International Journal of Plant & Soil Science

Volume 38, Issue 5, Page 320-331, 2026; Article no.IJPSS.158655
ISSN: 2320-7035

A Systematic Review of Soil Health Restoration Pathways and Ecosystem Functionality in Bhutan's Mountain Agro-ecosystems

Yenten Namgay [a*], Passang Wangmo [a], Tshetrim La [a], Tshering Tobgay [a] and Kinzang Dorji [a]

[a] *National Centre for Organic Agriculture, Department of Agriculture, Ministry of Agriculture and Livestock, Bhutan.*

Authors' contributions

This work was carried out in collaboration among all authors. Author YN conceptualized and designed the study, conducted the literature review, data analysis and prepared the first draft of the manuscript. Author PW contributed to the systematic review methodology and review of the first draft. Author TT managed the literature search, screening, and organization of references. Author KD contributed to the interpretation of findings and critical revision of the manuscript. Author TL supervised the overall study and provided technical guidance and editorial inputs. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i56084

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/158655

Review Article

Received: 07/03/2026
Accepted: 13/05/2026
Published: 16/05/2026

Abstract

This systematic narrative review evaluated soil health restoration pathways in Bhutan using evidence synthesized from peer-reviewed literature, national datasets, and technical reports. The review examined interventions across five domains: soil regeneration, nutrient cycling, crop diversification, hydrological resilience, and ecological pest regulation within farming systems characterized by steep slopes, fragmented

---

**Corresponding author: E-mail: yenten777@gmail.com;*

***Cite as:** Namgay, Y., Wangmo, P., La, T., Tobgay, T., & Dorji, K. (2026). A Systematic Review of Soil Health Restoration Pathways and Ecosystem Functionality in Bhutan's Mountain Agro-ecosystems. International Journal of Plant & Soil Science, 38(5), 320–331. https://doi.org/10.9734/ijpss/2026/v38i56084*

landholdings, and annual soil losses ranging from 3–21 t ha^{-1}. Findings showed that integrated soil and nutrient restoration practices comprising organic amendments, residue retention, reduced tillage, and diversified cropping systems substantially improved soil quality and ecosystem stability. Regenerative management increased soil organic carbon by approximately 17%, with sequestration rates ranging from 0.2–1.5 Mg C ha^{-1} yr^{-1} depending on management intensity and site conditions. Organically managed systems recorded higher total nitrogen (0.38%) and cation exchange capacity (22.26) compared to conventional systems (0.26% and 19.45, respectively). Between 2005 and 2023, sustainable land management initiatives established 1,347.42 ha of terracing, 2,097.02 ha of contour hedgerows, 355.17 ha of stone bunding, and 3,333.48 ha of landslide stabilization plantations, significantly contributing to erosion control and landscape restoration. However, labour shortages, limited mechanization, and weak market integration continue to constrain widespread adoption of regenerative practices in Bhutan.

Keywords: Soil health restoration; mountain agro-ecosystem; sustainable land management; integrated nutrient management; hydrological resilience.

1. Introduction

Bhutan's agricultural sector remains foundational to national livelihoods, culture, food security, and sustainable development, despite its structural and environmental constraints (Chhogyel et al., 2020). According to the report by National Statistics Bureau, agriculture, livestock, and forestry together contribute approximately 14.7% of GDP, while employing about 43.5% of the national workforce, with women comprising nearly 58% of agricultural employment - highlighting the sector's strong socio-economic and gender dimensions (NSB, 2025). In 2023, crop production contributed 6.57% to GDP and livestock 5.91% (NSB, 2024). However, the sector operates within a highly limited land base: although about 7% of Bhutan's total geographical area is considered cultivable, only around 2.93% is currently under cultivation (NSSC & PPD, 2011), reflecting both physical constraints and land-use limitations. Bhutan agro-ecology spans from an elevation of 150-4600 meters above sea level which support a wide range of crops from sub-tropical to alpine region (MoA, 1992).

Table 1. Major Agroecological Zones of Bhutan. Source adapted from (MoA, 1992)

Agro-Ecological Zone	Altitude (meters)	Temperature (°C)			Rainfall (mm/year)
		Monthly Max	Monthly Mean	Annual Mean	
Alpine	3,600–4,600	12	-0.9	5.5	< 650
Cool Temperate	2,600–3,600	22.3	0.1	9.9	650–850
Warm Temperate	1,800–2,600	26.3	0.1	12.5	850–1,200
Dry Sub-Tropical	1,200–1,800	28.7	3	17.2	850–1,200
Humid Sub-Tropical	600–1,200	33	4.6	19.5	1,200–2,500
Wet-Subtropical	150–600	34.6	11.6	23.6	2,500–5,500

However, Bhutan's agriculture is constrained by its mountainous topography with a substantial proportion of farmland is located on steep slopes -many exceeding 30 degrees and classified as marginal for cultivation (Parker et al., 2017). Farming under such conditions accelerates soil erosion and land degradation, with studies reporting annual soil losses of 3–21 t/ha under conventional tillage, as fertile topsoil is displaced downslope, leaving nutrient-poor subsoil on upper terraces (Dorji et al., 2020). The rugged terrain and scattered, fragmented landholdings further restrict mechanization, making farming highly labour-intensive and limiting economies of scale (Chhogyel & Kumar, 2018). These biophysical challenges are compounded by small and fragmented landholdings, reducing commercialization potential and reinforcing subsistence-oriented production systems (Parker et al., 2017).

Climate change further amplifies these vulnerabilities with empirical studies showing increasing erratic rainfall, prolonged droughts, drying irrigation sources, and rising pest and disease incidence, resulting in measurable crop losses of 10 - 19% in major staples such as rice and maize, alongside shifts in cropping patterns (Chhogyel et al., 2020). Smallholder vulnerability assessments in central Bhutan reveal that exposure to drought, windstorms, and other climatic hazards significantly elevates livelihood risk and reduces adaptive capacity, with marked regional differences (Rinzin et al., 2020). Historical climate analyses also confirm substantial variability in seasonal rainfall, flooding, and landslides (Dorji & Tamang, 2019). Emerging risks such as glacial lake outburst floods (GLOFs), increased flood frequency, loss of irrigation water, and wildlife-induced crop damage further intensify pressures on farming systems (Komori et al., 2012; PPD, 2016). Projections under the Sector Adaptation Plan of Action (SAPA) anticipate a temperature increase of up to 3.5°C by the 2050s, accompanied by more erratic precipitation patterns, underscoring the long-term climate risks facing Bhutanese agriculture (NBC, 2009).

Therefore, sustainable land management is particularly important for Bhutan given its steep slopes, continuous soil erosion, small fragmented landholdings, and increasing climate variability (Rinzin et al., 2020). Studies also show that regenerative and conservation-based practices have shown to significantly reduce soil erosion, enhance soil organic carbon (SOC), improve water infiltration and retention, and stabilize yields under climatic stress (Hobbs et al., 2008; Lal, 2015; Montgomery, 2007; Paustian et al., 2016). Moreover, in mountain and rainfed systems, these practices strengthen resilience to droughts and erratic rainfall while reducing land degradation and enhancing long-term productivity (Altieri et al., 2015; Pretty et al., 2018). Additionally, increasing SOC through regenerative management contributes to climate mitigation and ecosystem restoration, aligning with Bhutan's carbon-neutral development pathway (Lal, 2020; Smith et al., 2008). Therefore, this article critically reviews and a science-based approach to simultaneously address Bhutan's soil degradation, water stress, climate vulnerability, and smallholder livelihood challenges.

2. Methodology

This study employed a systematic narrative review combined with a functional classification framework to evaluate soil regeneration practices in Bhutan. Peer-reviewed journal articles, national technical reports, and soil datasets from Bhutanese agricultural institutions were synthesized to assess measurable changes in soil indicators such as soil organic carbon (SOC), total nitrogen, available phosphorus, cation exchange capacity, bulk density, and aggregate stability. Only technical and scientific sources reporting quantitative soil data were included, while non-empirical and non-verified materials were excluded. Where long-term Bhutan-specific data were limited, proxy values from comparable Himalayan agro-ecological systems were cautiously referenced and clearly identified.

Practices were classified based on their dominant regenerative mechanism rather than their conventional labels. Soil regeneration practices were identified by their capacity to increase SOC, improve aggregate stability, enhance infiltration, and reduce bulk density, while nutrient regeneration practices were defined by their contribution to nutrient recycling and plant-available NPK pools. Comparative analysis was conducted across management types (organic vs. conventional), agro-ecological zones, and land-use systems (cropland vs. forest reference sites) to determine measurable regenerative outcomes.

3. Sustainable Land Management and Soil Regenerative Practices

3.1 Soil Health Restoration and Biophysical Soil Processes

Bhutan's agricultural landscape is dominated by mountainous terrain, with over 70 % of cultivated land situated on steep slopes that are highly susceptible to erosion and degradation (Parker et al., 2017). Soil fertility and carbon stocks are therefore critical determinants of productivity and long-term sustainability. National SOC mapping indicates that Bhutanese croplands generally store lower organic carbon than forested areas (Bajgai et al., 2025). Soil and water conservation practices promoted under Bhutan's BHUCAT framework serve as essential measures to reduce erosion and stabilize soils in these fragile landscapes, creating conditions conducive for SOC accumulation under improved management (NSSC, 2025).

According to Patil et al., (2025), integrated regenerative practices - comprising organic amendments, reduced tillage, and crop residue retention - can increase SOC by approximately 0.17 percentage points, representing a ~17 % gain over baseline levels after several years of adoption, although responses vary with climate, soil type, and baseline conditions. The same study found that organic amendments such as farmyard manure, green manure, and compost often increase soil organic carbon more effectively than tillage reduction alone, while conservation tillage with residue return can raise SOC by 23–24% and reduce nitrous oxide emissions compared to conventional systems. Additionally, according to Meng et al. (2024), diversified rotations and cover cropping further enhance carbon stabilization by increasing organic matter within macroaggregate fractions, thereby improving soil porosity, water retention, and structural stability. Long-term studies also suggest SOC sequestration rates ranging from 0.2 to 1.5 Mg C ha^{-1} yr^{-1} depending on management intensity and site-specific conditions, highlighting the cumulative and gradual nature of soil regeneration (Gentsch et al., 2024; Kumar et al., 2025).

Table 2. Types and Area of ALD/SLM interventions from 2005 to 2023 (NSSC, 2024)

Type of ADL/SLM Interventions	2005-2017 (Ha)	Achievements in the 12FYP (2018-2023) in Hectares					
		2018-19	2019-20	2020-21	2021-22	2022-23	Total (2018-23)
Terracing (bench/dryland)	261.68	185.97	341.89	557.88	0.00	0.00	1085.74
Terrace consolidation	10.93	34.65	151.70	208.68	0.00	0.00	395.04
Orchard terracing	0.00	2.43	0.00	6.62	0.00	0.00	9.04
Contour hedgerow	1480.71	324.13	100.34	191.85	0.00	0.00	616.31
Contour stone bund	321.93	16.59	1.86	14.79	0.00	0.00	33.24
Orchard basin making	46.54	18.90	16.94	0.00	0.00	0.00	35.83
Surface stone removal	2.83	2.77	154.75	12.06	0.00	0.00	169.59
Check dams	80.94	72.44	0.00	0.00	0.00	0.00	72.44
Orchard establishment	994.68	19.42	23.67	1.82	0.00	0.00	44.92
Landslide stabilization (plantation)	3246.11	84.58	0.00	2.79	0.00	0.00	87.37
Integrated plant nutrient management (FYM, vermi-compost, bio-fertilizers)	223.59	175.61	0.00	0.00	0.00	0.00	175.61
Water source protection	32.94	2.83	0.00	9.67	0.00	0.00	12.50
Improving ground cover & soil ferility through legume promotion	0.00	0.00	0.00	83.41	0.00	0.00	83.41
Fallow land reversion	0.00	0.00	233.38	282.38	0.00	0.00	516.33

Note: Original data were reported in acres and subsequently converted to hectares to ensure uniformity and consistency throughout article

A 2025 study comparing organic fields, conventional fields, and natural vegetation across high, mid, and low-altitude sites in central Bhutan reported significantly higher SOC under organically managed fields at high altitudes, confirming the potential for regenerative practices to build carbon stocks relative to conventional systems (Bajgai et al., 2025). The study also found that SOC positively correlated with silt and clay fractions, indicating that soil texture interacts with management to enhance carbon stabilization (Lepcha, 2022). In potato-based systems, organically managed soils exhibited higher total nitrogen (0.38 %) compared to conventional soils (0.26 %), along with significantly higher cation exchange capacity (22.26 vs 19.45), reflecting improved nutrient retention and cycling under regenerative management (Yangzom & Choden, 2021). Similarly, rice fields in eastern Bhutan (Radhi, Trashigang) showed SOC ranging from 0.3 % to 2.9 % under different nutrient management practices, highlighting the potential for organic amendments and residue management to enhance carbon stocks even in irrigated paddy systems (Dorji et al., 2019).

The National Soil Services Centre carried out multiple sustainable land development (SLM) initiatives between 2005 to 2023 under different projects to stabilize and regenerate soil systems (Table 2). Under this initiative, a total of 1,347.42 ha of land was developed with bench terracing, 405.97 ha of terrace consolidation, around 2,097.02 ha of contour hedgerow planting, 355.17 ha of stone bunding and 3,333.48 ha of landslide stabilization plantation was carried which directly benefited in soil conservation and stabilization (NSSC, 2024). These findings collectively illustrate that regenerative soil practices can substantially enhance SOC, nutrient availability, and structural stability in Bhutanese mountain agriculture.

3.2 Nutrient Cycling and Internal Input Generation

Bhutan’s nutrient management is rooted in traditional reliance on farmyard manure (FYM) and organic soil amendments, which remain the dominant source of plant nutrients across smallholder fields, even as socio-economic change has increased limited use of inorganic fertilizers in recent decades (NSSC, 2009). Long-term experiments in Bhutan's rice - wheat systems demonstrate that application of ~7 t ha^{-1} FYM over multiple years increases soil organic carbon and that incorporation of green manuring (Sesbania aculeata) can replace synthetic NPK fertilizer for rice yields after several years, while also increasing total nitrogen and available potassium levels, illustrating practical outcomes of organic nutrient recycling in field conditions (Chettri et al., 2003). Despite this foundation, formalized nutrient cycling strategies such as systematic legume rotations, cover cropping, and integrated nutrient management (INM) remain underdeveloped in Bhutan, contributing to persistent nitrogen deficits at the farm and district levels (Tshotsho et al., 2024).

Table 3. Crop yield comparison between IPNS technology and farmers' soil fertility management (Chhetri, 2019)

Crop	Yield (t/ha)		Difference
	IPNS Technology	Farmers' SFM	
Rice	6.20	5.10	+1.10
Wheat	9.88	4.94	+4.94
Potato	15.91	10.92	+4.99
Onion	13.10	11.36	+1.74

Soil Nutrient and fertilizers trial carried out by NSSC also reported a market difference in crop yield under IPNS technology than yield under farmers management as shown in **Table 3** in major crops like rice wheat, potato and onion (Chhetri, 2019). Additionally, in alignment with Bhutan's environmental commitments, the Low Emission Development Strategy (LEDS) for Food Security (2021) promotes a phased shift from synthetic to organic fertilizers, targeting a 5% annual reduction in chemical fertilizer use and a 25% annual increase in organic fertilizer production through 2030 (Table-4) (MoAF, 2021).

Table 4. Annual organic fertilizer production targets (2023-30) (MoAF, 2021)

Financial Year	2023	2024	2025	2026	2027	2028	2029	2030
Production (MT)	3200	4000	5000	6250	7813	9766	12208	15260

Recent soil assessments in the Bhutanese Himalayas show that intensive organic management practices enhance soil macro-nutrients and influence soil properties, with organic fields exhibiting different nutrient availabilities across altitudes, suggesting that management and environmental factors jointly shape nutrient dynamics (Bajgai et al., 2025). Surveys of rice fields in eastern Bhutan document that combinations of organic manure and inorganic fertilizer often improve nutrient content and crop performance over single input practices, indicating the potential benefit of blending organic sources with limited mineral inputs to balance nutrient availability in paddy systems (Yangzom & Choden, 2021).

Studies also reported that integrated approaches to nutrient cycling - such as integrated nutrient management (INM), legume cover crops, and residue incorporation increases crop yields and soil quality, enhances water-use efficiency, and reduces nutrient losses and greenhouse gas emissions compared with conventional systems (Paramesh et al., 2023; Wu & Ma, 2015). Similarly, cover cropping and green manure incorporation are shown to boost nutrient cycling, improve soil organic matter and microbial activity, and limit nutrient leaching and erosion, although adoption remains limited and context-specific barriers exist (Arlauskienė & Šarūnaitė, 2023; Koudahe et al., 2022). Between 2005 to 2023, promotion of different fertilizers such as Farmyard Manure, vermi-compost and bio-fertilizers were carried out covering an approximate area of 986 acres across Bhutan. Additionally, to improve ground cover & soil fertility, legumes were promoted in around 206 acres of land (NSSC, 2024).

3.3 Crop System Diversification and Functional Complexity

Crop rotations and sequence planning is one of the primary mechanisms to restore soil processes, regulate pests, and stabilize yields under climatic stress (Rhodes, 2017; Schreefel et al., 2020). In Bhutan, traditional rotational systems such as rice - wheat/barley sequences in temperate valleys and maize - legume rotations in mid-altitudes enhance soil nitrogen availability through biological fixation and residue incorporation (Neuhoff et al., 2014). Legume-inclusive rotations improve nutrient access by increasing nitrogen supply and enhancing belowground microbial activity, thereby reducing dependence on external inputs (Lal, 2015; Zhao et al., 2022). Globally, diversified crop rotations significantly reduce pest and disease incidence by interrupting host cycles and lowering pathogen carryover compared to monocultures (Beillouin et al., 2021). Diversified rotations also enhance soil organic carbon stocks, which improves water retention and buffers crops against drought and erratic rainfall - critical in Bhutan's fragile mountain agroecosystems (Rai et al., 2022; Yang et al., 2024). Thus, Bhutan's traditional rotational diversity aligns strongly with soil regenerative principles linking nutrient cycling, pest suppression, and climate resilience.

Agroforestry, perennial integration of fruit trees, fodder species, and forest perennials within farms enhances vertical stratification, increases carbon sequestration, and improves microclimatic stability (Garrity, 2004; Jose, 2009). Perennial integration also supports biological pest regulation by increasing habitat heterogeneity and sustaining beneficial arthropod communities (Tamburini et al., 2016). Bhutan's maintenance of diverse landraces of rice, maize, buckwheat, millet, and legumes enhances genetic diversity, which strengthens resistance to pests, diseases, and climatic extremes (Oehri et al., 2017). Between 2005 to 2023 **(Table 2)**, orchards were established in 1,039.6 ha of land across the country and 516.33 ha of fallow land reversion was carried which directly contributed to productive agro-ecosystem and crop diversification (NSSC, 2024). Additionally, a study carried out by Tashi et al., (2023) in the southern part of Bhutan reported multiple cropping system practices in the region. Same study **(Table 5)** reported that farmers in the southern belt grew almost all subtropical cereals, vegetables, fruits, and other food plants from which paddy and maize were the dominant annual crops grown in wet and dryland respectively. Additionally, garlic, ginger, and turmeric were commonly grown spices, whereas areca nut, litchi, banana, mango, pineapple, jackfruit, and mandarin were the popular fruits.

Table 5. Cropping pattern in Sarpang district (Tashi et al., 2023)

Dryland Crops	Respondent (%)	Wetland Crops	Resp. (%)
Maize-Vegetables	43	Paddy-Fallow	49
Maize-Chilli	39	Paddy-Vegetables	34
Maize-Maize	23	Paddy-Chilli	32
Vegetables-Onion	15	Paddy-Maize	25
Ginger-Vegetables	13	Paddy-Wheat	12
Potato-Maize	12	Paddy-Mustard	13
Maize-Millet	12	Paddy-Onion	8
Maize-Vegetables-Maize	12	Paddy-potato	6
Maize-Fallow	12	Paddy Lentil	3
Vegetables-Fallow	10	Maize-Vegetables	3
Vegetables-Mustard	9	Ginger-Maize	2
Maize-Gram	3		

3.4 Water Regeneration and Hydrological Resilience

Restoring hydrological function in agricultural landscapes goes beyond irrigation efficiency to strengthen the water cycle through soil and landscape processes (Schreefel et al., 2020) and is increasingly important under climate variability in Bhutan, where seasonal droughts and erratic rainfall challenge rain-fed farming (Tariq et al., 2021). Soil organic matter plays a central role in hydrological regeneration by increasing soil moisture retention, aggregate stability, and infiltration capacity (Blanco-Canqui et al., 2013).In Bhutan's mountain agriculture, organic amendments and residue retention in fields contribute to improving soil structural quality and water holding capacity, which enhances drought buffering and reduces crop water stress, even in steep, rain-fed terrains (Dendup et al., 2021). Understanding and managing soil moisture dynamics is essential in Bhutan given the limited groundwater extraction potential and reliance on small rivers and springs for irrigation (Tariq et al., 2021).

Techniques such as earth bunds, check dams, and shallow trenches help capture and infiltrate runoff, increasing groundwater recharge and reducing dry-season water deficits (Ezz, 2025). National land management compilations like BHUCAT document traditional and modern soil & watershed conservation technologies - including contour bunds, grass strips, and micro-catchments - that slow surface flow, promote infiltration, and support landscape water storage (NSSC, 2025). Contour farming and terracing are long-established practices in

Bhutan; bench terraces on steep slopes reduce runoff velocity, trap soil moisture, and significantly mitigate erosion - practices central to resilient land use planning in mountainous paddy and upland fields (Gao et al., 2017) and reflected in local soil conservation programs (NSSC, 2025).

Soil cover strategies such as mulching, cover crops, and perennial vegetation protect the soil surface, slow overland flow, and increase infiltration and base flows in streams (Blanco-Canqui et al., 2013; Pretty et al., 2018). A critical review of water resources in Bhutan highlights the need for efficient, integrated water resource planning that balances hydropower, irrigation, and ecological needs, as well as improved irrigation water quality management to sustain agriculture and rural livelihoods (Jamyang, 2024). SLM projects between 2005 to 2023 (Table 2) supported 22.35 acres of terracing, 112.3 acres of water source protection and 379 acres of check dams across Bhutan which directly benefited in water regeneration and hydrological resilience (NSSC, 2024). Aligning traditional soil and water conservation with watershed-scale hydrological regeneration frameworks can strengthen Bhutan's capacity to manage water sustainably under climatic uncertainty.

3.5 Pest and Disease, Regulation through Ecology

Prior to the 1980s, pesticides were independently procured and freely distributed in Bhutan, resulting in misuse, over-application, and the accumulation of obsolete stocks nationwide (Dorji et al., 2019). Similar trajectories in many developing countries during the Green Revolution era have been associated with pesticide overuse, resistance development, environmental contamination, and human health risks (Pimentel & Burgess, 2014; Pretty & Bharucha, 2015). The institutionalization of the National Plant Protection Centre (NPPC) as the apex authority marked a structural shift toward centralized governance, regulatory oversight, and safer pesticide management (Dorji et al., 2019). Regenerative agriculture emphasizes redesigning systems to reduce external chemical dependence rather than merely improving application efficiency (Rhodes, 2017), and Bhutan's gradual withdrawal of pesticide subsidies in the early 1990s - completed by 1995 - functioned as an economic instrument to discourage indiscriminate chemical use. The collection and safe storage of 66 tonnes of obsolete pesticides in 1995 further signalled a transition toward environmental accountability and pollution mitigation, aligning with global calls for responsible pesticide lifecycle management (Tenzin, 2013).

The formal adoption of Integrated Pest Management (IPM) during the 7th Five-Year Plan (1992–1997) represented a paradigmatic shift from pesticide-based control to ecological regulation. IPM frameworks promote pest monitoring, economic threshold-based interventions, biological control, and habitat management as mechanisms to maintain pest populations below damaging levels rather than pursuing eradication (Kogan, 1998). Bhutan's EU-supported IPM Development Programme (1990-2000) strengthened research-extension-farmer linkages and facilitated the translation of IPM knowledge into field practice (Tenzin, 2013). Regenerative systems similarly prioritize preventive design - diversification, soil health enhancement, and ecological balance - to reduce pest outbreaks (Gurr et al., 2017). This approach is particularly relevant in Bhutan, where episodic pest epidemics have caused severe crop losses, including rice blast (total losses in some western districts in 1995-96), stem borer (>90% loss in Samtse in 2005), maize leaf blights (70-80% in eastern Bhutan in 2006 -2007), potato tuber moth (>95% in 2006), and fruit fly (up to 80% mandarin loss in 1990) (Tenzin, 2013). Ecological pest management literature indicates that diversified systems and biological regulation can substantially reduce outbreak intensity while maintaining yield stability (Tamburini et al., 2020).

Legislative consolidation through the Pesticide Act of Bhutan (2000) and the restriction of imports to relatively safer WHO Class II and III pesticides further institutionalized risk reduction (MoA, 2000). The banning of highly toxic and persistent chemicals between 1986 and 1990 mirrors international conventions aimed at eliminating hazardous pesticides due to ecological persistence and bioaccumulation risks (Carson, 2015). According to Pretty & Bharucha (2015), regenerative agriculture emphasizes redesigning farming systems to reduce dependence on chemical inputs through ecological processes rather than simply replacing them with safer alternatives. While moderate pest damage (often estimated at 10 - 20% under regular conditions) is accepted within managed systems, regenerative theory recognizes that zero pest presence is neither ecologically realistic nor necessary for productivity (Kogan, 1998; Rhodes, 2017).

A study conducted by Van Klinken et al.,(2018) (Table 6) identified pests and their damaging effects across different groups of invertebrates and pathogens. The asme study reported that among the invertebrates, insects recorded the highest number of pests (360), with 61.4% identified with high confidence and 17.5% reported as damaging pests. Among the pathogens, fungi showed the largest number of pests (219), with a high identification confidence of 76.3%. Overall, out of 645 pests recorded, 410 (63.6%) were identified with high confidence, while 112 (17.3%) were categorized as damaging pests, indicating that insects and fungi were the dominant pest groups affecting crops.

Table 6. Number of pest species recorded in Bhutan by taxonomic group and the number (and percentage) that were identified with high confidence and that were damaging (Van Klinken et al., 2018)

	No. pests	High confidence in identification (% total)	No. damaging pests (% total)
Invertebrates			
Insects	360	221 (61.4 %)	63 (17.5 %)
Mites	14	6 (42.9 %)	1 (7.1 %)
Molluscs	2	1 (50.0 %)	1 (50.0 %)
Nematodes[a]	24	5 (20.8 %)	0 (0.0 %)
Pathogens			
Fungi	219	167 (76.3 %)	36 (16.4 %)
Bacteria	7	5 (71.4 %)	5 (71.4 %)
Plasmodium	2	2 (100.0 %)	2 (100.0 %)
Virus	17	3 (11.8 %)	4 (23.5 %)
Total	645	410 (63.6 %)	112 (17.3 %)

[a]Nematodes were sampled from the soil associated with crops

4. Conclusion

Bhutan's mountain agro-ecosystems, confronted with steep topography, soil degradation, and accelerating climate vulnerabilities, require a transformative shift toward deep regenerative agriculture as a science-based pathway for enhancing long-term sustainability and smallholder resilience. The evidence synthesized across soil regeneration, nutrient cycling, crop diversification, and hydrological resilience domains confirms that integrated practices - combining organic amendments, reduced tillage, residue retention, diversified rotations, and agroforestry - can substantially increase soil organic carbon stocks (by approximately 17%), improve nutrient availability and retention, strengthen ecological pest regulation, and restore hydrological function across farm and landscape scales. National sustainable land management initiatives have established foundational infrastructure through terracing, contour hedgerows, and landslide stabilization, yet widespread adoption remains constrained by limited mechanization, acute labour shortages from rural out-migration, underdeveloped value chains, and persistent low profitability. Soil restoration initiatives require long-term planning, parallel investments in labour-saving technologies adapted to mountain conditions, market development for differentiated products, long-term monitoring across agro-ecological zones, and policy frameworks that internalize the full value of ecosystem services. With strategic investments and sustained commitment to farmer-centred innovation, Bhutan can strengthen soil regenerative pathways that align with cultural heritage, fulfill environmental commitments, and secures the well-being of mountain communities amid unprecedented climatic change.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Acknowledgement

I would like to acknowledge all the co-authors who have contributed in preparation, writing and review of this manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Altieri, M. A., Nicholls, C. I., Henao, A., & Lana, M. A. (2015). Agroecology and the design of climate change-resilient farming systems. *Agronomy for Sustainable Development*, *35*(3), 869–890. https://doi.org/10.1007/s13593-015-0285-2

Arlauskienė, A., & Šarūnaitė, L. (2023). Cover Crop Yield, Nutrient Storage and Release under Different Cropping Technologies in the Sustainable Agrosystems. *Plants*, *12*(16), 2966. https://doi.org/10.3390/plants12162966

Bajgai, Y., Adhikari, A., Lal, R., & Wangdi, T. (2025). Organic and Conventional Management Effects on Soil Organic Carbon and Macro-Nutrients Across Land Uses in the Bhutanese Himalayas. *Soil Systems*, *9*(3), 99. https://doi.org/10.3390/soilsystems9030099

Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V., & Makowski, D. (2021). Positive but variable effects of crop diversification on biodiversity and ecosystem services. *Global Change Biology*, *27*(19), 4697–4710. https://doi.org/10.1111/gcb.15747

Blanco-Canqui, H., Shapiro, C. A., Wortmann, C. S., Drijber, R. A., Mamo, M., Shaver, T. M., & Ferguson, R. B. (2013). Soil organic carbon: The value to soil properties. *Journal of Soil and Water Conservation*, *68*(5), 4. https://doi.org/10.2489/jswc.68.5.129A

Carson, R. (2015). *Silent spring. In Thinking about the environment. Routledge.* Taylor & Francis Group.

Chettri, G. B., Ghimiray, M., & Floyd, C. N. (2003). Effects of farmyard manure, fertilizers and green manuring in rice-wheat systems in bhutan: results from a long-term experiment. *Experimental Agriculture*, *39*(2), 129–144. https://doi.org/10.1017/S0014479702001163

Chhetri, S. (2019). *Integrated Plant Nutrition System Module for Major Crops and Cropping Systems in Bhutan*.

Chhogyel, N., & Kumar, L. (2018). Climate change and potential impacts on agriculture in Bhutan: A discussion of pertinent issues. *Agriculture & Food Security*, *7*(1), 79. https://doi.org/10.1186/s40066-018-0229-6

Chhogyel, N., Kumar, L., & Bajgai, Y. (2020). Consequences of Climate Change Impacts and Incidences of Extreme Weather Events in Relation to Crop Production in Bhutan. *Sustainability*, *12*(10), 4319. https://doi.org/10.3390/su12104319

Chhogyel, N., Kumar, L., Bajgai, Y., & Hasan, M. K. (2020). Perception of farmers on climate change and its impacts on agriculture across various altitudinal zones of Bhutan Himalayas. *International Journal of Environmental Science and Technology*, *17*(8), 3607–3620. https://doi.org/10.1007/s13762-020-02662-8

Dendup, C., Dorji, S., Tshomo, S., & Tshering, L. (2021). Impact of Improved Rice Variety on Productivity and Crop Diversity: A Case of Singye Gewog (Block) in Sarpang District of Southern Bhutan. *Asian Journal of Agricultural Extension, Economics & Sociology*, 96–104. https://doi.org/10.9734/ajaees/2021/v39i130510

Dorji, T., & Tamang, T. B. (2019). *Report on the analysis of historical climate and climate projection for Bhutan*. National center for hydrology and meteorology, royal government of Bhutan.

Dorji, T., Dorji, T., Pradhan, S., Tashi, D., & D.Dorji, K. (2019). *Digital Soil Mapping of Soil Organic Carbon Stock in Bhutan*. *2*(1).

Dorji, T., Wangdi, T., Tashi, D., D.Dorji, K., & Chedup, Y. (2020). *Soil Loss Prediction Using Revised Universal Soil Loss Equation (RUSLE) for Amochhu Watershed in South-western Bhutan*. *3*(1), 1–17.

Dorji, U., Dorji, K., & Azusa, F. (2019). *Inventory of Important Insect Pests, Diseases and the Beneficial Insects in Fruits and Vegetables in West Central Bhutan*. *2*(1), 143–159.

Ezz, H. (2025). Floodwater Harvesting for Groundwater Recharge: Techniques, Challenges and Applications. In Prof. A. F. Yousef (Ed.), *Geography, Earth Science and Environment: Research Highlights Vol. 6* (pp. 58–92). BP International. https://doi.org/10.9734/bpi/geserh/v6/4476

Gao, J., Jiao, K., Wu, S., Ma, D., Zhao, D., Yin, Y., & Dai, E. (2017). Past and future effects of climate change on spatially heterogeneous vegetation activity in China. *Earth's Future*, *5*(7), 679–692. https://doi.org/10.1002/2017EF000573

Garrity, D. P. (2004). Agroforestry and the achievement of the Millennium Development Goals. *Agroforestry Systems*, *61–62*(1–3), 5–17. https://doi.org/10.1023/B:AGFO.0000028986.37502.7c

Gentsch, N., Riechers, F. L., Boy, J., Schweneker, D., Feuerstein, U., Heuermann, D., & Guggenberger, G. (2024). Cover crops improve soil structure and change organic carbon distribution in macroaggregate fractions. *SOIL*, *10*(1), 139–150. https://doi.org/10.5194/soil-10-139-2024

Gurr, G. M., Wratten, S. D., Landis, D. A., & You, M. (2017). Habitat Management to Suppress Pest Populations: Progress and Prospects. *Annual Review of Entomology*, *62*(1), 91–109. https://doi.org/10.1146/annurev-ento-031616-035050

Hobbs, P. R., Sayre, K., & Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1491), 543–555. https://doi.org/10.1098/rstb.2007.2169

Jamyang. (2024). *Assessment of surface water quality for irrigation from six different districts in Bhutan* [Pdf]. 1.2 MB. https://doi.org/10.22004/AG.ECON.348581

Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: An overview. *Agroforestry Systems*, *76*(1), 1–10. https://doi.org/10.1007/s10457-009-9229-7

Kogan, M. (1998). Integrated Pest Management: Historical Perspectives and Contemporary Developments. *Annual Review of Entomology*, *43*(1), 243–270. https://doi.org/10.1146/annurev.ento.43.1.243

Komori, J., Koike, T., Yamanokuchi, T., & Tshering, P. (2012). Glacial lake outburst events in the Bhutan Himalayas. *Global Environmental Research*, *16*(1), 59–70.

Koudahe, K., Allen, S. C., & Djaman, K. (2022). Critical review of the impact of cover crops on soil properties. *International Soil and Water Conservation Research*, *10*(3), 343–354. https://doi.org/10.1016/j.iswcr.2022.03.003

Kumar, N. A., Jattan, P., Digambar, W. D., Mohapatra, R., Yadav, K. K., Sharma, C., & Chaudhary, S. (2025). A Review of Soil Organic Carbon Dynamics under Regenerative Agricultural Practices. *International Journal of Plant & Soil Science*, *37*(9), 142–153. https://doi.org/10.9734/ijpss/2025/v37i95693

Lal, R. (2015). Restoring Soil Quality to Mitigate Soil Degradation. *Sustainability*, *7*(5), 5875–5895. https://doi.org/10.3390/su7055875

Lal, R. (2020). Soil organic matter and water retention. *Agronomy Journal*, *112*(5), 3265–3277. https://doi.org/10.1002/agj2.20282

Lepcha, N. (2022). *Macronutrients (NPK) and other soil properties influenced by long term organic and conventional potato farming in West-Central Bhutan*. *18*(3).

Meng, X., Meng, F., Chen, P., Hou, D., Zheng, E., & Xu, T. (2024). A meta-analysis of conservation tillage management effects on soil organic carbon sequestration and soil greenhouse gas flux. *Science of The Total Environment*, *954*, 176315. https://doi.org/10.1016/j.scitotenv.2024.176315

MoA. (1992). *National research programme. Ministry of Agriculture (MoA). Royal Government of Bhutan, Thimphu; 1992.*

MoA. (2000). *THE PESTICIDES ACT OF BHUTAN 2000. Ministry of Agriculture, Bhutan*.

MoAF. (2021). *Low Emissions Development Strategy (LEDS) for Food Security in Bhutan: Agriculture & Livestock Sector. Royal Government of Bhutan. Thimphu, Bhutan*.

Montgomery, D. R. (2007). Soil erosion and agricultural sustainability. *Proceedings of the National Academy of Sciences*, *104*(33), 13268–13272. https://doi.org/10.1073/pnas.0611508104

NBC. (2009). *Biodiversity Action Plan for Bhutan; National Biodiversity Center, Ministry of Agriculture and Forests: Thimphu, Bhutan, 2009.*

Neuhoff, D., Tashi, S., Rahmann, G., & Denich, M. (2014). Organic agriculture in Bhutan: Potential and challenges. *Organic Agriculture*, *4*(3), 209–221. https://doi.org/10.1007/s13165-014-0075-1

NSB. (2024). *National Accounts Statistics 2024. National Statistics Bureau, Bhutan*.

NSB. (2025). *Integrated agriculture and livestock census of Bhutan 2025*.

NSSC, & PPD. (2011). *Technical Report: Bhutan Land Cover Assessment 2010 (LCMP-2010). National Soil Services Centre (NSSC) & PPD, MoAF*.

NSSC. (2009). *Soil Erosion-Measurement and Analysis of soil erosion plot data 200. The National Soil Services Centre, Department of Agriculture, Ministry of Agriculture and Forests*.

NSSC. (2024). *National Database on Agriculture Land Development (ALD)—Sustainable Land Management (SLM) for 12FYP* [Dataset].

NSSC. (2025). *Bhutan Soil and Water Conservation Approaches and Technologies: A Compilation of Selected Sustainable Land Management (SLM) Best Practices Promoted on Steep to Very Steep Slopes of Bhutan.* National Soil Services Centre (NSSC), Semtokha Department of Agriculture Ministry of Agriculture and Livestock Royal Government of Bhutan, Thimphu.

Oehri, J., Schmid, B., Schaepman-Strub, G., & Niklaus, P. A. (2017). Biodiversity promotes primary productivity and growing season lengthening at the landscape scale. *Proceedings of the National Academy of Sciences*, *114*(38), 10160–10165. https://doi.org/10.1073/pnas.1703928114

Paramesh, V., Mohan Kumar, R., Rajanna, G. A., Gowda, S., Nath, A. J., Madival, Y., Jinger, D., Bhat, S., & Toraskar, S. (2023). Integrated nutrient management for improving crop yields, soil properties, and reducing greenhouse gas emissions. *Frontiers in Sustainable Food Systems*, *7*, 1173258. https://doi.org/10.3389/fsufs.2023.1173258

Parker, L., Guerten, N., Nguyen, T. T., Rinzin, C., Tashi, D., Wangchuk, D., Bajgai, Y., Subedi, K., Phuntsho, L., & Thinley, N. (2017). *Climate change impacts in Bhutan: Challenges and opportunities for the agricultural sector*.

Patil, M., Perumal, C., Choudhari, P., Pasumarthi, R., Sawargaonkar, G., & Singh, R. (2025). Differential impacts of regenerative agriculture practices on soil organic carbon: A meta-analysis of studies from India. *Scientific Reports*, *15*(1), 33470. https://doi.org/10.1038/s41598-025-12149-6

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, *532*(7597), 49–57. https://doi.org/10.1038/nature17174

Pimentel, D., & Burgess, M. (2014). Environmental and Economic Costs of the Application of Pesticides Primarily in the United States. In D. Pimentel & R. Peshin (Eds.), *Integrated Pest Management* (pp. 47–71). Springer Netherlands. https://doi.org/10.1007/978-94-007-7796-5_2

PPD. (2016). *Bhutan RNR statistics 2016. Thimphu: Policy and Planning Division (PPD) of the Ministry of Agriculture, Royal Government of Bhutan; 2016.*

Pretty, J., & Bharucha, Z. (2015). Integrated Pest Management for Sustainable Intensification of Agriculture in Asia and Africa. *Insects*, *6*(1), 152–182. https://doi.org/10.3390/insects6010152

Pretty, J., Benton, T. G., Bharucha, Z. P., Dicks, L. V., Flora, C. B., Godfray, H. C. J., Goulson, D., Hartley, S., Lampkin, N., Morris, C., Pierzynski, G., Prasad, P. V. V., Reganold, J., Rockström, J., Smith, P., Thorne, P., & Wratten, S. (2018). Global assessment of agricultural system redesign for sustainable intensification. *Nature Sustainability*, *1*(8), 441–446. https://doi.org/10.1038/s41893-018-0114-0

Rai, P., Bajgai, Y., Rabgyal, J., Katwal, T. B., & Delmond, A. R. (2022). Empirical Evidence of the Livelihood Vulnerability to Climate Change Impacts: A Case of Potato-Based Mountain Farming Systems in Bhutan. *Sustainability*, *14*(4), 2339. https://doi.org/10.3390/su14042339

Rhodes, C. J. (2017). The Imperative for Regenerative Agriculture. *Science Progress*, *100*(1), 80–129. https://doi.org/10.3184/003685017X14876775256165

Rinzin, P., Sonam, T., Tshering, S., & Chapagai, P. P. (2020). Smallholder Farmers' Vulnerability to Impact of Climate Change in Central Bhutan. *International Journal of Environment and Climate Change*, 286–299. https://doi.org/10.9734/ijecc/2020/v10i1230305

Schreefel, L., Schulte, R. P. O., De Boer, I. J. M., Schrijver, A. P., & Van Zanten, H. H. E. (2020). Regenerative agriculture – the soil is the base. *Global Food Security*, *26*, 100404. https://doi.org/10.1016/j.gfs.2020.100404

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., & Smith, J. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1492), 789–813. https://doi.org/10.1098/rstb.2007.2184

Tamburini, G., Bommarco, R., Wanger, T. C., Kremen, C., Van Der Heijden, M. G. A., Liebman, M., & Hallin, S. (2020). Agricultural diversification promotes multiple ecosystem services without compromising yield. *Science Advances*, *6*(45), eaba1715. https://doi.org/10.1126/sciadv.aba1715

Tamburini, G., De Simone, S., Sigura, M., Boscutti, F., & Marini, L. (2016). Soil management shapes ecosystem service provision and trade-offs in agricultural landscapes. *Proceedings of the Royal Society B: Biological Sciences*, *283*(1837), 20161369. https://doi.org/10.1098/rspb.2016.1369

Tariq, M. A. U. R., Wangchuk, K., & Muttil, N. (2021). A Critical Review of Water Resources and Their Management in Bhutan. *Hydrology*, *8*(1), 31. https://doi.org/10.3390/hydrology8010031

Tashi, T., Tobgay, T., Wangmo, T., Kinley, R., & Gyeltshen, S. (2023). Cropping pattern and intensity in the lower belt of Sarpang District, Bhutan. *Asian Journal of Agriculture*, *7*(1). https://doi.org/10.13057/asianjagric/g070101

Tenzin, J. (2013). *Status of IPM in Bhutan Jigme Tenzin. Https://www.academia.edu/11502790/Status_of_IPM_in_Bhutan_Jigme_Tenzin*.

Tshotsho, Lippert, C., Zikeli, S., Krimly, T., Barissoul, A., & Feuerbacher, A. (2024). The role of management and farming practices, yield gaps, nutrient balance, and institutional settings in the context of large-scale organic conversion in Bhutan. *Agricultural Systems*, *220*, 104057. https://doi.org/10.1016/j.agsy.2024.104057

Van Klinken, R. D., Dorji, S., Om, N., Thinlay, Loday, P., & Zangpo, T. (2018). Benefits and challenges of maintaining national plant pest lists: An analysis of agricultural pests in Bhutan. *Annals of Applied Biology*, *173*(1), 71–79. https://doi.org/10.1111/aab.12436

Wu, W., & Ma, B. (2015). Integrated nutrient management (INM) for sustaining crop productivity and reducing environmental impact: A review. *Science of The Total Environment*, *512–513*, 415–427. https://doi.org/10.1016/j.scitotenv.2014.12.101

Yang, X., Xiong, J., Du, T., Ju, X., Gan, Y., Li, S., Xia, L., Shen, Y., Pacenka, S., Steenhuis, T. S., Siddique, K. H. M., Kang, S., & Butterbach-Bahl, K. (2024). Diversifying crop rotation increases food production, reduces net greenhouse gas emissions and improves soil health. *Nature Communications*, *15*(1), 198. https://doi.org/10.1038/s41467-023-44464-9

Yangzom, K., & Choden, S. (2021). *Study the Nutrient Management Practices and Soil Organic Carbon in Rice Fields, Radhi, Trashigang Bhutan*. *10*(5).

Zhao, J., Chen, J., Beillouin, D., Lambers, H., Yang, Y., Smith, P., Zeng, Z., Olesen, J. E., & Zang, H. (2022). Global systematic review with meta-analysis reveals yield advantage of legume-based rotations and its drivers. *Nature Communications*, *13*(1), 4926. https://doi.org/10.1038/s41467-022-32464-0

Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/158655