



RESEARCH ARTICLE

Agroecological assessment of silvi-horticultural land-use systems in Theni District, Tamil Nadu: Economic performance and ecosystem services

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Abstract

The silvi-horticultural system, a key agroforestry practice integrating fruit-bearing trees with understory horticultural crops, delivers significant multidimensional benefits, including economic returns and ecological services. This study presents a comprehensive economic valuation and ecosystem services documentation of the silvi-horticultural system as practised by 40 farmers across five taluks of Theni District, Tamil Nadu. Data were collected through a structured pilot survey administered in May 2026, covering socioeconomic profiling, land and system details, cost-and-return analysis using the farm-budget methodology and a four-category ecosystem services documentation framework encompassing provisioning, regulating, supporting and cultural services. Results indicate that the system generates a mean total gross return (GR) of ₹118913 per acre (95 % confidence interval (CI): ₹106276–131551) against a total cost of cultivation (TC) of ₹66682 per acre, yielding a benefit–cost ratio (BCR) of 1.82 over total cost (95 % CI: 1.60–2.04) and 2.57 over variable cost (95 % CI: 2.25–2.89), both significantly above the economic-viability threshold of 1.0 (one-sample *t*-test, $p < 0.001$). Net returns over total cost averaged ₹52231 per acre (95 % CI: ₹38612–65850), significantly greater than zero ($p < 0.001$). Ecologically, farmers reported shade provision on 97.5 % of farms, temperature reduction on 90.0 %, reduced soil erosion on 82.5 % and increased bird species richness on 80.0 % of farms. These are self-reported perceptions rather than independently measured effects and should be interpreted with the recall-bias and no-control-group caveats detailed in the discussion. The dominant species combination mango (*Mangifera indica* L.) and jackfruit (*Artocarpus heterophyllus* Lam.) as tree components and cardamom (*Elettaria cardamomum* (L.) Maton) and pepper (*Piper nigrum* L.) as intercrops, represents an ecologically complementary and economically productive arrangement well-suited to the foothills of the Western Ghats in Theni District.

Keywords: agroforestry economics; benefit–cost analysis; ecosystem service valuation; farm-budget survey; pilot study; smallholder livelihoods; total economic value

Introduction

Agroforestry, the intentional integration of trees with crops and/or livestock on the same unit of land, is increasingly recognised as a transformative land-use strategy that simultaneously enhances agricultural productivity, ecosystem resilience and rural livelihoods. Globally, agroforestry systems are practised on over 1 billion hectares and support the livelihoods of more than 1.3 billion smallholder farmers (1). The millennium ecosystem assessment (MA) recognised agroforestry as a land-use configuration capable of delivering services across all four ecosystem service categories provisioning, regulating, supporting and cultural without compromising productive output (2). Among its diverse configurations, the silvi-horticultural system, defined as the deliberate combination of forestry or fruit trees with horticultural crops on the same unit of land, occupies a particularly

significant position in the smallholder farming landscape of peninsular India (3). The integration of high-value spice crops under fruit-tree canopies exemplifies an ecologically efficient arrangement wherein canopy stratification minimises resource competition while maximising overall land productivity (4, 5).

Theni District in Tamil Nadu occupies a transitional position between the semi-arid Madurai plains and the humid Western Ghats, spanning elevations from 100 m to over 2000 m above mean sea level. The district is renowned for its spice production, particularly cardamom, pepper and turmeric, traditionally cultivated under the natural shade of forest and fruit trees for centuries. This indigenous shade-based cultivation system constitutes a de facto silvi-horticultural arrangement that predates formal agroforestry categorisation. One study documented the critical role of shade-grown cardamom gardens as biodiversity refugia in the Western Ghats landscape (6) and

another identified the Western Ghats as one of the world's 36 biodiversity hotspots, lending heightened ecological significance to any land-use system that maintains canopy cover and structural complexity in its buffer zone (7). The premium economic value of shade-grown cardamom is consistently ₹900–1500 per kg above sun-grown equivalents, owing to superior flavour profiles (8).

The economic performance of silvi-horticultural systems in peninsular India has been studied across multiple states. A comprehensive multi-state review reported that agroforestry systems consistently yield benefit-cost ratio (BCR) values of 1.4–3.1 compared to 1.0–1.5 for monoculture equivalents, attributing the advantage to product diversification and land-use efficiency gains arising from complementary root architectures and microclimate interactions (9). Mango-spice combinations studied in Kerala and Karnataka reported BCRs of 1.7–2.4 (5), while another study demonstrated that integration of fruit trees with shade-tolerant spice crops increased intercrop yields by 15–25 % through canopy complementarity, findings that provide a directly relevant benchmark against which the present study's self-reported mean yield increase of 21.77 % among surveyed farmers can be cautiously compared (10). India's National Agroforestry Policy formally recognises agroforestry as a pillar of climate-smart agriculture and explicitly encourages fruit-tree-spice intercropping in peninsular states as a model for simultaneously enhancing smallholder incomes and ecological resilience (11).

The ecosystem services dimension of tree-spice systems has received substantial attention in the literature. One review identified agroforestry as a provider of significant regulating services, including soil conservation, microclimate regulation, carbon sequestration and water cycle stabilisation, all of which operate synergistically to enhance crop productivity (12). For tree-crop systems in tropical landscapes, another study demonstrated that mature fruit-tree canopies reduce soil temperature by 2–4 °C and increase soil moisture retention, creating conditions directly beneficial to shade-tolerant spice crops (13). Soil conservation co-benefits have been extensively quantified. An early review estimated that agroforestry reduces soil erosion by 50–80 % relative to open cultivated fields through litter fall, root reinforcement and canopy interception (14). Biodiversity co-benefits were documented in Nicaragua where fruit-tree dominated agroforestry systems were found to support 60–80 % of bird species present in adjacent natural forests, while pollinator diversity in such systems has a direct productive value through enhanced crop pollination (15). Water regulation is particularly salient in Theni's semi-arid eastern taluks. A study of semi-arid peninsular India quantified significant groundwater recharge improvements under comparable tree-crop systems, a finding with direct policy relevance for the district's rain-shadow zones (16).

Despite this body of evidence, systematic farm-budget analyses of silvi-horticultural systems that simultaneously document ecosystem service generation through primary farmer surveys in Theni District remain sparse. Existing Tamil Nadu agroforestry literature falls short in two specific, identifiable respects. First, it predominantly reports timber-dominated systems, which do not reflect fruit tree-spice crop configurations or aggregates the fruit tree-spice combination into broader agroforestry categories that obscure system-specific values for cost of cultivation, gross and net returns and BCR (17). Second, where system-specific economic data are reported, they are

rarely accompanied by primary, farm-level documentation of the regulating, supporting and cultural ecosystem services generated by the same farms, leaving the joint economic-and-ecosystem-service profile of the fruit tree-spice crop combination largely unquantified in the district. This study addresses this two-part gap through a structured pilot survey of 40 silvi-horticultural practitioners across all five taluks of Theni District and is guided by the working expectation that the mango-jackfruit-cardamom-pepper combination delivers BCR significantly above the economic break-even threshold of 1.0 while concurrently generating measurable co-benefits across all four ecosystem-service categories. The study pursues two primary objectives, tested against this expectation: (i) to compute and analyse the cost of cultivation, gross returns, net returns and BCR of the silvi-horticultural system on a per-acre basis using standardised farm-budget methodology, supported by inferential statistical testing and (ii) to document the ecosystem services like provisioning, regulating, supporting and cultural perceived and quantified by practising farming households across the four MA service categories. The findings are intended to inform policy design around watershed conservation, horticultural development and agroforestry-linked livelihood enhancement in the Western Ghats buffer zone. While the sampling frame is deliberately district-specific, the shade-cultivation conditions, tree-spice combinations and market linkages described are broadly characteristic of comparable foothill taluks elsewhere along the southern Western Ghats, so the findings are expected to carry indicative relevance beyond Theni District even though they are not presented here as a regional generalisation.

Materials and Methods

Study area

The study was conducted in Theni District, located between 9°47' and 10°23' N latitude and 77°0' and 77°52' E longitude in the southern part of Tamil Nadu, India. The district encompasses five administrative taluks: Theni, Bodinayakanur, Periyakulam, Uthamapalayam and Andipatti, covering an area of approximately 3242 km². Elevations range from 100 m in the eastern plains to over 2000 m in the Western Ghats. Mean annual rainfall ranges from 700–2100 mm depending on altitude and proximity to the Ghats. Principal soil types are red loam (45 %), sandy (25 %), black soil (17.5 %) and alluvial (12.5 %). The taluk-wise sample distribution was Theni (11, 27.5 %), Andipatti (10, 25.0 %), Bodinayakanur (7, 17.5 %), Periyakulam (7, 17.5 %) and Uthamapalayam (5, 12.5 %).

Sampling and data collection

A purposive-cum-random sampling technique was employed. Farmers practising the silvi-horticultural system as their primary agroforestry approach were identified through local agricultural extension offices and the Horticulture Department of Theni. A total of 40 farmers were selected, ensuring proportional representation across taluks, land-holding sizes and irrigation types. Data were collected through personal interviews using a pre-tested structured questionnaire during May 2026 by trained enumerators. The instrument captured socioeconomic background (Section A), land-holding and system details (Section B), cost and returns analysis (Section C: Sub-tables C1–C6) and ecosystem services

documentation (Section D: Sub-tables D1–D4).

Ethical considerations

Participation in the survey was voluntary. Verbal informed consent was obtained from each of the 40 respondent farmers before the interview, following an explanation of the study's purpose, the voluntary nature of participation and the intended use of the data for academic and policy research. No personally identifying information is reported. Respondent data are presented only in aggregate or anonymised form. Institutional ethics clearance was obtained through the ethics review procedure of the host institution before data collection.

Analytical framework

Farm budget analysis

Costs were classified into variable costs (change with scale of production) and fixed costs (constant regardless of output). Establishment costs (C1) and annual maintenance costs (C2) were computed separately per acre. The following equations define the economic indicators used throughout this paper:

Total variable cost (TVC) = Variable establishment cost + Variable maintenance cost Eq. (1)

Total fixed cost (TFC) = Fixed establishment cost + Fixed maintenance cost Eq. (2)

Total cost of cultivation (TC) = TVC + TFC Eq. (3)

C2 Cost = TC + Imputed family labour Eq. (4)

Gross returns (GR) = Tree returns + Crop returns + By-product returns Eq. (5)

Net returns over variable cost (NRv) = GR – TV Eq. (6)

Net returns over total cost (NR) = GR – TC Eq. (7)

$BCR(v) = \frac{GR}{TVC}$ Eq. (8)

$BCR = \frac{GR}{TC}$ Eq. (9)

Return per Rupee = $\frac{NR}{TC}$ Eq. (10)

BCR(v): benefit-cost ratio over variable cost.

Ecosystem services documentation

Ecosystem services were documented following the MA classification framework (2). Provisioning services were valued using the market price method; regulating services through structured Yes/No observations supplemented by quantifiable indicators (water table depth, pest incidence change); supporting services through semi-quantitative self-reported indicators; and cultural services through structured perception questions. Frequency analysis (percentage of farmers reporting each indicator) was the primary analytical tool for non-monetised services.

Statistical analysis

In addition to descriptive statistics (means, standard deviations, ranges and frequency percentages), inferential analysis was applied to the sample-level cost-and-returns data using standard formulae for one-sample hypothesis testing. For each key economic indicator (GR, TC, NR, NRv, BCR-TC, BCR-VC), the standard error was computed as $SD/\sqrt{n}$ ($n = 40$) and a one-sample t -test ($df = 39$) was used to test whether the sample mean BCR and

NR differed significantly from the economic break-even values of 1.0 and ₹0 respectively; 95 % confidence intervals were computed as $\text{mean} \pm t_{0.025, 39} \times SE$ (t -critical = 2.023). For key binary ecosystem-service indicators, 95 % confidence intervals for the reported proportions were computed using the Wilson score method, which is more robust than the normal approximation at the sample size used here. Because the survey instrument recorded farm-level responses in aggregate summary form rather than as a retained micro-dataset disaggregated by taluk, land-holding class or irrigation type at the time of this analysis, formal tests of association or difference across these subgroups (e.g., one-way analysis of variance (ANOVA), chi-square) could not be computed for the present submission. This is acknowledged explicitly as a limitation in the discussion and the authors will incorporate subgroup-disaggregated inferential tests if the underlying farm-level dataset is made available for a further revision.

Results and Discussion

Socioeconomic profile of respondents

Table 1 summarises the key socioeconomic characteristics of the 40 surveyed farmers mean age was 49.3 years ($SD = 13.41$, range 27–68), indicating a predominantly middle-aged to older farming community. The near-exclusive male representation (97.5 %) reflects prevailing socio-cultural norms around land ownership in rural Theni. A mean family size of 6.12 members implies an available household labour pool that partially substitutes for hired labour, reflected in the C2 cost computation. Farming experience averaged 22.05 years, with agroforestry-specific experience averaging 10.7 years, suggesting most respondents transitioned to agroforestry as a diversification strategy during the past decade, a period corresponding to declining monoculture spice returns and increased institutional agroforestry promotion. Education was diverse: 25.0 % primary, 20.0 % postgraduate, 15.0 % each secondary and higher secondary. Land holdings averaged 3.79 acres ($SD = 1.44$), of which 2.06 acres (54.4 %) were under the silvi-horticultural system.

Agroforestry system description

All 40 respondents practised the silvi-horticultural system as their primary land-use approach. The dominant tree combination was mango (*Mangifera indica* L., 100 % of farms) as the primary tree and jackfruit (*Artocarpus heterophyllus* Lam., 100 % of farms) as the secondary tree. Mango's deep root system and jackfruit's shallower profile minimise inter-specific competition while both species contribute to a dense, overlapping canopy. The primary understorey crop was cardamom (*Elettaria cardamomum* (L.) Maton, 100 % of farms) and pepper (*Piper nigrum* L., 100 % of farms) as a secondary intercrop. Trees were planted at a mean spacing of 4.39 m, were on average 10.0 years old, with a stand density of approximately 76 trees per acre. Land-type distribution: 37.5 % rainfed, 37.5 % mixed, 30.0 % irrigated. Red soil dominated (45.0 %), followed by sandy (25 %), black soil (17.5 %) and alluvial (12.5 %).

Cost of cultivation

Establishment costs

Mean total establishment cost per acre was ₹32011, comprising variable costs of ₹24701 (77.2 %) and fixed costs of ₹7311 (22.8 %).

Table 1. Socioeconomic profile of silvi-horticultural farmers, Theni District (n = 40)

Characteristic	Category/statistics	n/value	Percentage (%)
Age (years)	Mean $\pm$ SD (range)	49.3 $\pm$ 13.41	27–68 years
Gender-male		39	97.5
Gender-female		1	2.5
Family size	Mean	6.12	—
Education-illiterate		5	12.5
Education-primary		10	25.0
Education-secondary		6	15.0
Education-higher Secondary		6	15.0
Education-graduate		5	12.5
Education-postgraduate		8	20.0
Farming experience	Mean $\pm$ SD	22.05 $\pm$ 11.3 yrs	—
Agroforestry experience	Mean $\pm$ SD	10.7 $\pm$ 5.8 yrs	—
Total land holding	Mean $\pm$ SD	3.79 $\pm$ 1.44 acres	—
Land under agroforestry	Mean	2.06 acres	—
Occupation-agriculture		10	25.0
Occupation-agroforestry		12	30.0
Occupation-business		13	32.5
Occupation-service		5	12.5

Planting material dominated variable costs (₹8051), followed by Year-1 input costs of farmyard manure (FYM), fertilisers and irrigation (₹8285) and planting labour including pit digging and transplanting (₹4338). Land preparation accounted for ₹4027. Fixed establishment costs were primarily fencing and orchard protection infrastructure.

Annual maintenance costs

Annual maintenance costs averaged ₹34671 per acre; variable maintenance costs contributed ₹22616 (65.2 %) and fixed costs ₹12055 (34.8 %). Human labour dominated variable maintenance at ₹15563 (68.8 %), comprising weeding, pruning, fertiliser application, irrigation, pest management and harvesting. Material inputs including organic manure, NPK fertilisers, pesticides, irrigation charges and seed replacement averaged ₹7054. Fixed costs included imputed land rental value, land revenue, interest on working capital (12 % of TVC, averaging ₹2714), depreciation, insurance and miscellaneous charges.

Total cost summary

Mean TVC was ₹47317 (SD = ₹5063) and TFC was ₹19365 (SD = ₹2645), yielding TC of ₹66682 (SD = ₹5946; 95 % CI: ₹64780–68585). Variable costs constituted 70.9 % and fixed costs 29.1 % of total

cultivation cost.

Gross returns

Mean Total GR per acre was ₹118913 (SD = ₹39500; 95 % CI: ₹106276–131551), ranging from ₹50705–₹219721. Intercrop returns dominated at ₹87857 (73.9 %), primarily cardamom and pepper, reflecting premium spice market prices. Tree product returns averaged ₹29400 (24.7 %), comprising principally fruit returns from mango and jackfruit (₹16436), NTFPs (₹6345) and supplementary fuelwood and fodder income. By-product returns averaged ₹1656 (1.4 %). GR distribution showed no farm below ₹50000 per acre, with 70.0 % exceeding ₹100000.

Net returns, benefit-cost ratios and inferential analysis

Table 2 presents the consolidated cost-returns summary. Net returns over variable cost (NRv) averaged ₹71596 (SD = ₹41465) and NR averaged ₹52231 (SD = ₹42569). The BCR over VC was 2.57 (SD = 0.99) and BCR over TC was 1.82 (SD = 0.70). One-sample *t*-tests confirmed that both ratios are significantly greater than the economic-viability threshold of 1.0: BCR-TC ($t_{39} = 7.41, p < 0.001$, 95 % CI: 1.60–2.04) and BCR-VC ($t_{39} = 10.03, p < 0.001$, 95 % CI: 2.25–2.89). Net returns over total cost were likewise significantly greater

Table 2. Cost and returns analysis of silvi-horticultural system, Theni District (n = 40, per acre basis, with 95 % confidence intervals for key indicators)

Economic parameters	Mean (₹/acre)	SD (₹)	95 % CI
Total variable establishment cost	24700.53	—	—
Total fixed establishment cost	7310.55	—	—
Total establishment cost	32011.08	—	—
Human labour—annual	15562.70	—	—
Material inputs—annual	7053.77	—	—
Total variable maintenance cost	22616.47	—	—
Total fixed maintenance cost	12054.75	—	—
Total annual maintenance cost	34671.22	—	—
Total variable cost (TVC)	47317.00	5063.35	—
Total fixed cost (TFC)	19365.30	2644.83	—
Total cost of cultivation (TC)	66682.30	5946.28	64780–68585
C2 Cost (TC + family labour)	72007.95	—	—
Gross returns - tree products	29400.25	9302.72	—
Gross returns - intercroops	87856.95	38808.70	—
Gross returns - by-products	1656.00	—	—
Total gross returns (GR)	118913.20	39499.74	106276–131551
Net returns over variable cost (NRv)	71596.20	41465.07	58333–84860
Net returns over total cost (NR)	52230.90	42568.71	38612–65850
BCR over variable cost	2.57	0.99	2.25–2.89
BCR over total cost	1.82	0.70	1.60–2.04
Return per rupee of variable cost	1.57	—	—
Return per rupee of total cost	0.82	—	—

than zero ($t_{39} = 7.76$, $p < 0.001$, 95 % CI: ₹38612–65850), as were net returns over variable cost ($t_{39} = 10.92$, $p < 0.001$, 95 % CI: ₹58333–84860). Among respondents, 32.5 % achieved BCR over TC above 2.0, 60.0 % between 1.0–2.0 and only 7.5 % below 1.0 (Wilson 95 % CI for the sub-unity proportion: 2.6–19.9 %, reflecting the wide uncertainty inherent in a subgroup of only three farms), the latter likely comprising farms in early establishment phases. Return per rupee of VC was 1.57 and of TC was 0.82. Formal comparative tests of BCR or GR variation across taluks, land-holding classes and irrigation types could not be performed for this submission, as noted in Section 2.4.3 and are flagged as a priority for the next revision pending availability of the disaggregated farm-level dataset.

Ecosystem services

Provisioning services

Table 3 documents provisioning services from the D1 survey sub-table. Total mean provisioning value was ₹33958 (SD = ₹11253) per acre. Vegetables were most universally available (92.5 %), followed by fruits (82.5 %; mean 415 kg/acre; value ₹15539). Medicinal plants were reported on 60.0 % of farms, yielding a mean of ₹5325 per acre, reflecting the ethnobotanical richness of this Western Ghats-proximate landscape. Green fodder (70.0 %) supported an average of 3.67 livestock per household. Honey production (37.5 %) reflects the bee-attractant quality of mango and jackfruit blossoms alongside cardamom flowers, which are primary foraging resources for *Apis cerana* and *Apis dorsata* and whose pollination simultaneously enhances cardamom pod set. Timber availability was low (20.0 %), as expected in a system where trees are primarily managed for fruit rather than timber.

Regulating services

Shade provision was the most universally observed service (97.5 %; Wilson 95 % CI: 87.1–99.6 %), reflecting the dense overlapping canopies of 10-year-old mango and jackfruit. Temperature reduction was reported by 90.0 % of farmers soil conservation benefits were widely perceived: 82.5 % noted reduced soil erosion, 77.5 % improved soil structure and 65.0 % reduced surface runoff consistent with the physical mechanisms of canopy interception, litter fall and root binding, though these are farmer perceptions rather than instrumented soil measurements. Groundwater recharge was reported by 55.0 % of farmers (Wilson 95 % CI: 39.8–69.3 %), corroborated by respondent-recalled water table depths averaging 56.33 feet before system establishment and 36.60 feet at survey, an average recalled improvement of 19.73 feet. As this figure relies on farmers' recall of historical water levels rather than instrumented time-series measurements and no non-adopting control farms were surveyed for comparison, it should be treated as an indicative, perception-based estimate

rather than a precisely measured hydrological effect. Carbon awareness was reported by 50.0 % of respondents, with 30.0 % expressing interest in participating in carbon credits; no on-farm carbon stocks were directly measured in this study (see Section 3.7). Pest incidence decreased for 57.5 % and increased for 35.0 % of respondents, the latter possibly associated with fruit crop concentration effects. Beneficial insects were observed by 72.5 % of farmers.

Supporting services

Soil quality improvement was reported by 75.0 % of respondents, attributable to continuous leaf litter fall. Crop yield was reported to have increased on 70.0 % of farms (Wilson 95 % CI: 54.6–81.9 %) at a self-reported mean of 21.77 %, while fertiliser use was reported to have been reduced by 72.5 % of farmers at a mean of 18.07 %, translating to indicative input cost savings. Because both figures rely on farmers' unaided recall of pre-adoption conditions rather than paired before/after measurement or a non-adopting comparison group, they are best read as perceived rather than measured changes. Leaf litter was utilised by 75.0 % at 161.82 kg per acre per year through mulching (25 %), composting (25 %), direct incorporation (22.5 %) and other methods (27.5 %). Green manure was incorporated by 67.5 % at 131.88 kg per acre annually. Biodiversity indicators were strongly positive: 80.0 % reported increased bird species richness (mean 8.0 species per farm; Wilson 95 % CI: 65.2–89.5 %), 82.5 % noted more pollinators, 67.5 % observed other wildlife and 75.0 % noted increased soil organisms, primarily earthworms again, farmer-perceived counts rather than standardised field surveys.

Cultural services

Farm beauty improvement was reported by 87.5 % and visitor satisfaction by 70.0 %. Farm tourism potential was recognised by 57.5 %, suggesting an emerging agri-tourism opportunity in the Theni–Western Ghats belt. Religious tree use (neem, peepal, coconut, banana) was acknowledged by 52.5 % and cultural significance through traditional farming practices by 72.5 %. Educational visitors were received by 37.5 % of farms (mean 7.05 per year) and 42.5 % participated in knowledge-sharing activities (Table 4).

Discussion

The findings collectively establish that the mango, jackfruit, cardamom and pepper silvi-horticultural system in Theni District is economically productive and ecologically multi-functional, with the economic conclusions now supported by significance testing rather than descriptive statistics alone (Section 3.5). The mean BCR of 1.82 over total cost compares favourably with the 1.4–2.4 range

Table 3. Provisioning services from silvi-horticultural system, Theni District (n = 40)

Provisioning services	Availability (%)	Mean quantity/year	Mean value (₹)	Home use
Fruits	82.5	415.07 kg	15539.48	—
Vegetables	92.5	—	4443.32	—
Honey	37.5	8.10 kg	3067.30	—
Green fodder	70.0	595.23 kg	1223.38	—
Dry fodder	47.5	278.60 kg	945.12	—
Fuel wood	65.0	415.75 kg	2814.72	~28 %
Timber	20.0	10.32 cubic feet	598.83	—
Medicinal plants	60.0	22.02 kg	5325.43	—
Total provisioning value	—	—	33957.57	—

Table 4. Ecosystem services documented in silvi-horticultural system, Theni District (n = 40)

Ecosystem service indicators	Reported (%)	Quantification/remarks
A. Regulating services		
Soil erosion reduced	82.5 %	Farmer-perceived; qualitative
Improved soil structure	77.5 %	Farmer-perceived; qualitative
Reduced surface runoff	65.0 %	Farmer-perceived; qualitative
Improved groundwater recharge	55.0 % (95 % CI 39.8–69.3 %)	Recalled WT: 56.33 → 36.60 ft
Water stress reduced	62.5 %	Farmer-perceived; qualitative
Temperature reduction	90.0 %	Farm microclimate; perceived
Humidity increase	75.0 %	Farmer-perceived; qualitative
Wind speed reduction	57.5 %	Farmer-perceived; qualitative
Shade provision	97.5 % (95 % CI 87.1–99.6 %)	Farmer-perceived; qualitative
Pest incidence decreased	57.5 %	23 of 40 farmers
Beneficial insects observed	72.5 %	Farmer-perceived; qualitative
Aware of carbon storage	50.0 %	Awareness only; no on-farm measurement
B. Supporting services		
Soil quality improved	75.0 %	Self-reported
Crop yield increased	70.0 % (95 % CI 54.6–81.9 %)	Self-reported mean: 21.77 %
Fertiliser use reduced	72.5 %	Self-reported mean: 18.07 %
Leaf litter utilised	75.0 %	Mean: 161.82 kg/year
Green manure incorporated	67.5 %	Mean: 131.88 kg/year
More bird species observed	80.0 % (95 % CI 65.2–89.5 %)	Mean: 8 species (farmer count)
More pollinators observed	82.5 %	Honeybees, butterflies, wild bees
Other wildlife observed	67.5 %	Birds, squirrels, frogs
Soil organisms increased	75.0 %	Earthworms predominant
C. Cultural services		
Farm beauty improved	87.5 %	Qualitative
Visitor satisfaction	70.0 %	Qualitative
Used for recreation	55.0 %	Qualitative
Farm tourism potential	57.5 %	Qualitative
Trees for religious purposes	52.5 %	Neem, peepal, coconut
Cultural significance	72.5 %	Traditional farming practices
Visitors for learning	37.5 %	Mean: 7.05 visitors/year
Knowledge sharing/Training	42.5 %	Agroforestry, soil health topics

reported for comparable mango-spice systems in South India (9) and significantly exceeds BCRs of 1.2–1.5 documented for monoculture cardamom cultivation (8), suggesting economic value-addition arising from tree integration though, as no monoculture comparison farms were surveyed within this study, the comparison remains literature-based rather than a matched within-study control. The positive GR distribution with no farm below ₹50000 per acre and 70.0 % exceeding ₹100000 reflects the productivity resilience of this multi-strata system, consistent with the risk-buffering function of product diversification documented in tropical agroforestry landscapes (18).

The substantial variability in gross returns (SD = ₹39500 on a mean of ₹118913) reflects the well-documented inter-annual price volatility of cardamom and pepper markets, both globally traded spices subject to climatic shocks and speculative pricing dynamics (8). The premium these shade-grown spices command over sun-grown equivalents (₹900–1500 per kg for cardamom alone (8)) further reinforces the economic rationale for formalising and supporting the silvi-horticultural system as a distinct land-use category rather than treating it as an informal variant of monoculture spice cultivation. Beyond price volatility, farm-to-farm differences in management intensity, irrigation availability, farm size and pest incidence are also plausible contributors to the observed variability in gross returns; the aggregate (rather than farm-level) form in which the survey data were retained does not permit these factors to be individually disaggregated and tested in the present analysis and this is noted as a specific limitation in Section 3.9. This heterogeneity has direct policy implications and calls for risk-management interventions including futures market access, farmer producer organisation (FPO) linkage and income diversification consistent with the broader finding that spice-dominated silvi-horticultural systems require institutional market

support to achieve stable income trajectories (19). The 7.5 % of farms with sub-unity BCR, likely in early establishment phases, underlines the importance of bridge financing and transitional support during the establishment period, as recommended in the National Agroforestry Policy (11). Given the wide confidence interval around this sub-group proportion (2.6–19.9 %, n = 3), targeted extension resources should be piloted at modest scale and re-evaluated as the dataset grows, rather than sized on the point estimate alone.

The self-reported mean water table improvement of 19.73 feet is a notable finding in the context of Theni's eastern rain-shadow taluks, where groundwater depletion has been an escalating challenge and is broadly consistent with comparable hydrological recharge benefits reported for tree-based systems in semi-arid peninsular India (16). However, in the absence of instrumented pre/post monitoring and a non-adopting control group, this figure should be read as an indicative farmer-perceived trend rather than a validated hydrological effect; a bore-well monitoring sub-study would be needed to confirm the magnitude of recharge attributable specifically to the silvi-horticultural system. With that caveat, the finding reinforces the case for exploring Payment for Ecosystem Services (PES) frameworks targeting silvi-horticultural farmers prior work on Western Ghats agroforestry has estimated willingness-to-pay values for watershed services from tree-covered farms that can exceed the administrative costs of scheme implementation (20). At the same time, PES schemes of this kind face well-documented implementation challenges that this study's findings do not resolve: transaction costs of monitoring and verifying diffuse hydrological and biodiversity outcomes at smallholder scale can be high relative to payment size; additionality is difficult to establish where, as here, indigenous shade cultivation already

predates any policy intervention, making it hard to attribute recharge or carbon gains specifically to a paid programme rather than pre-existing practice; and permanence is not guaranteed where land-use decisions remain at the discretion of individual smallholders facing volatile spice prices. Community-level or FPO-mediated aggregation of monitoring and payment rather than farm-by-farm contracting is one route through which these transaction-cost and additionality concerns could be partially addressed and is an area meriting explicit feasibility analysis for the Tamil Nadu policy context.

The carbon sequestration co-benefit, of which 50.0 % of respondents were aware, represents a potentially significant but currently unquantified income stream: no above- or below-ground carbon stocks were directly measured in this study. Published estimates for comparable tropical fruit-tree systems suggest 15–30 tonnes of carbon per hectare in above-ground biomass and integration into voluntary carbon markets or National Bank for Agriculture and Rural Development (NABARD's) agroforestry carbon programmes could, in principle, provide additional income of ₹7500–15000 per acre per rotation a figure that would materially improve the BCR of the currently marginal 7.5 % sub-group if realised (4). This remains a literature-derived projection rather than a site-measured estimate and direct biomass/carbon sampling on a subset of Theni farms is recommended before any such figure is used for policy or scheme design. Prior work has also argued that carbon credits for smallholder agroforestry in India remain systematically under-priced because on-farm carbon measurement transaction costs are prohibitive for individual farmers, reinforcing the case for aggregated, community-level carbon accounting mechanisms rather than farm-by-farm measurement (21).

The biodiversity findings a farmer-reported mean of 8.0 bird species per farm and 82.5 % reporting enhanced pollinator diversity are consistent with the function of the silvi-horticultural system as a biodiversity refuge in the Western Ghats buffer zone described elsewhere, where shade-grown cardamom farms were identified as critical habitat linkages between core forest areas, though the present study's counts are farmer-recalled rather than derived from standardised transect surveys (6). The direct economic value of pollinator diversity through enhanced cardamom pod set deserves explicit quantification, as prior studies have both demonstrated that pollinator-mediated crop yield enhancement in bee-dependent crops can contribute 10–20 % of farm income. This suggests that the biodiversity service in this system may have a productive value currently invisible in conventional cost-return accounts (12, 22). A production-function study directly relating pollinator abundance to cardamom pod-set on a subsample of Theni farms would be a valuable and tractable next step.

The cultural services dimension, while inherently subjective and self-reported, reveals an under-appreciated social value of the silvi-horticultural system. The 72.5 % of farmers reporting cultural significance aligns with the concept of biocultural landscapes, wherein traditional farming systems carry intergenerational ecological knowledge that is itself considered a form of ecosystem service of societal value (23). The 57.5 % identifying farm tourism potential corresponding to the scenic mango orchards and spice gardens characteristic of the Theni hills represents a plausible economic diversification

opportunity. Agri-tourism revenue in comparable spice-growing landscapes in Kerala has been documented to contribute 15–25 % of household income for participating farms, a benchmark that Theni's silvi-horticultural farms could potentially approach with appropriate infrastructure and institutional support, though local feasibility (market access, homestay regulation, seasonal demand) would need dedicated assessment before this is used as a planning target (24). The religious and spiritual dimensions (52.5 %) further embed the system within cultural conservation frameworks increasingly recognised in global biodiversity policy (24).

The high proportion of farmers (72.5 %) reporting reduced fertiliser use and 70.0 % reporting increased crop yields together point to a plausible productive supporting-service role of the mango-jackfruit canopy specifically through leaf litter nutrient cycling, enhanced soil organic matter and reduced thermal stress on understorey crops while remaining, as noted above, self-reported estimates rather than measured agronomic outcomes. These findings are broadly consistent with meta-analytic evidence on tree-mediated crop yield improvements across sub-tropical agroforestry systems (19) and with field-level documentation of mango-intercrops in Tamil Nadu showing 15–30 % yield advantages for shade-tolerant crops (25). If confirmed by measured (rather than recalled) yield data, the combined fertiliser savings (18.07 % reduction) and yield enhancement (21.77 % increase) would represent a dual efficiency gain that meaningfully improves the effective profitability of the system beyond the BCR figures based on financial accounts alone. At present this should be read as a plausible but unverified upside rather than an established result. This overall pattern is corroborated by more recent (2020–25) farm-level evidence from South Asia. Mango-based agroforestry systems incorporating fruit-tree and spice/vegetable intercrops have reported land-equivalent ratios well above 1.0 and benefit-cost ratios comparable to or exceeding those recorded here (26) and Indian tree-based agroforestry systems more broadly continue to outperform equivalent non-agroforestry cropping on cost-of-cultivation and net-income measures (27), reinforcing the plausibility of the present study's cost-and-return findings against the wider recent evidence base rather than resting solely on the earlier literature cited in the Introduction.

Trade-offs between economic returns and ecosystem services

This study has documented economic returns and ecosystem-service indicators largely as complementary outcomes of the same system, but genuine trade-offs are plausible and were not directly investigated here. For example, intensifying intercrop management to maximise cardamom and pepper yield and hence gross revenue (GR) could involve increased fertiliser or pesticide use that partially offsets the fertiliser-reduction and beneficial-insect benefits reported by other farmers in the sample, while denser tree stocking that maximises shade-related regulating services could, beyond an optimum, depress intercrop light availability and reduce spice yield. Similarly, prioritising fruit-tree density for carbon and shade benefits may compete with the spacing needed for optimal cardamom light penetration. A direct empirical test of these trade-offs for instance, relating tree density or canopy cover to both GR and to specific regulating-service indicators across the sample was not possible with the aggregated

data available for this submission and is recommended as a specific line of future analysis once farm-level data are retained.

Limitations

Several limitations should be considered when interpreting these findings. First, the ecosystem-service indicators (regulating, supporting and cultural services) are predominantly self-reported farmer perceptions rather than independently measured biophysical outcomes and several rest on unaided recall of conditions before system establishment (e.g., water table depth, crop yield, fertiliser use); recall bias and motivated reasoning (farmers who adopted the system may be predisposed to perceive it favourably) cannot be ruled out. Second, no non-adopting control or comparison farms were surveyed, so before/after and adopter/non-adopter comparisons in this paper are indicative rather than causal. Third, the cross-sectional pilot design (n = 40, single season) limits the precision of subgroup estimates, as illustrated by the wide confidence interval around the sub-unity BCR proportion. Fourth, formal inferential comparisons across taluks, land-holding classes, irrigation types, farm management intensity and pest incidence could not be conducted because farm-level (rather than only aggregated) data were not available for this analysis. This is the single most important addition planned for a subsequent revision. Finally, carbon stock and biodiversity figures discussed in Section 3.7 rely on secondary literature benchmarks rather than direct on-farm measurement in Theni District.

Future perspectives

Beyond the immediate recommendations above, three broader lines of future work would substantially strengthen the evidence base for policy use. First, formal non-market valuation methods should be applied for comprehensive total economic value computation of the silvi-horticultural system, following established international protocols such as Food and Agricultural Organization of United Nations (FAO's) ecosystem-service valuation framework and sampling should be expanded across additional Western Ghats districts to test the generalisability noted in the introduction (28). Second, long-term ecological monitoring, ideally paired with instrumented (rather than farmer-recalled) measurement of water-table depth, bird and pollinator diversity and soil carbon, would allow the perception-based findings reported here to be validated or revised. Third, a formal life-cycle assessment of the system and a production-function study directly relating tree density and canopy cover to both economic returns and specific regulating-service indicators, are recommended as the underlying farm-level dataset matures, so that the trade-offs identified in Section 3.8 can be tested empirically rather than described qualitatively.

Conclusion

This pilot study shows that the silvi-horticultural system, as practised by smallholder farmers in Theni District, delivers economic returns that are statistically significantly above the break-even threshold, alongside ecosystem-service co-benefits, largely self-reported, across all four millennium ecosystem assessment (MA) service categories. The mango-jackfruit-cardamom-pepper combination appears well-adapted to Theni's agro-climatic conditions and reflects a system with both productive value and cultural rootedness, though the perception-based ecosystem

findings warrant confirmation through instrumented, farm-level follow-up.

Five specific, actionable recommendations follow: (i) targeted, small-scale extension support for the minority of farms with sub-unity benefit-cost ratio (BCR), focused on cardamom productivity and market-linkage constraints; (ii) a feasibility study of community- or Farmer Producer Organisation (FPO)-aggregated payments for ecosystem services (PES) contracting for water-table and soil-conservation benefits, explicitly costing transaction, monitoring and additionality requirements; (iii) a dedicated on-farm carbon-stock measurement exercise as a precondition for any carbon-registry integration; (iv) a market and infrastructure feasibility assessment for agri-tourism in the Theni hills; and (v) retention and analysis of farm-level, rather than only aggregated, survey data in future rounds to enable taluk-, land-holding- and irrigation-type comparisons.

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Authors' contributions

SNS carried out the survey, analysed the data and formulated the manuscript. DSK provided guidance to write the manuscript in a proper format. AV contributed to the development of ideas, reviewing the manuscript and assisted in procuring research grants. MPD provided additional support and contributed to the review. MV assisted in data collection and analysis as part of the research study. All authors have read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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