Indian Journal of Traditional Knowledge
Vol 25(1), January 2026, pp 74-85
DOI: 10.56042/ijtk.v25i1.16158

Harnessing indigenous knowledge for soil fertility: Traditional agroforestry-based farming in the Sikkim Himalaya

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Received 15 April 2025; revised 09 December 2025; accepted 12 January 2026

This study was conducted to scientifically document indigenous knowledge and practices of soil fertility management and nutrient cycling in five different agroforestry-based farming systems (AbFS) in the Eastern Himalaya -Hee-Bermiok-Uttarey (800-2100 m), West Sikkim; Dzongu (600-2000 m), North Sikkim; Lingi-Sokpay (500-2000 m), South Sikkim; and Pendam (500-2000 m), East Sikkim. The research involved a mixed-methods design that combined biophysical and ethnographic assessments through focus group discussions, household surveys, participatory field investigations, and soil nutrient analysis. The main inventory of traditional practices of soil fertility management (TPSFM) included farmyard manure (FYM) preparation, *in situ* manuring, mulching with forest litter and crop residues, green manuring, controlled biomass burning, incorporation of N_2-fixing plants, ash application, silt trapping, and periodic land fallowing. FYM and bio-compost application were the most dominant practices while livestock integration was significant to nutrient cycling and microbial enrichment. Soil physico-chemical attributes across AbFS revealed substantial variation, with cardamom-based, farm-based and mandarin orange-mix tree-based agroforestry exhibiting higher total-N, total-P, available-P, and organic-C with enhanced soil moisture and optimal bulk density, which indicated high nutrient cycling efficiency and structural stability. These indigenously time-tested, low-input agroecological systems sustained adequate soil fertility, increased organic matter turnover, and reinforced the adaptive capacity of ecosystems. The research findings demonstrated that the practice of traditional AbFS represent scientifically grounded, low-carbon, and biodiversity-supportive model of sustainable agriculture. Integrating indigenous agroecological knowledge into development programs and policy frameworks is vital for advancing climate-resilient, economically inclusive, as well as agro-ecologically and agro-climatically sound farming systems, thereby scientifically validating the TEK of indigenous communities.

Keywords: Agroforestry, Organic farming, Sikkim Himalaya, Soil fertility maintenance, Soil nutrient dynamics

IPC Code: Int Cl.[26]: A01C 3/00, A01G 23/00

The diversity of agroforestry systems in the Eastern Himalaya plays a fundamental role in indigenously designed traditional farming systems while also offering essential ecosystem services and a significant contribution to food security. When observed critically, these systems integrate multipurpose tree-crop associations in the altitudinal gradients, with the highest diversity of crops, fruits, tubers, vegetables, and cross- and multifunctional species observed in alpine, temperate, subtropical hills and the shiwaliks[1-3]. However, soil fertility management remained a significant challenge due to low scientific inputs, particularly with the growing transition toward cash-oriented, often monoculture and intensive farming systems. Notwithstanding these challenges, the marginal and smallholder farmers have competently incorporated tree-crop agroforestry practices as a foundational element of their farming strategies[4].

Sikkim Himalayan agriculture accounts roughly 16% to the state's Gross State Domestic Product, demonstrating its central significance to the rural economic framework. This state has been a pioneer in organic agriculture since 2003 in India. It is due to its unique geographical location and ethnic diversity of farming practices, the state has been at the forefront of traditional-based sustainable organic farming practices, emphasizing long-term soil fertility enhancement and environmental protection with zero chemical application[5]. By the year 2016, the total agricultural land area of 79,000 ha was fully declared organic, with organic support systems, consequent of a complete ban on use of chemical fertilizers and weedicides/pesticides[6]. Sikkim's marginal and smallholder farmers have depended on traditional manure production and application to sustain soil fertility, enhancing crop productivity for over many generations[7]. Regrettably, however, the region has been facing exacerbating vulnerabilities due to climate unpredictability, including, highly variable rainfall patterns, emergence of new crop diseases, unsteady shifts in growing seasons, and increased nutrient leaching[7].

Even though the noteworthiness of indigenously crafted agroforestry and traditional practices of soil fertility management (TPSFM) in Sikkim has substantive value, scientific studies on indigenous soil nutrient enrichment practices remain limited. These agroforestry-based farming systems (AbFS) extended across altitudes from 300 to 4300 m a.s.l. integrated a diversity of agroecosystems with adjacent forest ecosystems[4,5,7]. The employment of traditional ecological knowledge (TEK) in soil fertility management for enhancing farm productivity, crop irrigation, pest control, tree-crop combination, terrace and slope farm stabilization and biodiversity conservation play a pivotal role in ensuring climate resilience yet remain inadequately studied and documented[8].

The Government of Sikkim's initiatives after 2003 in promoting organic farming contributed to enhancing soil quality and fertility, in line with the sustainable development goals (SDGs), and augmented farmers' livelihoods, further substantiating the relevance of traditional TEK in achieving these objectives[5,8]. However, organic farming policies and development action-plans have yet to formally recognize indigenous agroecological systems and practices, as well as family farming strategies through a "Comprehensive Agricultural Policy" clearly delineating significance of family farming of marginal and small holders and validating their TEK.

Therefore, the current study aimed to document, TEK related to soil fertility management practices within the Sikkim Himalayan AbFS, and assess its role in climate change adaptation, particularly in the promotion of sustainable agroecological strategies. The idiosyncratic objectives were to: (1) study and document TPSFM, production of organic manure and application to crops, (2) indigenous methods of organic and composted manure preparation/application; (2) analyze organic manure nutrient composition and functional properties; and, (3) evaluate soil physical and chemical properties, such as texture, moisture, pH, and nutrient status across five distinct agroforestry systems.

Study sites

The four sites selected for the study were: Hee-Bermiok-Uttarey (800-2100 m), West Sikkim; Dzongu (600-2000 m), North Sikkim; Mamlay-Sokpay (500-2000 m), South Sikkim; and Pendam (500-2000 m), East Sikkim. These locations represented the altitudinal variation for the cultivation of a diversity of high-value cash crops, including large cardamom, mandarin orange, ginger, potatoes, broom grass, vegetables, and various cereals and horticultural crops, alongside lesser-known crops and wild edibles. They house high repository of agrobiodiversity and medicinal plants, unique farming systems along the altitudinal transects, transhumance and agropastoralism with approximately 95% of the tribal and other ethnic community engaged in agriculture. These locations also represent diverse agroforestry systems, including alder-cardamom-based, mixed tree-cardamom-based agroforestry, farm-based, farm-forest-based and mandarin orange-mix tree-based agroforestry systems[8]. The inhabitant's landholding pattern indicated that approximately 44% of households were marginal farmers (< 0.5 ha), 53% were smallholders (0.5-2 ha), and 3% were large-scale farmers (>2 ha).

The average annual precipitation across the study locations was 3000 mm, with higher elevations (3800-4500 m) receiving 1000-1300 mm, mid elevation (2000-3500 m) receiving 2000-3500 mm and lower elevations (250-1600 m) receiving 300-1500 mm. The rugged terrain predominantly faces southwest, with slopes ranging between 15° and 30°. Study sites such as Upper Dzongu, Jaubari-Sokpay, and Uttarey experience occasional snowfall and frost during winter, leading to a 30-60% reduction in productivity for cash crops and vegetables.

In the northeastern states of India including Sikkim, TEK related to soil conservation and traditional farming has long enabled indigenous and tribal communities to physiologically acclimate to environmental stresses and variability, and thus sustainably manage natural resources around them. The region systemically integrates a broad range of agroecosystem practices and forest management-soil fertility enrichment methods and practices, agrobiodiversity perfection and conservation, medicinal plants cultivation, water resource management, protection of sacred landscapes, weather forecasting, seed selection, and livestock rearing. The best examples of integrated traditional farming system are -Apatani tribe's wetland rice cultivation in Arunachal Pradesh, the Zabo system and alder-based agroforestry in Nagaland, large cardamom-based agroforestry in Sikkim, and bamboo drip irrigation in Meghalaya-all of which continue to support natural, low-input agriculture while balancing climate resilience[8-11]. Farmers practicing these systems have integrated deep ecological understanding with practical sustainability, maintaining soil health, biodiversity, and productivity across fragile mountain landscapes. The Nyishi tribe of Arunachal Pradesh illustrate ethnopedological knowledge demonstrating an advanced contextual understanding of soil-topography interactions closely in line with contemporary pedological concepts[12]. Regardless of this, recognition of ethnopedological knowledge, ingenious soil fertility practices, agroecosystem management, and agrobiodiversity conservation are largely unrecognized in the regional and national agricultural policies giving due consideration to integrate TEK to sustainable agriculture and climate resilient development frameworks.

Methodology

Traditional knowledge on soil fertility maintenance

The study and documentation of TEK related to TPSFM take into account: (1) specific knowledge generated by environmental and cultural contexts, (2) tacit knowledge shaped through interactions within or with other ethnic communities, exchanging and learning, (3) transmission of knowledge through generations and hands-on learning, advancing over time and space, (4) empirically grounded, field-based knowledge in contrast to abstract theoretical constructs, (5) site specific experiential knowledge acquisitions, and (6) perpetually evolving dynamic adaptation practices.

This study adopted a mix-methods design bringing together quantitative and qualitative approaches across diverse agroclimatic zones. As high as 16 focused group discussions (FGDs), 20 transect walks, and 160 households' interviews were conducted while also integrating participatory observation and case discussions with practitioners. The FGD participants and household respondents were selected for interview, using a stratified random sampling methods considering balanced representation across gender, landholding size, altitudinal gradients, ethnic composition and age groups. Around 15-20 male and female farmers were engaged in each FGD which facilitated systematic recording of knowledge and practices, while transect walks across altitudinal gradients and agroecosystems provided direct field-based observations and interactions on land-use patterns, soil fertility indicators, and soil types.

The quantitative and qualitative data on crop rotation, organic manure production and application methods, and adaptive responses to climate variation was obtained through interviews with 30-40 respondents. Colloquial and local terminologies for various farm-based activities including soil classification, manure production and application, crop season, and rainfall patterns were validated by consulting elderly farmers and FGD participants to ensure cultural accuracy. All these empirical and local methods inherently provided multi-dimensional understanding of socio-economic, cultural and ecological context of TPSFM study in the region.

Production of organic manure and application to crops

Production of organic manure and application to crops was estimated by counting the number of manure-filled *doko* (bamboo baskets; 1 *doko* = 20 kg dry weight) from the cattle sheds of sampled households. The mean household level production of organic manure - farmyard manure (FYM), bio-compost, goat dung, and poultry waste was quantitatively estimated in 10 representative households per site. Similarly, application of manure in various crops was quantified by counting the number of *doko-bhari* (headloads) for each crop. Manure application for cash crops was quantified by counting the number of *doko* used for each crop combination.

Nutrient analysis of organic manures

Fresh samples of organic fertilizers- goat dung, FYM, bio-compost and poultry waste collected from the study site were oven dried at 80°C until a constant weight was achieved, and calculated sample moisture percentage. Another batch of dried samples were air dried, ground into fine powder and sieved in a 2-mm sieve and were used to analyze nutrient contents. Widely used modified Kjeldahl method was used to analyze total-N[13], while total-P was analyzed using an acidified ammonium fluoride extract oxidized with hydrogen peroxide, and determined through chlorostannous reduced molybdophosphoric blue colour method[14].

Soil chemical analysis

A batch of soil samples from 0-30 cm depth were collected and immediately brought to the laboratory for pH estimation using a glass electrode digital pH meter (Systronics). Another batch of fresh soil samples were brought to the laboratory, oven dried at 80°C to constant weight and sieved in a 2-mm sieve. Widely used Walkley-Black method was used to estimate soil organic-C, Kjeldahl method was used to estimate total-N[13], chlorostannous reduced molybdophosphoric blue colour method for estimating total-P, while sodium bicarbonate extract following colorimetric method was used to estimate available-P[14].

Results

Indigenous system of soil fertility management practices

Marginal and smallholders accounted for nearly 97% of the farming population, cultivating operational landholdings of 0.2–1.0 ha. Closely, 98% of all interview respondents reported an advancing decline in landholding size, which was chiefly attributed to infrastructure expansion, road building, establishment of pharmaceutical industries and hydropower development. Ninety-six per cent of FGD respondents and 98% of household interviews revealed that land conversion and fragmentation, and increasing agrarian stress constitute irreversible challenges to the long-term sustainability of ingeniously designed and traditionally managed agroforestry systems posing threat on food security. Ninety-eight per cent farmers reiterated that *in situ* manuring, application of FYM, legume-based crop rotation, green manuring, land fallowing, cultivation of N_2-fixing species, flood-water and silt-trapping, recycling or kitchen waste, controlled burning of organic matter and crop residues constitute traditional methods of soil fertility practices (Table 1).

Around 99% of farmers reported that livestock manure was the main source of crop nutrients while 20% of farmers had additionally employed vermicomposting/biocomposting methods for manure production (Fig. 1a, b) and maintain AbFS. While 92% respondents of household interviews and 90% of FGD participants demonstrated that the ethnic

Table 1 — Traditional practices of manure production and soil fertility maintenance

Practices of manure production	Traditional manure production and management systems	Farm land parcels	% practice
FYM	- Stored in stone-walled pits (*mal-khadi*) of varying sizes or as open heaps. - Prepared by mixing dung with leaf litter, fodder, or crop residues. - Applied to fields either before or after ploughing, depending on the crop season and management schedule	*Khet, kothebari, Pakho-bari*	32.53
In situ manuring	- Farm animals are kept in the *khet* or *bari* under the temporary sheds (*chhahari*) - Sheep and goats kept in open field during fallow winter period	*Khet, kothe-bari, Maslo-bari*	14.75
Legume crop in rotation	- Farmers plant as many as 26 different varieties of beans, pulses and peas across different seasons.	*Khet, kothe-bari, Maslo-bari*	10.85
Land fallowing	- Farmers often leave land fallow for 3-5 years or convert it into farm-forest agroforestry to cultivate fodder trees, timber species, and grass fodder like broom grass	*Khet, bari, bhasmey, pakho -bari*	6.85
Burning organic matter/crop residue	- In winter, farmers burn crop residues and weeds to enrich soil with ash for crops	*Khet, bari, bhasmey, pakho -bari*	6.54
Slicing/burning terrace risers	- *Bari-phadnu* involves clearing weeds and coppicing tall trees during winter, followed burning of biomass to manage shade and recycle nutrients	*Bari, khet*	8.45
Green manuring	- Involves incorporating wild shrubs like *Adhatodavasica, Artemisia vulgaris, Walsuratrijuga, Sesbania* spp., and *Sapium* spp. into *khet* and *bari* lands to enhance soil fertility	*Bari, khet*	6.55
N_2-fixing species	- *Alnus nepalensis, Albizia* spp., and *Erythrina* spp. are integrated as shade trees in cardamom plantations, contributing nitrogen through root nodulation and nutrient-rich litter for soil fertility enhancement - Traditional farming commonly utilizes *Flemingia macrophylla, Leucaena leucocephala, Gliricidia sepium* and *Tephrosia candida*	*Alinchibari, pakhobari*	8.5
Trapping flood-water	- During the rainy season, nutrient-rich floodwater is trapped on terraced fields using raised bunds, either before or after paddy planting, to enhance soil fertility	*Khet*	2.48
Silt-trapping	- Silt trapping in sloppy land by erecting stone walls along the furrows - Silt and biomass is collected eventually and a terraced is built	*Pakhobari*	2.00
Use kitchen waste	- Commonly applied in home gardens cultivating diverse vegetables, fruits, tubers, and spices	*Gharbari*	0.50

communities' house rich TEK for TPSFM for optimizing locally available resources while also minimizing external inputs in the systems. Moreover, 83% of respondents reported that they possess rich knowledge on preparation of biopesticides, liquid bio-fertilizers, and advanced techniques of FYM preparation while 97% also use livestock urine as a base for preparation of plant-based composts, weedicides and pesticides. Elderly farmers, household interviews, and FGDs, reported that traditional practices enhanced soil fertility (32%), reduced crop infestation (60%), improved soil moisture retention (24%) and workability (14%), increased production efficiency (60%), and resulted in yield gains exceeding 50%.

***FYM and bio-compost* (Ghusmut-mal)**

Bio-compost and FYM production and application constituted the most prevalent TEK-based soil fertility practices. Almost 99% of farming households prepare and apply FYM and bio-compost in the farms to grow a variety of cereals, cardamom, ginger, pulses, vegetables, millets and medicinal plants. The per capita livestock holding ranged from 3 to 13 animals with stall-fed livestock. Around 17% households graze their cattle in the agroforestry or in the adjacent forests. Prominently, paddy straw (*Paral*), corn stover (*makaiko-dhod*), millet straw (*kodoko-naruwa*), buckwheat stubble (*faparko-naruwa*), chayote (*eskush*, *lahara*), other crop residues, weeds, litter, leaves and twigs of chopped trees were the main ingredients of compost production. Crop residues and on-farm litter were used as livestock bedding, where they absorbed urine and dung and were subsequently composted to produce organic manure (Fig. 1a). Seventy-eight per cent of farmers reported that the regular use of livestock bedding followed by batch-wise composting in large pits locally referred to as *maal-khadi* formed an integral component of on-farm nutrient recycling and manure production systems.

With the onset of growing season, adjusting application frequency and quantity, farmers periodically transfer manure to the farms according to the requirements of crops. FGDs across sites revealed that certain crops such as ginger, require up to three times more manure and consequently considered as nutrient exhaustive.

The application of organic manures across major cropping systems exhibited clear crop-specific nutrient management patterns reflecting input intensity, crop value, and landholding size (Table 2). Ginger and vegetables/chillies received the highest organic inputs, with FYM+bio-compost ranging from 10-15 t hh^{-1} $year^{-1}$ and 8-12 t hh^{-1} $year^{-1}$, respectively, indicating their economic importance and high nutrient demand. Large cardamom received 8-10 t hh^{-1} $year^{-1}$, supported by litter mulching and manuring, while cereals such as rice and wheat received lower FYM inputs (1.9-2.1 and 2.2-3.12 t hh^{-1} $year^{-1}$), and maize moderate levels (2.5-4 t hh^{-1} $year^{-1}$). Live stock manureuse was highest in maize (321-456 kg hh^{-1} $year^{-1}$) and wheat (146-368 kg hh^{-1} $year^{-1}$), while poultry waste was primarily applied to cereals and vegetables (10-130 kg hh^{-1} $year^{-1}$) as a rapid nutrient source.

Household application of organic manures varied markedly across land-use types, with highest inputs in *bari* (rainfed) fields (10-18 t hh^{-1} yr^{-1}), moderate inputs in *khet* (irrigated) systems (5-12 t hh^{-1} yr^{-1}), and minimal application in *bhasmey* (slash-and-burn–derived) farms (1-3 t hh^{-1} yr^{-1}). Across agroecological zones, bio-compost and livestock manure production exhibited strong spatial heterogeneity reflecting differences in nutrient cycling efficiency, biomass access, and livestock management intensity (Table 3).

Table 2 — Application of organic fertilizer for different crops on household basis in the study sites

Organic fertilizer	Rice	Maize	Ginger	Cardamom	Wheat	Vegetables/ chilli
FYM+bio-compost (t hh^{-1} $year^{-1}$)	1.9-2.1	2.5-4	10-15	8-10	2.2-3.12	8-12
Goat dung (kg hh^{-1} $year^{-1}$)	33-51	321-456	14-54	—	146-368	60-120
Poultry waste (kg hh^{-1} $year^{-1}$)	20-60	70-130	—	—	—	40-60

Table 3 — Average household (hh) production of organic manures

Study sites	FYM production (t hh^{-1} $year^{-1}$)	Compost preparation (t hh^{-1} $year^{-1}$)	Goat dung (kg hh^{-1} $year^{-1}$)	Poultry waste (kg hh^{-1} $year^{-1}$)	Forest litter collection (t hh^{-1} $year^{-1}$)
Pendam	6.85±1.81	2.72±0.76	154±8.55	53±5.65	3.62±0.81
Mamley-Sokpay	4.96±1.87	3.76±1.59	190±12.71	123±6.21	5.86±1.21
Hee-Bermiok-Uttarey	5.85±0.98	2.58±0.98	165±8.89	87±9.79	5.98±1.31
Dzongu	7.98±1.31	4.89±0.89	198±5.98	123±10.21	6.85±0.91

Fig. 1 — Different traditional and modern methods of soil fertility maintenance

Dzongu showed the most efficient crop–livestock integration, with highest FYM (7.98±1.31 t hh^{-1} yr^{-1}) and biocompost outputs (4.89±0.89 t hh^{-1} yr^{-1}), whereas Mamley-Sokpay recorded the lowest FYM production (4.96±1.87 t hh^{-1} yr^{-1}). Forest litter extraction was highest in high-altitude sites-Dzongu, Uttarey, and Sokpay (5.86-6.85 t hh^{-1} yr^{-1}) - highlighting strong forest–farm interdependence.

***Field-based biomass burning* (barima-dadelo)**

Farm clearing such as *bari-fadnu* that involved systematic removal of weeds and unwanted shrubs, selective coppicing of trees called as *rukh-chashney* were mandatory during winter months (December through March) to facilitate light penetration and microclimatic balance (Fig. 1b). Most farmers (93%) collected large- and small-sized tree branches for firewood while remaining leaves and twigs were subjected to controlled burning. The ash produced was collected and spread across the farms either during crop showing or to some selective crops such as potatoes to control ant infestation or applied to *dalley* chilli to enhance nutrient uptake. The process of biomass burning, ash deposition, and litter decomposition synergistically supported farmers to enhance overall soil productivity, enriching crop nutrient uptake and accelerating nutrient cycling.

***Burning of fodder remains* (sita-balnu)**

Scientific observations of a variety of farm-level operations conducted by the farmers demonstrated that indigenous farmers had nothing to dispose-off from the farm. The residues of branched fodder after livestock feeding were meticulously heaped in the nearby *bari* or *khet* and were subsequently burnt following sun-drying (Fig. 1c). Large-sized woody branches were bundled and stored in the livestock sheds for use as fuel wood in cooking fodder. The subsequent ash produced from biomass processing activities was evenly broadcasted over the field to augment soil fertility, followed by ploughing operations to facilitate the amendment of ash-derived nutrients into the soil matrix.

***In situ manuring* (khet-barimalnu)**

Field livestock manuring was an indigenously rooted method of improving farm nutrient status by allowing livestock to graze during the day and remain in the fields at night. This management procedure across study sites facilitated livestock urine and excreta to deposit in the soil directly and supported farmers in strengthening ecological functioning. Sixty-nine per cent of farmers graze ruminants in the farm during fallow periods, and house them under temporary shelter (*chharaari*) at night to enable further field manuring especially after crop harvest.

***On-farm mulching* (Sottar mal)**

Systematic field observations and interactions with farmers during their farm operations demonstrated their rich knowledge, skills and practices to improve productivity through regular mulching - a criticalagronomic practice for soil moisture conservation, suppression of weed colonization, and organic matter deposition and decomposition. Almost all the farmers who were interviewed re-emphasized that, in response to growing market demand for high-value crops, soil amendment through periodic mulching evolved into a promising cultivation intervention (Fig. 1d). Some educated farmers (47%) reported that crop residues, fodder waste, fallen leaves and twigs, and litter collected from agroforestry floors served as ready-made mulch for promoting microbial activity and nutrient mineralization, facilitating soil moisture retention and accelerating decomposition and nutrient cycling.

***Poultry waste* (kukhurako-suli)**

Eighty-five per cent farmers across sites expressed that they entered a new venture of high yielding poultry farming business realizing the increasing demand since 2010 (Table 2) while traditional poultry farming had significant income generation option. Consequently, this intervention further improved rural livelihood and facilitated enhancement of soil fertility. The FGD respondents stated that poultry manure, rich in N, P, and K, was extensively used in commercial crops such as *Dalley* chilli (GI Certificate No. 414) and vegetable cultivation. As high as 53% farmers had enough knowledge to systematically rank poultry manure as the most nutrient-abundant fertilizer-of higher quality than ruminant waste-for promoting soil physical properties and structure, higher nutrient availability, and boost crop yield.

***Green manure* (hariyo mal)**

The incorporation of N_2-fixing and non-N_2-fixing species for green manuring was a prevalent age-old practice of soil fertility improvement. Sixty-four percent farmers had combined a few commonly suited species such as *Adhatoda vasica*, *Artemisia vulgaris*, *Alnus nepalensis*, *Albizia* spp., *Erythrina* spp., *Eupatorium hterophyllum*, *Sesbania* spp., *Sapium* spp., and *Walsura trijuga*, into farm-based, mix-tree-forest-cardamom, and mandarin orange-mix tree-based agroforestry. Approximately, 32% farmers had planted fast-growing, and N_2-fixing species –*Gliricidia sepium, Azolla pinnata, Flemingia macrophylla, Leucaena leucocephala*, *Tephrosia candida*, *Ipomoea fistulosa* and legume crops (*Glycine max, Lens culinaris, Vigna unguiculata, Vigna mungo, Vigna radiata, Pisum sativum, Phaseolus vulgaris, Vigna umbellata, Cicer arietinum, Crotalaria juncea*) in their terraced farms. Farmers inhabited in the lower elevations (<1000 m) had additionally planted legumes like *Desmodium intortum* and *Tephrosia candida* to further elevate soil nutrient status. Discussions in the FGDs established that these species were regularly planted along terrace risers for stabilizing soil erosion and improving fertility effectively in the mountain farming systems.

***On-farm decomposition practices for rice* (hilo-kuhaunu)**

Wet rice cultivation on terraced slope lands and along river valleys has been an indigenous cultural farming practice, employing a unique traditional method of fallowing puddled soil for 5-15 days after ploughing. Many farmers (57%) identified this practice as an effective biomass decomposition process (*hilo-kuhaunu*), enhancing nutrient mineralization and soil fertility. On the day of rice transplantation (*ropain*), fields undergo sequential ploughing (*hilyaunu*), flooded soil leveling using draft-animal-drawn levellers (*daandey-launu*), and final surface smoothing (*baausey-garnu*) with wooden tools (*phyauri*), ensuring thorough incorporation of soil and organic residues. During the FGDs, this practice was reported to enhance the yield performance of rice and pulses/soybean cultivated on raised bunds intercropped with rice by approximately 80%. The system represents a nutrient-efficient, low-input organic cultivation practice that has been well established since ancient times.

***Fallowing of land* (Bhasmey-kheti)**

Through a long-standing historical farming tradition, fallowing of land for a 3-5-year cycle or a 2-3-year cycle had been embedded as a method to replenish soil micro flora and fauna, and rejuvenate soil nutrient status alongside allow natural regeneration of diverse herbs, shrubs and trees. When asked about the salience of *bhasmey-kheti* during the household interviews and FGDs, respondents provided explanations that were exceptionally scientific and methodological, highlighting crop-land rehabilitation, diversification of crops while also maintaining farm-based agroforestry species for ecological stabilization. Approximately, 99% of farmers at Dzongu and 91% at Hee-Bermiok-Uttareyarticulated that *Bhasmey* agriculture reactivate efficient nutrient cycling through litter fall, decomposition, nutrient supply to the soil and subsequent uptake by plants (Fig. 1f). The respondents also stated that this process accelerates nutrient-holding capacity, improves edaphic structural configuration, replenishes nutrient pools, dramatically reduces land degradation, and soil erosion on steep terraces affected by continuous cultivation. Farmers periodically introduce multipurpose agroforestry (fruit, fodder/fuelwood/timber) species including *Acer campbellii*, *Alnus nepalensis, Betula alnoides*, *Bauhinia variegata*, *Bauhinia purpurea*, *Macaranga nepalensis*, *Michelia excelsa*, *Symingtonia populnea*, *Schima wallichii*, *Quercus lamellosa*, *Toona ciliata*, *Terminalia myriocarpa*, *Pterocarpus santalinus*, and *Prunus napaulensis*. Complementarily, fast-growing N_2-fixing species like *Alnus nepalensis*, *Albizia lebbeck*, and *Albizia stipulata* were also integrated to increase N, P, and K inputs and allow organic matter accumulation. Soon after the fallow period, farmers carry out selective thinning of trees and fallow vegetation, introduce understory cereals, pulses, ginger or vegetable crops, and establish broom grass along terrace edges, thus facilitating smooth transition between fallow and active agriculture.

New soil fertility techniques

The Government of Sikkim officially announced an organic farming initiative in 2003, and eventually banned the use of chemical fertilizers, pesticides and weedicides under *The Sikkim Agricultural, Horticultural Input and Livestock Feed Regulatory Act, 2014*. Sikkim was later declared a fully organic farming state by the Prime Minister of India on 8 January 2016 in Gangtok. Following this, organically produced biopesticides, weedicides, herbicides and farm-based manures were given due importance drawing an age-old traditional knowledge on the production of *Beejamrut*, *Jeevamrut*, *Jholmaal*, *Gaut-mal*, and *Panchagavya*. Subsequently, agriculture extension agencies including the Government of Sikkim’s Department of Agriculture/Horticulture introduced *Ganeula-mal* (vermicomposting), *Azolla* (a fast-growing aquatic fern), and Effective Microorganisms (EM) technology to meet the added challenges of maintaining soil nutrient availability

(Fig. g, h). When asked about the effectiveness of these technologies, the field officials of the Government of Sikkim stated that these technologies were believed to enrich soil macro- and micronutrients, augment enzymatic compounds, promote the nutrient mineralization process, intensify soil biological activity, and ultimately improve plant metabolic function.

Nutrient concentrations in organic manure

Household interviews confirmed that piggery and goat husbandry had been a notable economic option for marginal and small holders (10-15%), and traditional breeds of poultry farming for around 80% of small holders, while pig dung and poultry waste had been used as manure across the surveyed sites. Laboratory analysis confirmed that pig manure and poultry waste contains high total-N (3.12±0.18%), total-P (0.42±0.08%) (Table 4). Around 15% of families used poultry waste as manure in addition to compost and livestock-based excreta. Besides, goat-dung also had considerable percentage of total-N (32.68±0.93) and total-P (0.29±0.04), widely used for cereals, vegetables, and fodder cultivation, and often integrated into agroforestry systems, or sometimes making organic slurries such as *Jhol-maal*, to supplement essential nutrients for healthier and more resilient farms. FYM and bio-composts were universally applied by all farming families. Bio-compost and FYM also had high percentage of total-N and total-P and were widely used by all the traditional farmers (99%) across study sites.

Table 4 — Per cent nutrient concentrations in different organic manures

Organic fertilizer	Total-N	Total-P
FYM	2.57±0.31	0.39±0.04
Pig dung	3.12±0.18	0.42±0.08
Goat dung	2.68±0.93	0.29±0.04
Poultry waste	2.88±0.19	0.32±0.06
Bio-compost	2.56±0.98	0.35 ±0.12

Soil chemical characteristics

Soil physical and nutrient related chemical characteristics varied markedly across the five different agroforestry systems (Table 5). Alder-cardamom agroforestry showed highest soil moisture content (39.17±7.63%) and organic-C (3.78±0.61%), exhibiting substantial water retention and accumulation of organic matter. Similarly, farm forest-based systems recorded highest bulk density (1.27±0.05 g cm^{-3}), signifying moderate compaction under low intensity ploughing. Soil pH reflected higher acidity in alder–cardamom systems (4.56±1.21), while farm-based and mixed-tree forest-cardamom agroforestry had maintained soil conditions with near-neutral pH (6.34±1.64). The alder–cardamom and farm-based systems recorded comparatively higher total-N and total-P contents, whereas available-P peaked in mixed-tree forest-cardamom agroforestry (0.008±0.002%), illustrating pronounced impact of N_2-fixing species and litter inputs on accelerating soil nutrient dynamics.

Correlation analysis of the soil parameters across the five AbFS (Fig. 2) showed clear patterns of association among key nutrients. A positive relationship was observed between soil moisture, total-N, and organic-C, suggesting that higher moisture levels enhance microbial processes and the breakdown of organic materials, thereby supporting improved nutrient release. Total-P also showed a moderately strong positive association with organic-

Table 5 — Soil properties in the traditional farms at 0-30 cm soil depth

Agroforestry systems	Soil texture	Soil moisture	Bulk density	pH	Total-N (%)	Total-P (%)	Available-P (%)	Organic-C (%)
Farm-based agroforestry	Sandy-loam	32.47±6.17	0.87± 0.02	6.54±1.45	0.28±0.09	0.14±0.08	0.006±0.001	2.75±0.45
Alnus-cardamom-based agroforestry	Silty, clay-loam	39.17±7.63	0.98±0.05	4.56±1.21	0.29±0.11	0.16±0.09	0.006±0.002	3.78±0.61
Mix-tree-forest-cardamom agroforestry	Sandy-loam	24.76±5.14	0.76±0.03	6.34±1.64	0.26±0.09	0.10±0.02	0.008±0.002	2.78±0.62
Forest-based agroforestry	Silty, clay-loam	28.76±3.27	1.27±0.05	5.38±1.43	0.24±0.10	0.12±0.08	0.007±0.002	3.68±0.38
Mandarin orange-mix tree based agroforestry	Silty-loam	26.34±4.42	0.82±0.03	6.23±1.21	0.27±0.01	0.11±0.006	0.007±0.001	2.74±0.45

ANOVA for nutrient concentration: Sites- Pendam, Lingee, Dzongu and Hee-Bermiok; Stands- Agroforestry Stands: Soil moisture- Sites NS, Stands $p<0.0001$, Sites x Stands $p<0.0001$; pH- Sites NS; Stands $p<0.0001$, Sites x Stands NS; Total-N- Sites NS, Stand $p<0.0001$, Sites x Stands $p<0.005$; Total-P- Sites NS, Stands $p<0.0001$, Sites x Stands $p<0.005$; Available Phosphorus- Sites NS, Stands $p<0.0001$, Sites x Stands $p<0.0001$; Organic-C- Sites NS, Stand $p<0.0001$, Sites x Stands $p<0.005$

C, indicating their simultaneous accumulation through organic inputs and litter decomposition. Contrary to this, bulk density displayed a negative correlation with soil moisture and organic-C, indicating how soil compaction restricts aeration, reduces pore space, and suppresses biological activity. Correlations between soil pH and nutrient concentrations were weak and inconsistent, pointing to site-specific differences in soil acidity across agroforestry systems. This correlation matrix substantiates the combined influence of organic matter and soil moisture in stabilizing soil fertility and reinforcing structural stability across traditional agroforestry landscapes.

Discussion

The AbFS in the eastern Himalayan region demonstrate a highly advanced degree of ecological functioning and system sophistication, supporting sustained productivity across environmentally sensitive and fragile mountain ecosystems. The results of this study corroborate that farm-based, forest-based, alder-cardamom-based, mix-tree-forest-cardamom-based, and mandarin orange mixed-tree-based agroforestry exhibited superior soil quality, characterized by higher soil moisture, organic-C, total-N and total-P levels. Earlier reports confirm that N_2-fixing species enhance biological N_2-fixation, improve soil aggregation, and stabilize slopes-confirming the environmental and ecological efficiency of traditional agroforestry models[15-17].

The integrated application of FYM, in situ manuring, N_2-fixing species and legume rotations, land fallowing, terrace-riser slicing and controlled burning, green manuring, floodwater and silt trapping, and recycling of kitchen waste constitutes a highly adaptive soil nutrient management strategy on marginal and smallholder farms, substantially reducing reliance on external agricultural inputs. The use of FYM (10-35 t ha^{-1}) and composting cycles of 6 to 12-months maintained soil fertility sustainability, consistent with studies across the Himalaya[18,19]. Several studies consequently confirmed that these organic inputs improve soil texture, enhance soil moisture, improve water retention, and invigorate microbial activity while lowering acidity and curbing nutrient leaching[20-22]. The incorporation of poultry and livestock farming enterprises reinforced soil nutrient cycling efficiency, contributing to the household level food and economic sustainability[23].

Sikkim's complete transition to organic farming represents a successful convergence of TEK and enabling policy frameworks. The Sikkim Organic Mission institutionalized the systematic use of organic inputs-such as *Jholmal*, *Jeevamrut*, *Panchagavya*, FYM, biocompost, *Azolla*, and N_2-fixing species-with a strong emphasis on microbial activation and enzyme-rich formulations to enhance soil health and nutrient regeneration. Regrettably, the ongoing erosion of TEK, youth migration out of farming, and

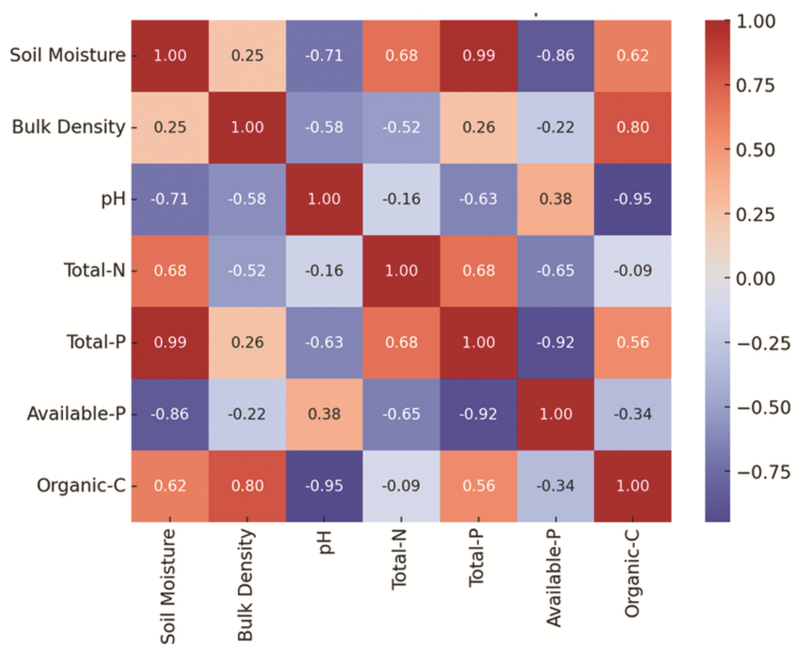

Fig. 2 Correlation matrix of soil physico-chemical properties (0-30 cm depth) across traditional agroforestry systems

limited market access continue to pose major challenges. Advancing co-production of TEK and science-based knowledge, and bolstering farmer-led innovation, documentation, and participatory research can advance continuity and scalability[20,24,25]. Comparable practices have been reported from the Garhwal and Nepal Himalayas, where farmers incorporate forest-tree litter with FYM to enrich soil in agroecosystems[20-21].

With the growing need to devise “climate resilient agriculture”, the TPSFM practices substantially advance climate resilience, through improved soil moisture retention, erosion control, yield improvement, and C-sequestration[21]. Earlier studies have substantiated that traditional technologies for water storage, the management of agricultural residues, and revitalization of family farming contribute to sustaining agriculture in the face of climate variability[5,6]. Similarly, reports confirm that TEK systems in Bhutan and Nepal Himalayas accentuate the incorporation of N_2-fixing crops, green manure, and legumes, while practices involving FYM, chicken manure, bio-slurry, and compost further enhance soil fertility and crop yields[20,26].

The traditional TPSFM practices of the Sikkim Himalaya-including the use of organic bio-composts and manures, green manuring, mulching, agroforestry integration, and moisture-retentive terracing are functionally consistent with Andean systems such as *Waru-Waru*, *Qochas*, and *Albarradas*, as all draw attention to the synergistic management of soil, water, and biomass through indigenous, low-carbon, and climate-resilient methods that enhance moisture regulation, sustain fertility, and maintain agroecosystem productivity under diverse mountain conditions[27]. Another notable example of TEK-based farming practices is the alder-based agroforestry, an age-old system designed and developed by indigenous tribes of Nagaland, including the Chakhesang, Angami, Yimchunger, Konyak and Chang[18].

This study strengthens that TPSFM systems are in line with the principles of Climate-Smart Agriculture by increasing productivity, fostering adaptation, and contributing to mitigation[28]. Sikkim Himalayan agroforestry systems function as ecosystem-based adaptation (EbA) models, integrating provisioning, regulating, and cultural ecosystem services through diversified tree-crop associations that enhance carbon storage and environmental resilience. Integration of TEK with modern soil science an optimize sound soil fertility management system. This approach can bridge empirical wisdom and modern sustainability science.

Conclusion

TPSFM in the Sikkim Himalaya demonstrate a sustainable, low-carbon, pollution-free, and biodiversity-supportive agricultural frame work that integrates livestock husbandry, agroforestry, and organic nutrient cycling, thereby sustaining soil health and ecosystem functionality under dynamic and fluctuating climatic conditions. The Sikkim model of AbFS represents a scientifically sustained and policy-salient framework for mountain agricultural sustainability, where in ecological integrity, socio-economic resilience, and TEK function as interdependent and mutually reinforcing pillars of long-term environmental stewardship.

Acknowledgements

This study was supported by Jawaharlal Nehru University (JNU) under the National Mission for Sustaining the Himalayan Ecosystem. I thank Dr. Rajeev Semwal and Prof. S.C. Garkoti for their technical support. I acknowledge field assistance extended by Dr. Santosh K. Chettri and Durga P. Sharma. Sincere thanks are due to the indigenous communities for sharing their invaluable traditional knowledge and practices. TMI India and GB Pant Himalayan Institute (GBPIHED) Tadong provided facilities.

Conflict of Interest

The author declares no conflict of interest.

Author Contributions

The study was conceptualized, data collected, analyzed, and the manuscript drafted and finalized by the author.

Ethics Statement

The study followed institutional ethical guidelines.

Informed Consent

Prior informed consent was obtained from all informants.

Data Availability

Data will be available upon reasonable request.

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