**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, conserve biodiversity, and promote the sustainable rearing of livestock. These systems play a crucial role in enhancing 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. However, its sustainability is under threat due to challenges such as fodder shortages, land degradation, and climate change. Silvopastoral systems offer a viable alternative by integrating multipurpose tree species, nutrient-rich forage crops, and resilient livestock species in a synergistic manner. These systems improve soil fertility, enhance carbon sequestration, reduce heat stress in animals, and ensure year-round fodder availability. This review examines the importance, structure, advantages, disadvantages, and future scope of silvopastoral systems in India, focusing on their role in enhancing fodder productivity and ensuring livestock sustainability under changing climatic conditions.

**Keywords:** Silvopastoral, livestock, forage crops and conservation diversity

**Introduction**

Livestock rearing in India is a vital sector of the farm economy, providing milk, meat, draught power, and employment to countless rural families (Phand and Das, 2022). The livestock sector plays a crucial role in ensuring food security and contributing to the national GDP (Metaferia et al., 2011). However, it faces significant challenges, including fodder shortages, shrinking pasturelands, land degradation, and the adverse effects of global climate change (Thornton et al., 2007). Additionally, historical pasturelands are increasingly being converted for other uses, such as urbanization, intensive monoculture agriculture, and deforestation, further intensifying 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 integrate tree crops with grazing pastures or fodder cultivation, while agrosilvopastoral systems combine livestock with crops, multifunctional hedgerows, woodlots, or fodder trees (Moreno and Rolo, 2019). These systems exhibit significant 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 include establishing high-density tree and shrub plantations in pastures, implementing cut-and-carry systems where livestock are fed with leaves from specific plantings, and cultivating fast-growing shrubs and trees for use in fencing and windbreak systems (Nair et al., 2021).



(Source, Lemes et al., 2021)

Fig 1: A hypothetical model of thermal comfort for livestock sustainability

Figure 1 shows 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 can be managed either intensively or extensively. Intensive systems involve cultivating fodder shrubs at high densities (4,000–40,000 plants per hectare) alongside enhanced tropical grasses and trees or palms, which are planted at densities of 100–600 trees per hectare (Dagar & Gupta, 2020). These systems typically adopt rotational grazing methods characterized by high stocking rates, short grazing periods, and long recovery periods (Donaghy et al., 2021). In contrast, semi-intensive silvopastoral systems incorporate three levels of vegetation—shrubs with edible leaves, trees that also produce edible foliage, and pasture (Vega Quintero, 2024). These systems generate higher plant biomass and animal production than conventional pasture-based systems, while also allowing the harvest of tree and shrub foliage for livestock feed during periods of drought (Gabriel, 2018).

Silvopastoral systems are practiced worldwide, either through farmers' intentional adoption or as a result of the natural evolution of ecosystems that provide protection and ecological services (Moreno & Rolo, 2019). Notable examples include the Dehesa and Montado ecosystems of the *Iberian Peninsula*, the El Chaco region of South America, and various landscapes across Africa and Asia (Verdade et al., 2011). In Argentina, forest-pasture systems have expanded significantly, covering more than 34 million hectares, including both communal and indigenous lands.

In North America and Europe, there is growing interest in integrating trees and shrubs into farming systems for purposes such as wood, fruit, and nut production, as well as windbreaks or supplementary livestock feed through direct browsing or post-pruning coppicing. Similarly, Australian farmers have established high-density *Leucaena* plantations intercropped with grasses (Adegbeye et al., 2024).

Silvopastoral systems promote sustainable land management by enhancing cattle production through natural ecological processes (Pezo et al., 2018). They improve resource efficiency and provide numerous environmental benefits, including reducing deforestation and land degradation, improving soil fertility through nutrient uptake from deeper soil layers, and maximizing water retention and infiltration capacity (Sileshi et al., 2020). Additionally, these systems regulate the hydrological cycle by minimizing runoff, sequestering carbon in above- and below-ground biomass, and fostering 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)

Additionally, silvopastoral systems enhance animal well-being by providing greater nutritional access than conventional pasture systems, alleviating heat stress through natural shading, and offering shelter that reduces fear and anxiety while lowering the risk of ectoparasites (Broom et al., 2013). By utilizing livestock breeds well-suited for tropical conditions, intensive silvopastoral systems can achieve high productivity levels through the use of high-quality, locally sourced feed resources (Kumar et al., 2024). Furthermore, the integration of nitrogen-fixing crops eliminates the need for synthetic fertilizers, while improved forage quality reduces dependence on external nutritional supplements (Abdel-Raouf et al., 2012).

Given that India has the world’s largest livestock population, ensuring sufficient and sustainable fodder resources is critical (Singh et al., 2022). The current fodder shortage, estimated at 30–40% annually, significantly impacts livestock productivity and rural livelihoods (Dhamodharan et al., 2024). Climate change, overgrazing, and the shrinking size of traditional grazing areas further exacerbate this issue. Therefore, there is an urgent need to establish a sustainable and resilient fodder supply system (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, enhance soil fertility, and improve livestock productivity (Jose & 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**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **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) |

**Table-4: Shrub Species Used in Silvopastoral Systems**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **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-5. Grass Species Used in Silvopastoral Systems**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **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, as a form of agroforestry, present a viable and sustainable option (Vandermeulen et al., 2018). By integrating multipurpose trees, high-yielding pasture grasses, and livestock in a mutually beneficial relationship, these systems maximize land use efficiency, enhance biodiversity, and promote soil health (Machebe et al., 2023). Additionally, silvopastoral practices sequester carbon, improve microclimatic conditions, and generate economic benefits by diversifying farmers' income sources (Chappa et al., 2024). Consequently, these systems have become a crucial approach to ensuring long-term sustainability in India's livestock industry.

**Table-6. 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 represent a sustainable livestock production strategy that balances productivity with environmental stewardship (Jose & Dollinger, 2019). Integrating trees, forages, and livestock into a well-organized system enhances soil fertility, biodiversity, and economic resilience for farmers (Haddad et al., 2021). With proper planning and management, silvopastoral systems offer a practical solution for sustainable agriculture across various climatic regions (Louhaichi et al., 2022).

**Table 7. 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) | 33,000–35,000seedlings 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 forone 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 such as *Leucaena leucocephala, Acacia nilotica, Albizia lebbeck,* and *Prosopis cineraria* provide high-quality fodder, shade, and soil enrichment through nitrogen fixation and organic matter contribution (Rao, 2002). These trees also help sequester carbon, regulate microclimate by controlling temperature and humidity, and act as windbreaks, reducing soil and water loss (Raj, 2017). Additionally, they serve as sources of firewood, timber, and medicinal products, offering multiple benefits to farmers and rural communities. In silvopastoral systems, trees play a crucial role by enhancing soil fertility, providing fodder, and offering shade. Incorporating fruit and timber trees can further increase economic returns (Dagar and Gupta, 2020).

**Forage Component**: Leguminous species (e.g., *Stylosanthes spp., Medicago sativa*) and perennial grasses (e.g., *Cenchrus ciliaris, Panicum maximum*) play a vital role in enhancing fodder availability and improving soil fertility through nitrogen fixation and organic matter accumulation (Jank et al., 2019). These forages enhance livestock nutrition, leading to higher milk production, better meat quality, and overall improved animal health. Their deep root systems improve soil structure and water retention, increasing drought resistance (Ponnampalam et al., 2022). By incorporating diverse, high-yielding forage species, silvopastoral systems can significantly reduce reliance on costly commercial feed, ensuring greater economic sustainability for farmers (Pezo et al., 2018).

**Table 8. 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 consists of grasses, legumes, and shrubs, serving as the primary feed source for livestock (Tarawali, 1995). Drought-resistant, high-yielding species such as Guinea grass, Buffel grass, and leguminous forages are widely cultivated. The selection of forage species is based on climate, soil conditions, and livestock nutritional 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, boosts reproductive efficiency, and reduces mortality rates (Capstaff & Miller, 2018). Effective grazing management ensures the sustainable use of fodder, while rotational grazing prevents overgrazing and promotes pasture regrowth.

Silvopastoral systems further enhance livestock well-being by providing shade, alleviating heat stress, and reducing exposure to adverse climatic conditions, ultimately improving productivity and profitability for farmers. Livestock species such as goats, sheep, and cattle play a crucial role in these systems, contributing to vegetation management and nutrient cycling through grazing (Cuartas Cardona et al., 2014). Maintaining appropriate stocking rates and adopting rotational grazing practices help sustain pasture health and prevent overgrazing (de Faccio Carvalho et al., 2010).

**Table 9. 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. Techniques such as mulching, contour planting, and agroforestry trenches help minimize soil erosion and enhance water retention (Xing & Wang, 2024). Trees within the system improve soil structure and organic matter content, leading to better moisture conservation and increased fertility (Fahad et al., 2022).

**Biodiversity and Ecosystem Services**

Silvopastoral systems enhance biodiversity by creating diverse habitats for wildlife and beneficial microorganisms (Yadav et al., 2019). They contribute to ecological balance by supporting a variety of plant species, which helps reduce the prevalence of pests and diseases. Additionally, silvopastoral systems play a crucial role in carbon sequestration by capturing atmospheric carbon in biomass and soil, thereby mitigating 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, enriching it by replenishing essential nutrients (Ayamba, 2021). Effective manure management practices such as composting and controlled grazing enhance nutrient availability while minimizing environmental pollution (Ayilara et al., 2020).

**Economic and Social Benefits**

The diversified production system of silvopasture enhances farmers' economic resilience by providing multiple income sources, including livestock, timber, fruits, and fodder sales. Additionally, these systems generate employment opportunities in tree planting, forage management, and livestock rearing, thereby improving rural livelihoods (Vijay Kumar et al., 2014).

**The Need for Alternative Farming Systems**

Given the increasing challenges posed by climate change, land degradation, and fodder shortages, alternative farming systems like silvopasture have become essential. These systems promote sustainable land use, enhance soil fertility, and improve farm productivity while reducing environmental impact. By integrating trees, forage crops, and livestock, silvopastoral systems ensure long-term agricultural sustainability and economic stability for farmers.

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

Traditional farming systems have contributed to extensive environmental degradation, leading to soil nutrient depletion and the overexploitation of natural resources (Lal, 2009). The decline in soil fertility reduces farm productivity, often forcing farmers to expand agricultural land—an action that accelerates deforestation and increases environmental pollution (Hossain et al., 2020). Additionally, global warming, coupled with a rapidly growing human population, has placed immense pressure on global food security. Given these challenges, there is an urgent need to develop sustainable production systems that enhance food production while conserving natural resources and mitigating deforestation (Newton et al., 2013).

**Silvopastoral Research in Mexico**

A five-year Mexican research project, adapted from a national initiative, investigated silvopastoral systems (SPS) as an alternative to traditional livestock farming in tropical regions (Erales Villamil et al., 2017). Conducted in the Tepalcatepec Valley of Michoacán, the study aimed to assess the benefits and challenges of SPS compared to conventional ranching practices (Villamil, 2017).

The project surveyed 115 farmers to analyze key farm characteristics, including livestock populations, cattle breeds, farming and feeding systems, animal performance, commercialization strategies, and health management practices. Additionally, it evaluated the evolution of various national SPS programs to identify research gaps, collaboration needs, stakeholder education requirements, and implementation challenges in Mexico (Nigenda et al., 2015).

A comprehensive system analysis was conducted, examining carbon sequestration, biodiversity, soil health, nutrient cycling, and large-scale ecological processes such as the water cycle (Feng et al., 2024). Precise measurement of the economic and environmental impacts of SPS was a top research priority. Furthermore, the study emphasized the need for improved communication and coordination among scientists, government agencies, and stakeholders to enhance research effectiveness and facilitate the successful implementation of SPS practices (Abera, 2016).

**Animal Health Component of the Study**

One of the key areas of focus in this research was the examination of livestock health in silvopastoral system (SPS) farms. The study documented traditional animal health practices and identified common cattle diseases in the region (Mahato, 2004). To improve disease surveillance, a community-based livestock syndromic surveillance system was implemented for two years across five farms (Kijazi, 2023). Farmers' reports were cross-checked with veterinarians' findings to ensure accuracy and validity. Disease incidence rates were calculated monthly across different cattle categories (adults, growers, and calves), and the most frequent and economically significant syndromes were identified (Renault et al., 2028). The strong correlation between farmer observations and veterinary assessments confirmed the reliability of this community-based approach.

Additionally, the research analyzed the risk of bovine tuberculosis introduction into the silvopastoral epidemiological compartment (Erales Villamil et al., 2017). Using @Risk™ software, six different scenarios were simulated to estimate the probability of disease introduction through replacement heifers and sires (Villamil, 2017). The analysis considered the national bovine tuberculosis control and eradication program, regional disease prevalence, and contemporary cattle management practices in the Tepalcatepec Valley. Findings revealed that the lowest probability of tuberculosis introduction occurred when replacement cattle underwent both the tuberculin caudal fold test and the cervical comparative test simultaneously.

**Economic and Social Barriers to Adoption**

Despite the clear benefits of silvopastoral systems—including environmental sustainability, higher productivity, and economic profitability—several barriers hinder their widespread adoption (Lee et al., 2020). One of the most significant challenges is the high initial capital investment required for SPS implementation, as many small-scale farmers lack the necessary financial resources. To promote SPS adoption, measures such as low-interest loans, credit programs, and government subsidies should be considered (Alam & Tomossy, 2017).

Additionally, better cost estimation for establishing SPS is essential. The first three years of production tend to be the most financially demanding. However, revenue from timber and fruit production could help offset these initial costs, making the system more economically viable in the long run (Dawson et al., 2014).

**Scaling Up Silvopastoral Systems in the Future**

o fully harness the potential of silvopastoral agriculture, further research is needed to refine economic models, quantify ecological benefits, and assess its impact on both animal and human health (Smith et al., 2022). Expanding knowledge on diverse tree, forage, and livestock species combinations will facilitate the development of optimized SPS configurations suited to various ecological zones (Lecegui et al., 2022).

Despite its promise, research funding for silvopastoral systems remains limited. However, increasing consumer demand for environmentally sustainable livestock products presents an opportunity for market-driven reforms. Greater public awareness and support for sustainable agriculture can also encourage investment from government agencies, industry stakeholders, and non-governmental organizations, ultimately enhancing agricultural resilience to climate change (Ignaciuk, 2015).

By combining ecological sustainability with farm productivity, silvopastoral systems provide a viable pathway toward resilient and sustainable farming (Haddad et al., 2021). As research and policy efforts continue to gain momentum, large-scale adoption of SPS could significantly contribute to global food security, carbon sequestration, and biodiversity conservation (Solorio, 2017).

**Environmental Benefits of Silvopastoral Systems**

Silvopastoral systems deliver numerous environmental benefits compared to other livestock production methods 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 pasturelands, silvopastoral systems create a more secure agro-landscape that helps mitigate the negative impacts of climate change (Haaland et al., 2021).

One of 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 ability of these systems to sequester and store atmospheric CO₂ is essential for mitigating greenhouse gas emissions and supporting climate-resilient agriculture. Several scientific studies have examined the carbon sequestration capacity of silvopastoral systems, focusing 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). These include improved soil health, biodiversity, water retention, and, most significantly, carbon sequestration. By cultivating trees, shrubs, and forage plants within pasturelands, silvopastoral systems contribute to a more climate-resilient farming landscape, countering the negative impacts of global warming (Vaishnav et al., 2021).

One of the primary environmental benefits of silvopastoral systems is their ability 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 crucial for controlling greenhouse gas emissions and supporting climate-resilient agriculture (Singh and Mishra, 2023). Research has estimated the carbon sequestration capacity of silvopastoral systems, emphasizing their significance for long-term environmental sustainability.

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

**Varsha et al. (2019)** The study analyzed three fodder species in terms of their forage productivity, nutritional quality, and carbon sequestration potential: hybrid Napier grass (*Pennisetum purpureum*), Mulberry (*Morus alba*), and Stylosanthes (*Stylosanthes* sp.), a nitrogen-fixing leguminous plant. The research examined these species both as monocultures and in mixed cropping systems, using two or all three fodder types.

The findings revealed that the hybrid Napier monoculture, which is the most widely adopted system among farmers in southern India, produced the highest forage dry matter. However, despite its high productivity, it had the poorest fodder quality and the lowest carbon storage potential (Raj et al., 2023). In contrast, the Mulberry monoculture exhibited the highest carbon sequestration potential but yielded significantly lower forage production. When comparing crude protein yield and carbon sequestration, the most effective system was a mixed silvopastoral approach combining hybrid Napier and Mulberry trees (Gupta et al., 2020). This combination provided a balanced strategy, optimizing forage production for livestock while enhancing environmental sustainability through improved carbon sequestration and soil enrichment (Adegbeye et al., 2024).

The inclusion of multiple plant species in silvopastoral systems ensures a more stable and diversified ecosystem. The incorporation of nitrogen-fixing plants such as Stylosanthes enhances soil fertility, reducing the need for chemical fertilizers (Epifanio et al., 2020). Additionally, deep-rooted plants like Mulberry improve soil structure and water retention, making the system more resilient to drought conditions (Rahman & Hoque, 2007).

**Carbon Sequestration in Mexican Silvopastoral Systems**

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

Aboveground and root biomass were estimated in this study using allometric models, measuring down to the third deepest level at a 30 cm depth. The results confirmed that both the silvopastoral system and the natural forest retained substantially greater amounts of aboveground biomass compared to the monoculture pasture (Moreno & Rolo, 2019). The highest accumulation of belowground biomass was observed in the silvopastoral system, further demonstrating its capacity for carbon sequestration below ground (Morales Ruiz et al., 2021).

While the natural forest exhibited the highest soil organic carbon (SOC) levels at all depths, the silvopastoral system had a greater total carbon sequestration potential than the monoculture pasture (Amézquita et al., 2004). This finding underscores the ecological benefits of integrating trees into pasturelands, as they enhance carbon capture without compromising agricultural productivity (Aryal et al., 2022). Additionally, the deep-rooted systems of trees such as *Leucaena leucocephala* contribute to soil stabilization, preventing erosion, and improving nutrient cycling.

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

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

As the world's agricultural systems strive to balance food production with environmental preservation, silvopastoral systems present a promising solution. Promoting these practices can lead to more sustainable farming systems that support both economic and environmental sustainability. Investing in research, farmer training, and policy support for silvopastoral practices will be essential for advancing climate-smart agriculture and ensuring a sustainable future for livestock farming.

**Aryal et al. (2019)** study in Mexico compared the carbon storage potential of a multi-tree-based silvopastoral system with that of a traditional open-pasture system. Researchers estimated tree and root biomass using allometric models, along with grass biomass and soil organic carbon (SOC) concentration up to a depth of 15 cm.

The study found that carbon storage in the herbaceous vegetation layer was greater in the silvopastoral system than in the open pasture. A similar trend was observed in SOC content, further reinforcing the higher carbon sequestration potential of silvopastoral systems (Aryal, 2022). These findings underscore that integrating trees and diverse plant species into grazing areas can significantly enhance carbon sequestration, contributing to 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:** The inclusion of multiple plant species in silvopastoral systems supports a diverse range of flora and fauna (Perez-Alvarez et al., 2023). Enhanced biodiversity improves ecosystem stability, boosts pollination, and naturally regulates pest populations without the need for chemical pesticides.

**Soil Health Enhancement:** Deep-rooted trees in silvopastoral systems improve soil aeration and porosity while minimizing erosion (Sharrow et al., 2009). Additionally, the organic matter from tree litter and root exudates enriches soil microbial populations, fostering healthier and more fertile soils.

**Effective Water Management:** The multi-layered vegetation of silvopastoral systems enhances water retention by reducing runoff and maximizing soil infiltration (Vinodhini, 2023). This is particularly beneficial in drought-prone areas, as it helps maintain soil moisture levels for extended periods, reducing dependence on irrigation.

**Mitigation of Livestock Heat Stress:** Trees provide natural shade, creating a more favorable microclimate for grazing animals (Masters et al., 2023). Reduced heat stress improves livestock productivity, leading to better weight gain, increased milk yields, and overall improved animal health.

**Reduction of Greenhouse Gas Emissions:** Silvopastoral systems help lower methane and nitrous oxide emissions by improving forage quality and enhancing ruminant digestion efficiency (Vargas et al., 2022). High-quality forage reduces enteric fermentation, a major source of methane emissions in livestock production.

**Forage Production in Silvopastoral Systems**

The quality and yield of forage grown in silvopastoral systems are crucial factors determining paddock productivity and overall system profitability (Sarvade et al., 2019). Trees influence the availability of key environmental resources such as light, water, and nutrients, potentially leading to competition. Consequently, tree presence can affect forage growth and nutritional content, depending on forage selection and system design.

**Pang et al. (2019)** examined the effects of different light intensities—full sunlight (100%), moderate shade (45%), and dense shade (20%)—on the yield of 43 forage plants. To eliminate root competition and ensure sufficient water and nutrients, the forages were grown in pots. The results indicated that all 43 species had lower yields under full sunlight compared to moderate shade, with 31 species even performing better under dense shade. Additionally, C3 grasses demonstrated greater shade tolerance than C4 grasses. The study emphasized that both legumes and grasses can thrive in agroforestry systems and open pastures, provided root competition is minimized.

Similarly, **Ford et al. (2019)** investigated forage yield, quality, and livestock performance across open pasture, silvopasture, and woodland systems on three Central Minnesota farms with varying soil types. Calf pairs were rotationally grazed on 2-hectare paddocks, and forage was assessed before each grazing cycle. Open pastures produced the highest forage yields, followed by silvopastoral systems, with the lowest yields recorded in woodland systems. However, during drought conditions, silvopastoral systems outperformed both woodland and open-pasture systems. While forage quality varied by season and site, the overall impact of the production system on forage quality was minimal, and livestock productivity remained comparable across all systems.

**Fannon et al. (2019)** conducted a similar study in Appalachia, comparing open pastures to 8-year-old honey locust and black walnut silvopastoral systems. Pre-grazing forage biomass was consistently higher in open pastures than in honey locust or black walnut silvopastures, though honey locust systems produced more summer forage than black walnut systems. Post-grazing biomass followed the same trend, while forage quality remained similar across all systems, with no observed impact on hair sheep carcass attributes.

**Clavijo et al. (2019)** explored a different silvopastoral approach by incorporating perennial cool-season grasses into commercial poplar plantations in Argentina’s Paraná River delta. Comparisons between sown and unsown plots revealed minor differences in summer forage yield, but production gradually increased through autumn, peaking in winter. The study concluded that integrating grass into poplar stands could raise cattle carrying capacity from zero to 0.2 cows per hectare in autumn, with a tenfold increase during winter.

Given the extensive spatial and seasonal variability of understory forest forages, their quality may not always be sufficient to support grazing. Mendarte et al. (2019) developed a VIS-NIRS-based rapid assessment method to evaluate the nutritive quality of Pinus radiata understory shrubs, such as *Rubus* sp. and *Ulex gallii*. This method successfully predicted forage quality by accounting for seasonal and spatial variations, facilitating more effective grazing management. However, its practical application requires large calibration datasets.

**Livestock Performance in Silvopastoral Systems**

The productivity of livestock in silvopastoral systems is primarily determined by forage quality and its year-round availability (Dagar and Gupta, 2020). In arid, semi-arid, or drought-prone environments, understory forage alone may be insufficient to meet the nutritional requirements necessary for economically viable livestock production. Silvopastoral systems address this challenge by providing supplementary feeds, including the leaves and pods of trees, to sustain livestock and poultry, particularly in drought-prone and temperate agroforestry ecosystems (Dupraz et al., 2018).

**Pent and Fike (2019)** investigated lamb productivity in two silvopastoral systems and an open pasture while evaluating the feasibility of honey locust pod supplementation in temperate agroforestry. The silvopasture was established by thinning 17-year-old black walnut and honey locust stands. Lambs in the honey locust silvopasture initially received a combination of pod-wheat grain supplementation, whereas those in other systems were provided wheat grain alone. Although the lambs were unfamiliar with honey locust pods at first, they began consuming them voluntarily by the fourth week. The study concluded that animals require an adaptation period to develop a preference for the pods, and productivity remained comparable across all systems.

**Ascencio-Rojas et al. (2019)** analyzed the chemical composition and in vivo rumen degradation of six Mexican shrubs and trees: *Diphysa robinioides, Gliricidia sepium, Erythrina americana, Bursera simaruba, Bambusa vulgaris,* and *Zanthoxylum riedelianum*. The study found variations in dry matter content and chemical composition across species and seasons, with leguminous species exhibiting higher crude protein levels and digestibility than non-leguminous ones. Notably, *G. sepium* maintained a stable nutritional profile year-round, making it a reliable feed source during periods of drought.

**Melesse et al. (2019)** assessed the nutrient composition and digestibility of 12 tropical tree species for their potential use as cattle feed and their ability to mitigate enteric methane emissions. The research identified *Moringa stenopetala, Moringa oleifera, Millettia ferruginea, Acacia abyssinica,* and *Leucaena leucocephala* as valuable protein supplements for improving tropical forage quality. Additionally, *Sesbania sesban* and *L. leucocephala* were suggested as important sources of calcium and magnesium, while *Moringa* spp. and *M. ferruginea* were recognized for their phosphorus supplementation potential. The study also highlighted *Acacia nilotica, Prosopis juliflora, Cajanus cajan,* and *M. ferruginea* pods as promising candidates for reducing methane emissions. The authors recommended further research on integrating these plant materials with grasses and agro-industrial residues to enhance protein availability while minimizing methane emissions in ruminant livestock.

**Advantages of Silvopastoral Systems**

**The Role of Forage Crops in Silvopastoral Systems**

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

**Key Benefits of Silvopastoral Systems**

**1. Improved Fodder Supply**

The inclusion of high-yielding forage crops, nitrogen-fixing legume plants, and multipurpose fodder trees ensures a year-round balanced feed supply. This diversification reduces reliance on external commercial feeds, improves nutritional quality, and minimizes seasonal feed deficits. Additionally, these systems enhance soil fertility by increasing organic matter content and promoting nutrient recycling, further supporting sustainable livestock production (Sales-Baptista et al., 2021).

**2. Soil Health Enhancement**

Deep-rooted trees in silvopastoral systems improve soil structure by breaking compacted layers, enhancing water percolation, and reducing surface runoff. These roots stabilize the soil, limiting erosion and degradation. Additionally, decomposing tree litter enriches the soil with organic carbon and essential minerals. The incorporation of nitrogen-fixing species further enhances soil fertility, supporting long-term forage productivity (Dubeux et al., 2015).

**3. Livestock Productivity**

High-quality fodder, diverse nutrient sources, and shade significantly reduce heat stress in animals, leading to improved metabolic efficiency, better weight gain, increased reproductive success, and higher milk production. Furthermore, silvopastoral systems enhance animal welfare by reducing physiological stress, lowering disease prevalence, and improving overall livestock health and longevity (Jose et al., 2019).

**4. Carbon Sequestration & Climate Resilience**

The integration of trees, forage crops, and livestock promotes carbon sequestration by capturing atmospheric carbon dioxide in biomass and soil. This process reduces greenhouse gas emissions from livestock production while improving soil organic matter and ecosystem health. Moreover, silvopastoral systems act as natural buffers against climate change by mitigating temperature extremes, enhancing moisture retention, and strengthening biodiversity resilience, thereby supporting long-term livestock sustainability (Montagnini et al., 2013).

**5. Biodiversity Conservation**

By incorporating diverse plant species, silvopastoral systems create habitats for pollinators, beneficial insects, and wildlife. These ecological interactions contribute to ecosystem stability by facilitating natural pest control, enhancing soil microbiota, and supporting food web processes. Additionally, silvopastoral systems help conserve native plant species and promote genetic diversity, ensuring resilience against environmental changes (Torres-Manso et al., 2018).

**6. Economic Advantages**

Silvopastoral systems offer multiple revenue streams, including fodder production, high-value timber, livestock commodities, and by-products such as manure and biogas. This diversification enhances farmers' financial resilience by reducing reliance on a single income source, mitigating risks from market fluctuations, and ensuring a steady cash flow throughout the year. Additionally, these systems lower input costs by maximizing on-farm resource utilization and reducing dependence on costly external feeds, thereby improving overall farm profitability (Devendra, 2014).

**7. Water Conservation**

Increased soil organic matter, deep-rooted plants, and extensive ground cover enhance water infiltration and retention, reducing surface runoff and soil erosion (Huertas et al., 2021). These improvements decrease irrigation frequency, enabling sustainable water management, particularly in arid and semi-arid regions. Additionally, tree canopies lower evapotranspiration rates, preserving soil moisture and increasing agricultural resilience to droughts and climate change.

**8. Pest and Disease Management**

A diverse plant ecosystem fosters natural pest control by supporting predator species, disrupting pest life cycles, and reducing the occurrence of monoculture-related pests and diseases. The coexistence of various plant species sustains beneficial microbes and insects, contributing to biological pest management. This reduces the need for chemical pesticides, creating a healthier farming environment (Gabriel, 2018).

**9. Sustainable Land Use**

Silvopastoral systems maximize land efficiency by integrating trees, forage crops, and livestock within the same land area, optimizing resource use and productivity. These systems prevent overgrazing, minimize soil erosion, enhance biodiversity, and promote long-term land sustainability. Furthermore, they contribute to ecological balance by preserving soil health, enhancing carbon sequestration, and increasing resilience to environmental degradation (Broom, 2017).

**10. Enhanced Farmer Livelihoods**

The long-term productivity and sustainability of silvopastoral systems improve rural livelihoods by ensuring stable income sources, lowering production costs, and enhancing food security. By fostering economic stability and ecological sustainability, these systems empower farming communities and support rural development (Yadav et al., 2019).

**Challenges and Restrictions in Silvopastoral Systems**

One of the primary challenges in developing silvopastoral systems is the successful establishment of trees in livestock-grazed paddocks. Newly planted seedlings are often browsed by animals, while mature trees may suffer from debarking, both of which can hinder growth and survival.

A study by Karki et al. (2019) on the diurnal activity of Kiko goats in southern-pine silvopastoral systems in Alabama, USA, found that goats spent approximately 2% of their time debarking trees. Similarly, Nicodemo conducted a review of bark stripping in silvopastoral systems and identified several contributing factors, including:

**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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