplar stands had the potential to increase cattle carrying capacity from zero to 0.2 cows per hectare in autumn, which would be tenfold greater in winter.

Due to the extensive spatial and seasonal variability of understory forest forages, they might not always be of a quality adequate to support grazing**. Mendarte et al. (2019)** created a VIS-NIRS-based rapid assessment procedure to assess Pinus radiata understory shrubs like Rubus sp. and Ulex gallii. Through seasonal and spatial variability assessments, this method successfully predicted forage nutritive quality, enabling effective grazing management. Yet, large calibration datasets are required for application.

**Livestock Performance in Silvopastoral Systems**

Productivity of livestock in silvopastoral systems is mostly based on forage quality and all-year-round availability (Dagar, and Gupta, 2020). Understory forage only in arid, semi-arid, or drought-prone environments might be inadequate to meet the nutritional requirements for economically sound livestock production. Silvopastoral systems mitigate this by providing supplementary feeds, including leaves and pods of trees, to ensure the maintenance of livestock and poultry, particularly in drought-prone and temperate agroforestry ecosystems (Dupraz et al., 2018).

**Pent and Fike (2019)** examined lamb productivity in two silvopastoral systems and an open pasture while determining the feasibility of honey locust pod supplementation in temperate agroforestry. Silvopasture was established through thinning 17-year-old black walnut and honey locust stands. Lambs in the honey locust silvopasture were initially given a combination of pod-wheat grain supplementation, while others in other systems were supplied with wheat grain alone. Even though the lambs were not used to honey locust pods in the beginning, they started eating them willingly in the fourth week. The experiment ended with a conclusion that the animals need an adaptation period to acquire preference for the pods and productivity was equal across all systems.

**Ascencio-Rojas et al. (2019)** examined the chemical composition and in vivo rumen degradation of six Mexican shrubs and trees, namely *Diphysa robinioides, Gliricidia sepium, Erythrina americana, Bursera simaruba, Bambusa vulgaris,* and *Zanthoxylum riedelianum*. Variations among species and seasons in dry matter and chemical composition were found by the study, with legumes having a higher content of crude protein and digestibility compared to non-legumes. Certain species like *G. sepium,* retained stable nutritional value year-round and served as a dependable source of feed during times of drought.

**Melesse et al. (2019)** evaluated the nutrient content and digestibility of 12 tree species in the tropics for their potential as cattle feed and their ability to mitigate enteric methane emissions. The research named *Moringa stenopetala, Moringa oleifera, Millettia ferruginea, Acacia abyssinica, and Leucaena leucocephala* as important protein supplements for enhancing the nutritional quality of tropical forages. *Sesbania sesban* and *L. leucocephala* were also suggested as calcium and magnesium supplements. *Moringa* spp. and *M. ferruginea* were found suitable for phosphorus supplementation. Leaves of *Acacia nilotica, Prosopis juliflora, Cajanus cajan*, and *M. pods* were named. ferruginea were identified as promising candidates for minimizing methane emissions. The authors proposed additional studies on combining these plant materials with grasses and agro-industrial residues to maximize protein availability while reducing methane emissions in ruminant animals.

**Advantages of Silvopastoral Systems**

The productivity and quality of forage crops cultivated within silvopastoral systems play a crucial role in determining the cattle carrying capacity of paddocks and the overall economic viability of these systems (Cubbage et al., 2012). The presence of trees affects light and water availability and may also introduce root competition for essential nutrients. Consequently, depending on system design and forage selection, trees can influence forage yield and nutritional composition. Silvopastoral systems provide multiple ecological, economic, and social benefits that contribute to sustainable livestock production and environmental conservation (Alonso, 2011). These systems enhance resource efficiency and promote resilience in livestock farming communities.

**Improved Fodder Supply:** The inclusion of high-yielding forage crops, nitrogen-fixing legume plants, and multipurpose fodder trees provides a year-round balanced feed supply. This diversification decreases dependence on external commercial feeds, improves nutritional quality, and minimizes seasonal deficits. These systems also improve soil fertility through increased organic matter content and nutrient recycling, further enhancing sustainable livestock production (Sales-Baptista et al., 2021).

**Soil Health Enhancement:** Tree roots grow deep into the ground, structuring the soil by fracturing sealed layers, promoting water percolation, and minimizing runoff. The roots of trees stabilize soil, limiting erosion and soil degradation. Moreover, the trees add nutrients back into the soil by decomposing litter, infusing the soil with organic carbon and vital minerals. The incorporation of nitrogen-fixing species adds extra fertility to the soil, aiding in sustainable forage development and long-term farm productivity (Dubeux et al., 2015).

**Livestock Productivity:** Improved quality of fodder, multiple sources of nutrients, and shade significantly mitigate heat stress in animals, resulting in enhanced metabolic efficiency, better weight gain, increased reproductive success, and more milk production. The systems also promote better animal welfare through less physiological stress, less prevalence of diseases, and better overall health and longevity of the livestock (Jose et al., 2019).

**Carbon Sequestration & Climate Resilience:** The incorporation of trees, forage crops, and livestock increases carbon sequestration by fixing atmospheric carbon dioxide in biomass and soil. This reduces greenhouse gas emissions from livestock production while enhancing soil organic matter and ecosystem health. Moreover, these systems serve as natural buffers against climate change by alleviating temperature extremes, enhancing moisture retention, and improving biodiversity resilience, thus maintaining long-term sustainability of livestock production (Montagnini et al., 2013).

**Biodiversity Conservation:** The combination of various plant species forms a haven for pollinators, beneficial insects, and wildlife, and provides ecological interactions that improve ecosystem stability. Silvopastoral systems support multiple flora and fauna, which helps in natural pest management, enhances soil microbiota, and enhances food web processes (Torres-Manso et al., 2018). Silvopastoral systems also conserve native plant species and enhance genetic diversity, which ensures ecosystem resilience in the face of environmental change.

**Economic Advantages:** Silvopastoral systems provide various income sources through fodder production, timber of high value, livestock commodities, and by-products like manure and biogas. This diversification improves the economic resilience of farmers by minimizing dependence on single income sources, countering economic risk from market variations, and providing a constant flow of cash all year round. The systems also reduce input costs through enhanced utilization of on-farm resources, minimizing dependence on costly external feeds, and increased farm profitability (Devendra, 2014).

**Water Conservation:** Enhanced soil organic matter, deep-rooted plants, and increased ground cover greatly enhance water infiltration and storage, lowering surface runoff and soil erosion (Huertas et al., 2021). These enhancements reduce the frequency of irrigation, allowing for sustainable water management, especially in arid and semi-arid areas. Tree canopies also lower evapotranspiration rates, preserving soil moisture content and enhancing the resistance of agricultural landscapes to long-term droughts and climate change.

**Pest and Disease Management:** A diverse plant ecosystem promotes natural pest control by supporting predator species, interfering with the life cycle of pests, and minimizing the incidence of monoculture-related pests and diseases. Further, the coexistence of various plant species helps to sustain beneficial microbes and insects that aid in biological pest management, reducing chemical pesticide use and creating a more healthy environment (Gabriel, 2018).

**Sustainable Land Use:** These systems maximize land use efficiency by combining trees, forage crops, and livestock within the same landholding, thus maximizing use and productivity of resources. They prevent overgrazing, minimize soil erosion, increase biodiversity, and promote long-term land sustainability. Silvopastoral systems also promote ecological balance by preserving soil health, enhancing carbon sequestration, and maintaining resilience to environmental degradation (Broom, 2017).

**Enhanced Farmer Livelihoods:** The long-term productivity and sustainability of silvopastoral systems help improve rural livelihoods by ensuring stable sources of income, lowering the cost of production, and enhancing food security (Yadav et al., 2019).

**Challenges and Restrictions in Silvopastoral Systems**

One of the main difficulties in silvopasture development is the effective establishment of trees in livestock-grazed paddocks. Newly planted seedlings are frequently browsed, whereas established trees are debarked, both of which affect growth and survival. In a study on the diurnal activity of Kiko goats in southern-pine silvopastoral systems in Alabama, USA, by Karki et al. (2019), goats were found to spend around 2% of their time debarking trees. In the same vein, Nicodemo and conducted a review of bark stripping in silvopastoral systems and found several contributing factors. They include dietary insufficiencies (fiber, protein, energy, and minerals), social learning, post-ingestive feedback, stress, and boredom. In a bid to mitigate bark stripping, they recommended several methods: increasing the quality of pasture, dietary supplementation with some critical nutrients, optimum stocking, enhancing animal comfort, giving the environment some kind of enrichment, addition of tannin content to diets, avoidance of mixes between naive and experienced animals, applying proper health and parasite management, and selection of less susceptable tree species to browsing.

**Land Availability and Tenure Challenges:** Small farm holding sizes, split ownership, and pending tenure conflict challenges the massive deployment of silvopastoral systems through restricted scalability and long-term sustainability.

**Initial Investment & Farmer Literacy:** Extensive initial investment and technical capabilities required for establishing such systems create significant challenges towards widespread deployment by restricting the access of rural farming communities to requisite initial investment and technical know-how.

**Competition for Resources:** Forage crops and trees compete for vital resources like water, space, and nutrients, necessitating careful species choice, suitable spacing, and productive management strategies to maximize productivity and sustainability.

**Policy and Institutional Gaps:** Poor policy regimes, a lack of economic incentives, and a shortage of extension services hamper the widespread adoption and successful implementation of silvopastoral practices.

**Future Prospects and Recommendations**

**Research and Development:** Selection and assessment of region-specific forage and tree combinations to improve productivity, enhance soil fertility, and maximize livestock nutrition.

**Policy Support:** Integrating silvopastoral systems into national livestock development plans, agroforestry regulations, and sustainable land-use plans to improve adoption and scalability.

**Capacity Building:** Integrated training packages for farmers, extension agents, and stakeholders to share knowledge on optimal management practices, effective use of resources, and sustainable livestock rearing methods.

**Public-Private Partnerships:** Interactive collaboration between government agencies, research institutions, and private companies with the objective of easing financial investment, technology improvement, and knowledge transfer for increased implementation and scalability of silvopastoral systems.

**Conclusion**

Silvopastoral systems offer a long-term solution to fodder deficits and increasing livestock productivity in India. Through the combination of trees, forage crops, and livestock, the systems ensure environmental sustainability, economic efficiency, and climate resilience. Enhanced research, policy support, and farmer awareness can drive their increased adoption, promoting long-term prosperity for the livestock industry and rural livelihoods.

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