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Geospatial Assessment of Temperate Fruit Sites for Sustainable Horticultural Diversification in Meghalaya

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ABSTRACT

Meghalaya has significant potential for horticultural diversification, particularly for temperate fruit crops. This study evaluates site suitability for apple, pear, and peach cultivation in Meghalaya using geospatial techniques, with a specific focus on sustainable land use and soil conservation in a landscape prone to degradation. Key parameters considered include soil depth, drainage, texture, pH, organic matter, nutrient availability (P and K), climatic variables (temperature, rainfall, and chilling hours), and topographic variables (slope, elevation, and slope aspect). Suitable areas were classified into highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and not suitable (N) zones using the FAO Land Evaluation Framework. The suitability model was validated against 785 ground-truth observations, yielding an overall accuracy of 90% and a Kappa coefficient of 0.86, confirming its predictive reliability. West Khasi Hills emerges as the district with the highest concentration of suitable land for all three crops, particularly in the blocks of Mawthadraishan, Nongstoin, and Mairang. A total of 64,485.92 hectares were identified as suitable for at least one crop, of which 24,259.52 hectares are highly suitable for all three simultaneously — representing the most promising zones for integrated orchard development and long-term soil stabilization. By providing a spatially explicit framework, this study supports evidence-based planning for nursery development, cold-chain infrastructure, marketing linkages, and climate-resilient horticultural diversification in Meghalaya.

1 | INTRODUCTION

Soil degradation is a critical challenge for agricultural sustainability in the hilly regions of South and Southeast Asia. Steep terrain, heavy rainfall, and shallow soils contribute to processes such as surface runoff and sheet erosion, which constantly deplete fertile topsoil essential for farming. It takes nature 300–1,000 years to form just one inch of topsoil (NRSC; Mishra *et al.*, 2024), highlighting the long-term and often irreversible nature of such losses (Singh *et al*., 2023; Verma *et al*., 2023). The North Eastern Region (NER) of India exemplifies this issue with its complex terrain, high rainfall, and fragile ecosystems, making its soils highly vulnerable. As of 2005- 06, degraded land in the NER covered 46, 46,946 sq. km, or 17. 91% of the total area, with an additional 2, 2,164 sq. km degraded over the next decade. Acidification is the primary degradation process, followed by water erosion; waterlogging is most severe in Assam and significantly affects Arunachal Pradesh, Manipur, Meghalaya, and Tripura (Das *et. al*., 2026). Meghalaya, in particular, exemplifies these challenges with steep slopes, shallow soils, and annual rainfall ranging from about 1,000 mm to over 11,000 mm. This climate promotes intense overland flow during the monsoon, leading to high rates of surface erosion and nutrient-rich topsoil loss. According to NRSC and NESAC, roughly 623,148 ha of Meghalaya are degraded, with water erosion affecting 73,905 ha, acidification affecting 458,458,765 ha, and other human factors affecting 6,910 ha. The shallow soils on steep slopes have little capacity to buffer against these processes; once topsoil is removed, land productivity drops sharply, and natural recovery is nearly impossible without intervention. Traditional farming practices, such as jhum (shifting cultivation), worsen these vulnerabilities. Jhum remains common in Meghalaya but causes severe soil loss- up to 40 tonnes per hectare annually (Shangpliang, 2019) — which far exceeds natural soil formation rates, leading to ongoing land degradation. The cycle of clearing, burning, and short-term cropping leaves slopes exposed during the monsoon, increasing topsoil exposure to rainfall impacts and runoff erosion.

Perennial fruit crop cultivation on slopes offers a practical way to stabilize soil and rehabilitate land. Unlike annual crops, orchards provide a continuous canopy, reduce erosion, and improve soil health through organic inputs (Liu *et al*., 2024). Studies show well-managed orchards can cut soil loss by 60–80%. Diversifying horticulture serves as both an economic and conservation strategy, especially in Meghalaya's diverse climate, supporting crops like bananas, oranges, strawberries, and indigenous fruits (Deshmukh *et al.*, 2013). Out of 2.24 million hectares, 15.28% is cultivated, and 24.75% remains unused, offering potential for eco-friendly economic growth. Temperate fruits like apple, pear, and peach are promising, with apple being a newer opportunity due to climate change. Spatial data on soils, climate, and topography are essential for planning. The Meghalaya Small Farmer's Agri-Business Consortium, partnering with NESAC, aims to identify suitable areas for these crops, develop a diversification plan, and create a land conservation framework to align orchard placement with slope stabilization and land rehabilitation.

2 | MATERIALS AND METHODS

2.1 | Study Area

Meghalaya is a North-Eastern state of India, extending from 25°13'06" N to 25°17'45" N latitude and 89°49'52" E to 92°48'17" E longitude (Fig. 1). The state covers a total geographical area of 2,242,900 ha and is characterized by three main plateau systems — the Khasi Hills, Jaintia Hills, and Garo Hills — separated by deep river valleys. Elevation ranges from near sea level in the valley fringes to approximately 1,920 m in the higher Khasi Hills. This topographic diversity, combined with one of the world's highest rainfall regimes in the Cherrapunji–Mawsynram belt, creates a landscape of exceptional agronomic diversity but also heightened erosion risk.

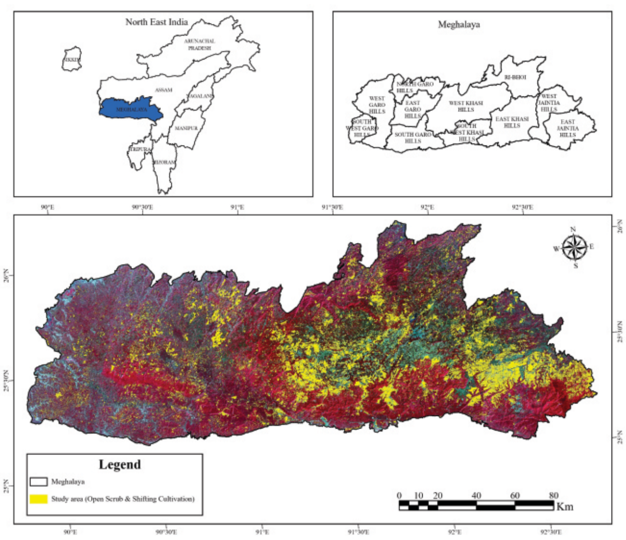

FIGURE 1 Study Area Map

2.2 | Data Sources And Thematic Map Preparation

Suitable areas for apple, pear, and peach were identified and mapped following the FAO Land Evaluation Framework (FAO, 1984). Multiple thematic maps were generated from different data sources. Soil maps at 1:50,000 scale, prepared by NESAC and SLUSI, were updated with soil fertility maps by NESAC (Das *et al.*, 2022). Thematic maps for texture, depth, drainage, pH, organic carbon (OC), phosphorus (P), and potassium (K) were derived from the updated soil map. Chilling hour maps (0–7°C) for apple and peach were created from ERA5-Land hourly temperature data (2003–2023). Daily chilling hours were extracted using Python, and annual maps were prepared (Das et al., 2025). Average rainfall maps were based on 27 years of data (1997–2023) from IMD. Mean annual temperature maps used 16 years of MODIS LST data (2007–2023). Elevation and slope maps were generated from Cartosat DEM, with slope aspect classified into eight directional classes. A LULC map from LISS-IV imagery (2024) was visually interpreted, with an accuracy of 92% (Kappa = 0.89). Suitability analysis focused on 483,482.47 ha of open scrubland, fallow, and shifting cultivation, representing degraded or transitional land. A flowchart illustrating the overall methodology is presented in (Fig. 2), while (Fig. 3) depicts the thematic maps representing soil site characteristics of the study area.

HIGHLIGHTS

- Geospatial analysis identifies 64,486 ha of degraded land in Meghalaya suitable for temperate fruit cultivation across apple, pear, and peach.
- West Khasi Hills emerges as the primary hotspot, with 24,259 ha highly suitable for all three crops simultaneously, enabling integrated orchard systems.
- Orchard establishment on identified slopes can potentially prevent over 485,000 tonnes of annual topsoil loss, delivering measurable soil conservation co-benefits.

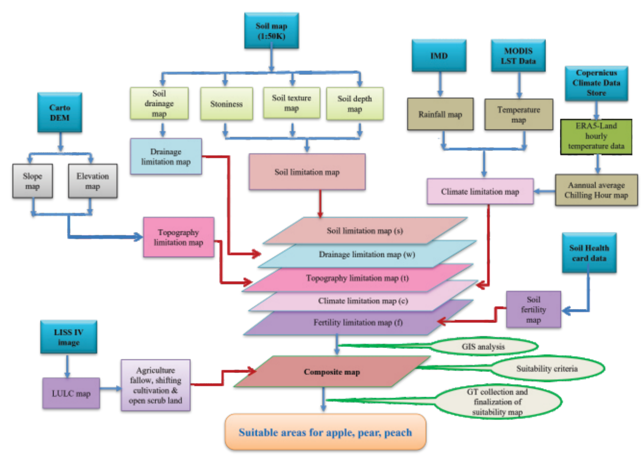

FIGURE 2 Methodology flow chart

2.3 | Suitability Criteria And Limitation Scoring

Suitability assessment followed the FAO parametric framework, assigning each land quality parameter a limitation score from 0 (no limitation) to 4 (very severe limitation) based on deviation from optimal crop ranges. Table 1 shows threshold values for suitability classes (S1–N) for apple, peach, and pear. The scores are detailed in Table 1, ensuring transparency. The overall suitability for each unit was determined by the most limiting parameter, ensuring no unit is rated highly suitable if any critical parameter is below the threshold, following FAO (1984). All maps were projected to a common coordinate system and rasterised at 30 m resolution before overlay, using ArcGIS Pro. Suitability classes: Highly Suitable (S1) — no limitations; Moderately Suitable (S2) — one or more parameters with score 1, none ≥2; Marginally Suitable (S3) — one or more with score 2, none 3–4; Not Suitable (N) — one or more with scores 3–4 Table 2. Sub-classes identify specific limiting factors like temperature, slope, soil depth, and elevation, detailed in Tables 3-5.

2.4 | Slope Aspect Integration

Aspect was added to refine microclimate assessment, especially for apple cultivation, where isolation and chilling hours are vital. In the Northern Hemisphere, north- and northeast-facing slopes get less sun, stay cooler, and accumulate more chilling hours during dormancy, compared to south- and southeast-facing slopes at the same elevation. The latter warm earlier in spring and have longer growing seasons, benefiting crops like peach and pear that need early bud-break and extended fruit development. In the suitability model, aspect refined borderline chilling-hour zones (250–350 hours). North- and northeast-facing slopes in these zones upgraded the chilling-hour score by one subclass, as aspect-driven temperature differences of 1–3°C can significantly affect chilling hours at the site level. South- and southeast-facing slopes kept the original score.

2.5 | Model Validation

To evaluate suitability map accuracy, a stratified random sample of 785 locations was collected across all four classes (S1, S2, S3, N) in three districts with highest mapped suitability (West Khasi Hills, East Khasi Hills, West Jaintia Hills). The sample was proportional to each class's area, with at least 50 observations per class. At each site, soil pH (field meter), soil depth (auger), soil texture (field and lab for 20%), and slope (clinometer) were recorded. Microclimate data (temperature loggers) were collected at 120 locations across elevation gradients. Recorded values were compared to the model's predictions. Map accuracy was assessed via a confusion matrix comparing field-observed and model-predicted classes, calculating overall accuracy and Kappa coefficient (Congalton and Green, 2019). Results showed an accuracy of 90% and Kappa of 0.86, indicating [substantial/good] agreement. Misclassifications mainly involved S1–S2 confusion in transitional areas, consistent with known DEM slope limitations in rugged terrains. The validated map is shown in (Fig. 4).

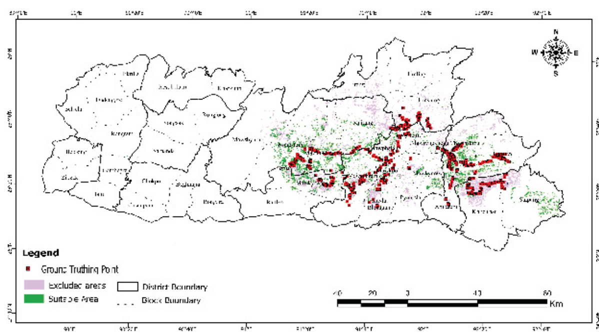

FIGURE 4 Ground Truth Verification Sites

TABLE 2 Criteria for determination of land suitability classes

Land classes	Criteria
S1: Highly suitable	Land units with no or only 4 slight limitations
S2: Moderately suitable	Land units with more than 4 slight limitation sand/or no more than 3 moderate limitations
S3: Marginally suitable	Land units with more than 3 moderate limitation sand/ or one or more severe limitation
N: Not suitable	Land units with very severe limitation

TABLE 3 Area under suitability subclass for Apple

Suitability Class	Suitability subclass	Area (ha)	Limitation/Improvement
S2	S2c	16067.39	Chilling Temperature
	S2t	4041.19	Slope
	S2ts	0.12	Slope & Death
S3	S3s	0.35	Depth
	S3e	0.35	Elevation
	S3t	2519.63	Slope
	S3ts	0.26	Slope & Depth

TABLE 4 Area under suitability subclass for Apple

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	S3t	2519.63	Slope
	S3ts	0.26	Slope & Depth

TABLE 5 Area under suitability subclass for Pear

Suitability Class	Suitability subclass	Area (ha)	Limitation/Improvement
S2	S2c	0.10	Depth
	S2t	9722.90	Slope
	S2ts	0.11	Slope & Death
S3	S3s	0.10	Depth
	S3e	0.02	Elevation
	S3t	0.03	Slope
	S3ts	0.11	Slope & Death

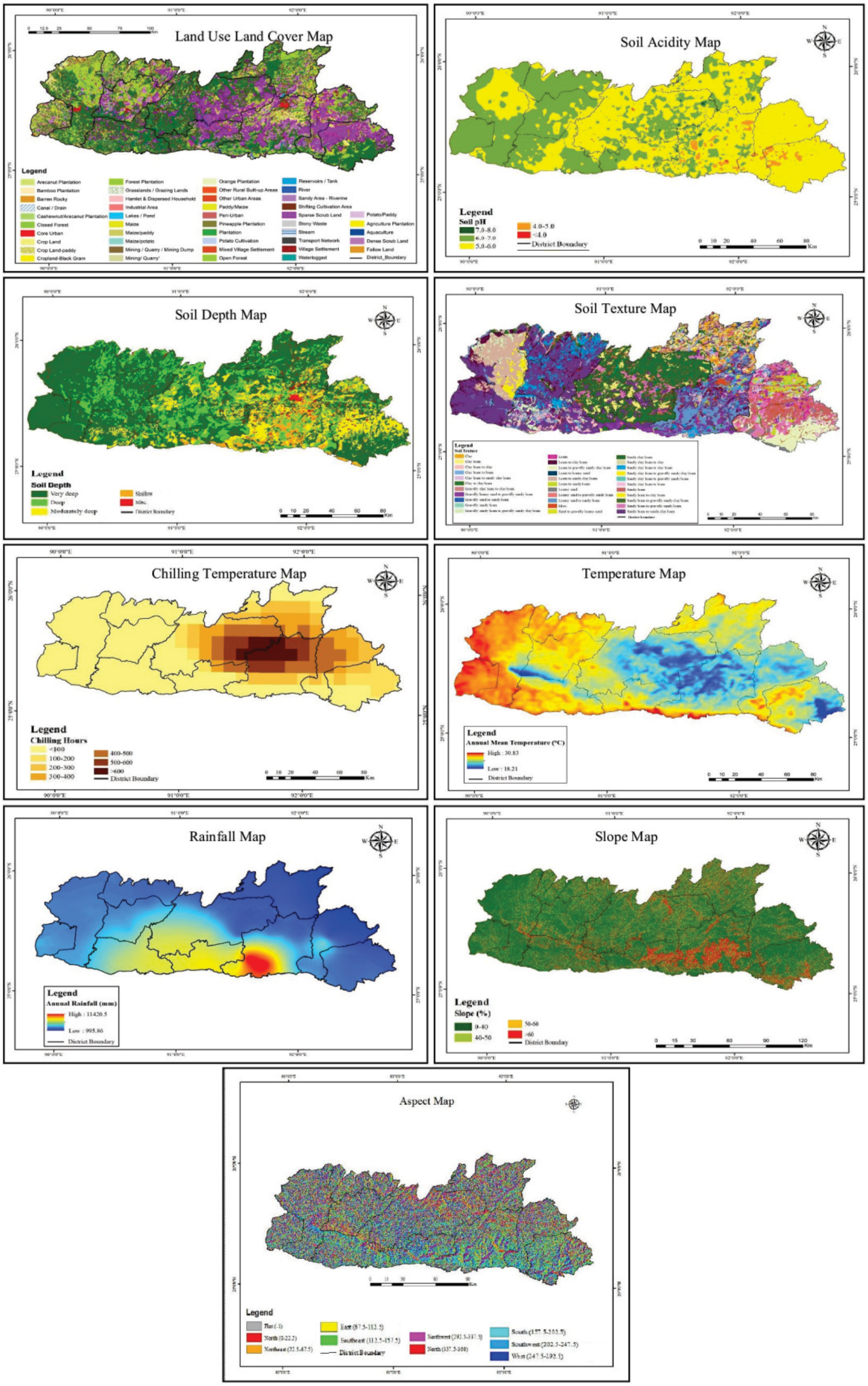

FIGURE 3 Maps showing soil site characteristics of Meghalaya

TABLE 1 Limitation Rating for Evaluation of Soil Site Suitability of Apple, Peach, and Pear in Meghalaya

FAO Land Evaluation Framework (FAO, 1984). Limitation scores: 0 = None (S1), 1 = Moderate (S2), 2 = Severe (S3), 3–4 = Very Severe (N). Overall class by minimum/most-limiting factor rule.

Parameter	APPLE (Malus domestica) - Low-chilling cultivars				PEACH (Prunus persica) - Sub temperate cultivars				PEAR (Pyrus communis / P. pyrifolia) - Temperate cultivars			
	S1 Highly Suitable	S2 Moderatel Suitable	S3 Marginall Suitable	N Not Suitable	S1 Highly Suitable	S2 Moderatel Suitable	S3 Marginall Suitable	N Not Suitable	S1 Highly Suitable	S2 Moderatel Suitable	S3 Marginall Suitable	N Not Suitable
Soil Depth (cm)	>100	70-100 (S2s)	50-70 (S3s)	<50	>100	70–100 (S2s)	50–70 (S3s)	<50	>100	70-100 (S2s)	50–70 (S3s)	<50
Soil Texture	Loam, Sandy clay loam, Clay loam	Sandy loam, Loamy sand, Gravelly sandy loam	-	other	Loam, Sandy clay loam, Clay loam	Sandy loam, Loamy sand, Gravelly sandy loam	-	other	Loam, Sandy clay loam, Clay loam	Sandy loam, Loamy sand, Gravelly sandy loam	-	Other
Soil Drainage	Well drained	Mod. well drained (S2d)	Imperfectly drained (S3d)	Poorly drained	Well drained	Mod. well drained (S2d)	Imperfectly drained (S3d)	Poorly drained	Well drained	Mod. well drained (S2d)	Imperfectly drained (S3d)	Poorly drained
Soil pH	5.8-6.5	<5.8 & 6.5–7.5 (S2pH)	<5.5 & 7.5–8.0 (S3pH)	>8.0	5.9-6.8	<5.9 & 6.8–7.5 (S2pH)	-	>7.5	5.9-6.8	<5.9 & 6.8–7.5 (S2pH)	-	>7.5
Organic Carbon (%)	>0.75	0.50–0.75 (S2oc)	0.25–0.50 (S3oc)	<0.25	>0.75	0.50–0.75 (S2oc)	0.25–0.50 (S3oc)	<0.25	>0.75	0.50–0.75 (S2oc)	0.25–0.50 (S3oc)	<0.25
Available P (kg ha^{-1})	>25	10–25 (S2p)	5–10 (S3p)	<5	>25	10–25 (S2p)	5–10 (S3p)	<5	>25	10–25 (S2p)	5–10 (S3p)	<5
Available K (kg ha^{-1})	>280	120–280 (S2k)	60–120 (S3k)	<60	>280	120–280 (S2k)	60–120 (S3k)	<60	>280	120–280 (S2k)	60–120 (S3k)	<60
Chilling Hours (0–7°C, hrs yr^{-1})	>400	300–400 (S2c)	200–300 (S3c)	<200	>100	- (broad tolerance)	-	<100	Not a primary limiting factor; elevation & temp. used as proxy			<100
Mean Annual Temp. (°C)	<20	20–23 (S2temp)	23–25 (S3temp)	>25	<30	-(entire state suitable)	-	>30	<20	20–23 (S2temp)	23–25 (S3temp)	>25
Annual Rainfall (mm)	995.8–11,420.5 — entire state suitable; no limitation applied			-	995.8–11,420.5 — entire state suitable; no limitation applied			-	995.8–11,420.5 — entire state suitable; no limitation applied			-
Slope (%)	0-40	40–50 (S2t)	50–60 (S3t)	>60	0-40	40–50 (S2t)	50–60 (S3t)	>60	0-40	40–50 (S2t)	50–60 (S3t)	>60
Elevation (m asl)	>1,700	1,500–1,700 (S2e)	1,200–1,500 (S3e)	<1,200	1,100–2,000	-	-	<1,100 or >2,000	1,100–2,000	-	-	<1,100 or >2,000
Slope Aspect*	N, NE - maximises chilling hour accumulation	E, W facing (S2asp)	S, SW facing (S3asp)	-	S, SE - early bud-break & longer season	E, W facing (S2asp)	N, NW facing (S3asp)	-	S, SE - extended growing season	E, W facing (S2asp)	N, NW facing (S3asp)	-

Sub-class codes: s = soil depth; d = drainage; pH = soil reaction; oc = organic carbon; p = available phosphorus; k = available potassium; c = chilling hours; temp = mean temperature; t = slope; e = elevation; asp = slope aspect. Combined limitations shown by concatenation (e.g., S2ts = slope + soil depth). Grey rows = identical thresholds across all three crops.
* Slope aspect applied as refinement layer in chilling transition zones (250–350 hrs/yr) for Apple; applied across all elevation-suitable zones for Peach and Pear.
Aggregation rule: Overall suitability class determined by the minimum (most-limiting factor) rule — the most severely limited parameter governs the composite class (FAO, 1984).
Apple cultivar note: Chilling hour thresholds apply to low-chilling cultivars (e.g., HRMN-99, Anna, Dorsett Golden). Standard high-chilling varieties (>1,000 hrs) are not viable under Meghalaya's current climate.

3 | RESULTS AND DISCUSSION

3.1 | Land Use and Land Cover

Analysis of the 2024 LISS-IV LULC map shows dense/closed forest as the main land cover, covering 44.47% of the area, with open forest at 21.56% and open/sparse scrubland at 10.06%. The combined area of open scrubland, fallow, and shifting cultivation—spanning 483,482.47 ha—is mainly degraded land with low productivity and high erosion risk during high rainfall, especially in active and post-jhum fallow. Converting these areas to perennial orchards could boost economic value and stabilize slopes.

3.2 | Soil Characteristics

Soil texture in the study region varies from gravelly sand to clay loam, with sandy loam being most common (51.59%), followed by sandy clay loam (19.19%), loam (9.87%), and loamy sand (7.08%). These textures, especially sandy loam and loam, are favorable for temperate fruit crops because they balance water retention and drainage; however, their low cohesion on steep slopes makes them prone to rill and sheet erosion when uncovered. Most soils are very deep (>100 cm, covering 60.23%) or deep (18.46%), which benefits orchard crops that require unrestricted root growth. Slightly shallow (13.37%) and shallow soils (5.59%) occur mainly on upper slopes, where erosion has reduced root depth, potentially benefiting from biological loosening of subsoils through the establishment of deep-rooted perennial orchards over time. Soils are mainly moderately well-drained (39.04%) and well-drained (37.62%), with some valley bottom areas having imperfectly drained (16.10%) or poorly drained (4.70%) soils. Proper drainage is vital for temperate fruit crops, as they are sensitive to waterlogging and root asphyxiation. Most soils are slightly acidic (69.61%) or moderately acidic (27.25%), with a tiny fraction (0.09%) strongly acidic. Acidic soils pose challenges such as increased phytotoxic aluminium and manganese, reduced phosphorus availability due to fixation, and impaired microbial activity. Apple trees grow best at a pH of 5.8–6.5, while pears and peaches prefer a pH of 5.9–6.8. Soils below pH 5.5, present in some areas, require periodic liming (using dolomitic limestone or calcium carbonate) to raise pH to optimal levels, based on soil buffering capacity. Liming also supplies calcium and magnesium, critical nutrients for fruit quality. Organic carbon (OC) is high in most areas (88.22%), supporting good soil structure and nutrient cycling, reducing erosion, and fostering microbial communities vital for nutrient availability and plant health. Enhancing OC through mulching, cover cropping, and adding pruning residues should be a priority in new orchards. Medium available phosphorus (69.89%) is typical, with 18.73% of soils low in P and 11.38% high. Potassium levels are more concerning: 47.35% of soils are low in K, 45.54% are medium, and only 7.11% are high. Potassium is crucial for fruit quality, cell turgor, and winter hardiness. Soils identified as suitable but low in K will need systematic supplementation with muriate of potash (MOP) or sulfate of potash (SOP), incorporated into fertilizer plans for orchard establishment. Soil test-based fertilization, reviewed every 2–3 years, should be part of ongoing orchard management to prevent the K depletion observed in intensive orchards on low-K soils.

3.3 | Climate and Topographic Parameters

Chilling Hours: The distribution of chilling hours (0–7°C) is a primary determinant of apple and peach suitability in Meghalaya. Apple cultivars requiring >300 chilling hours are climatically suitable across 21.52% of the state's area, while peach (requiring >100 chilling hours) is suitable across 45.25% of the area (Das et al., 2025). It is important to note that the apple thresholds applied in this study are calibrated for low-chilling cultivars (e.g., HRMN-99, Anna, Dorsett Golden), which have been developed specifically for non-traditional apple-growing regions. Standard high-chilling commercial varieties (requiring >1,000 hours) are not considered viable in Meghalaya's current climate regime. Policymakers and extension services should ensure that nursery and planting material programmes exclusively promote low-chilling cultivars in identified S1 and S2 zones.

Temperature: Mean annual temperature ranges from 18.21°C to 30.84°C across the state. Approximately 60.62% of the state meets the temperature requirements for apple cultivation (20–25°C mean annual), while the entire state meets temperature criteria for both peach and pear (mean annual <30°C).

Slope and Slope Aspect: Approximately 72.93% of Meghalaya's total geographical area falls under the highly suitable slope category (0–40%), while 11.74% is moderately suitable (40–50%), 7.13% is marginally suitable (50–60%), and 8.20% is not suitable (>60%) for orchard cultivation. These slope thresholds were established in consultation with the Meghalaya Horticulture Department and reflect both agronomic requirements and practical constraints in plantation management.

Slope aspect is an important modifier of microclimate and was explicitly incorporated into the suitability model for apple cultivation (see Section 2.4). Analysis of the state's aspect distribution reveals that southeast-facing slopes are most prevalent (15.02%), followed by northwest (13.83%), south (13.46%), southwest (13.09%), east (12.63%), and west (12.88%) facing slopes, with minimal flat and true north-facing terrain. South- and southeast-facing slopes in Meghalaya's high-altitude zones warm rapidly in spring, providing longer effective growing seasons that benefit peach and pear by supporting timely bud-break and fruit development. In contrast, north- and northeast-facing slopes at comparable elevations accumulate additional chilling hours during the winter dormancy period, making them particularly advantageous for apple cultivation in the borderline chilling-hour zones of the West Khasi Hills. In the model, north- and northeast-facing aspects in the 250–350 chilling-hour transition zone contributed to the upward reclassification of approximately 24000 ha from S2 to S1 for apple, demonstrating the substantive influence of aspect integration on final suitability outputs. Ignoring slope aspect in favour of gridded temperature data alone would have systematically underestimated apple suitability on north-facing slopes in these transitional zones.

Elevation: Elevation ranges from near sea level to approximately 1,920 m. Apple cultivation, restricted to elevations above 1,200 m in this study, is viable across only 16.40% of the state's area. Pear and peach, which thrive above 1,100 m, are suitable across 20.41% of the state based solely on elevation criteria.

Rainfall: Annual average rainfall ranges from 995.8 mm to 11,420.5 mm. Given the wide range and the fact that the minimum value of ~1,000 mm meets or exceeds the water requirements of all three target crops, rainfall is not a limiting factor anywhere in the study area. However, the extreme rainfall values in the Cherrapunji–Mawsynram belt (>8,000 mm) may increase disease pressure (particularly fungal pathogens) and require drainage management in orchard planning.

3.4 | Crop Suitability Results

Apple: West Khasi Hills is the most suitable district for apple, with 21,591.41 ha of total suitable land, of which 12,706.64 ha are highly suitable (S1). East Khasi Hills (11,838.08 ha total; 7,568.43 ha S1) and West Jaintia Hills (11,353.95 ha total; 3,262.23 ha S1) are the next most important districts, with the blocks of Mawthadraishan, Nongstoin, and Mairang showing particularly high suitability concentrations (Table 6 and Fig. 5). The primary limiting factor for apple suitability is chilling hours (S2c classification covers 16,067.39 ha), followed by slope (S2t: 4,041.19 ha), reflecting the narrow high-altitude niche in which chilling requirements are reliably met (Table 3 and Fig. 5).

Peach: Peach has the widest geographic suitability of the three crops, reflecting its lower chilling-hour requirement and broader temperature tolerance. West Khasi Hills leads with 24,695.27 ha total suitable area (20,474.13 ha S1), followed by East Khasi Hills (13,978.52 ha) and West Jaintia Hills (13,517.26 ha). The primary limitation for moderate suitability areas is slope (S2t: 9,003.87 ha), consistent with the steep terrain characteristic of the Khasi and Jaintia plateaus (Table 7 and Fig. 5). Peach's broader suitability also makes it the most appropriate initial crop for piloting orchard-based slope stabilization interventions in higher-risk erosion areas.

Pear: Pear's suitability distribution closely mirrors that of peach, reflecting similar temperature and elevation tolerances. West Khasi Hills has the largest suitable area (24,695.27 ha; 20,474.13 ha S1), with East Khasi Hills (13,978.52 ha) and West Jaintia Hills (13,517.26 ha) as key districts (Table 8 and Fig. 5). Slope is the dominant limiting factor for S2 pear areas (S2t: 9,722.90 ha), and marginally suitable areas are largely absent, indicating that most terrain either meets pear requirements or is excluded due to slope exceeding 60% (Table 5 and Fig. 5).

TABLE 6 District wise suitable areas for Apple

District	Area (ha) under different suitability class			Total area (ha)
	Highly	Moderate	Marginal	
East Jaintia Hills	-	305.56	1.68	307.24
East Khasi Hills	7568.43	3492.2	777.45	11838.08
Ri-Bhoi	3.06	156.12	7.51	166.69
South West Khasi Hills	727.96	830.34	80.88	1639.17
West Jaintia Hills	32362.23	7744.67	347.04	11353.95
West Khasi Hills	12706.64	7579.7	1305.07	21591.41
Total	24268.32	20108.59	2519.63	46896.54

TABLE 7 District wise suitable areas for Peach

District	Area (ha) under different suitability classes			Total area (ha)
	Highly	Moderate	Marginal	
East Garo Hills	33.91	9.49	-	43.4
East Jaintia Hills	5263.46	594.44	42.6	5900.51
East Khasi Hills	11430.56	2354.89	193.08	13978.52
Ri-Bhoi	201.57	40.76	1.31	243.64
South Garo Hills	-	0.02	-	0.02
South West Khasi Hills	5061.37	706.04	6.02	5773.43
West Garo Hills	18.21	3.58	-	21.79
West Jaintia Hills	11991.25	1367.82	158.3	13517.26
West Khasi Hills	20474.13	3926.84	294.3	24695.27
Total	54474.36	9003.88	695.61	64173.84

TABLE 8 District wise suitable areas for Pear

District	Area (ha) under different suitability classes			Total area (ha)
	Highly	Moderate	Marginal	
East Garo Hills	33.91	9.49	-	43.4
East Jaintia Hills	5552.15	660.46	-	6121.61
East Khasi Hills	11430.56	2547.96	-	13978.52
Ri-Bhoi	201.57	42.07	-	243.64
South Garo Hills	-	0.02	-	0.02
South West Khasi Hills	5061.37	712.06	-	5773.43
West Garo Hills	18.21	3.58	-	21.79
West Jaintia Hills	11991.15	1526.12	-	13517.26
West Khasi Hills	20474.13	4221.14	-	24695.27
Total	54763.05	9722.9	-	64485.94

3.5 | Soil Conservation Implications of the Suitability Maps

A key element of the suitability analysis that deserves explicit discussion—especially for soil conservation planning—is the spatial match between the high-suitability zones identified and areas currently facing high soil degradation risk. The 483,482 ha study area includes active and recent jhum fallow, open scrubland, and agricultural fallow—land types that, under current management, are exposed to bare soil for significant portions of the year and are vulnerable to the high rainfall erosivity characteristic of the Khasi and Jaintia Hills. Establishing permanent orchards across the 24,259 ha identified as highly suitable for all three crops, and across the 30,214 ha suitable for pear and peach, would mark a fundamental shift in the erosion balance of these landscapes. Evidence from similar hilly orchard systems in South and Southeast Asia shows that well-managed orchards on slopes of 15–40% can reduce annual soil loss by 50–75% compared to jhum fallow conditions, mainly through canopy cover, root reinforcement, and the development of an organic surface layer (Pimentel *et al*., 2006; García-Ruiz *et al*., 2013; Liu *et al.,* 2024). At the soil loss rates reported for jhum in Meghalaya (up to 40 t/ha/yr; Shangpliang, 2019), even a conservative 50% reduction in erosion across the 24,259 ha S1 zone could prevent the loss of approximately 485,180 tonnes of topsoil annually—a significant ecosystem service benefit of the proposed horticultural diversification. Additionally, the soil amendment strategies needed for orchard establishment directly address underlying degradation processes. Liming to raise soil pH in moderately acidic zones (27.25% of the study area) will reduce aluminum toxicity and improve soil biological activity. Potassium supplementation in the 47.35% of low-K soils will enhance tree health and yield stability. Regular organic matter additions through mulching and green manuring will build the organic carbon pool, further improving soil structure and reducing erodibility. These agronomic practices, incorporated into an orchard management schedule, serve a dual purpose: they boost crop productivity and address the acidification and nutrient depletion pathways identified as dominant land degradation processes in Meghalaya (Das *et al.*, 2026). Finally, the distribution of suitability by slope class has direct implications for conservation planning. The 7.13% of the study area classified as marginally suitable due to slopes of 50–60% is explicitly not recommended for orchard development in this study. However, these areas overlap with some of the highest erosion-risk terrain in the region. For these marginal slope lands, the diversification plan suggests integrating soil and water conservation infrastructure—such as contour bunds, check dams, and vegetative barriers—before any agricultural use, or prioritizing their conversion to afforestation with native species as a permanent erosion control measure.

3.6 | Horticultural Diversification Plan

The multi-crop spatial overlay analysis identifies 64,485.92 ha as suitable for at least one of the three target crops (*Table 9*). The diversification plan is structured around four landscape-level categories:

Zone 1 — Integrated Three-Fruit Systems (24,259.52 ha, S1S1S1): These areas, concentrated in West Khasi Hills (particularly Nongstoin and Mawthadraishan blocks), East Khasi Hills, and West Jaintia Hills, offer optimal conditions for high-density integrated orchards combining apple, pear, and peach. These zones are the primary targets for infrastructure investment — including nursery establishment, cold storage, and all-weather road access — and for the development of high-value temperate fruit value chains.

Zone 2 — Pear–Peach Dual Systems (30,214.23 ha, highly suitable for pear and peach): These extensive zones, distributed across the Khasi and Jaintia Hills districts, are ideal for two-fruit systems where apple is precluded by insufficient chilling hours or elevation. Pear–peach intercropping systems offer complementary harvest timing and can optimize labour utilization across the growing season.

Zone 3 — Moderate Pear–Peach Zones with Improvement (5,453.83 ha, S2 for pear and peach): These areas are currently constrained by slope or soil depth limitations but hold significant potential with targeted interventions including terracing or contour planting, soil amelioration, and water conservation structures. They are suitable for phased development after the priorities for Zones 1 and 2 are established.

Zone 4 — Pear Mono-Cropping (289.27 ha): Limited areas exclusively suited to pear may support mono-cropping where intercropping with other species is not feasible.

The transition from biophysical suitability to functional landscapes requires a complementary Micro-Level Validation phase integrating: socio-economic synthesis (overlaying suitability maps with household surveys assessing farmer willingness, land tenure, and labour availability); economic viability analysis (farm-level cost-benefit ratios for high-density orchards versus traditional systems); logistics and cold-chain assessment (proximity of suitable areas to road networks and refrigerated transport infrastructure); and value chain development (identification of locations for localized processing units for juices, jams, and preserved fruit to stabilize prices and reduce post-harvest losses).

TABLE 9 Horticultural Diversification Plan for Meghalaya based on multi-crop suitability

Suitability category	Area (ha)	Diversification Scope
Highly suitable for Apple, Pear, Peach	24,259.52	Best diversification zones, focus on 3-fruit systems
Highly suitable for Pear & Peach	30,214.23	Best diversification zones of pear & peach fruit crops
Moderately suitable for Pear & Peach	5,453.83	Moderate diversification zones with site improvement
Highly suitable for Pear	289.27	Pear mono-cropping recommended

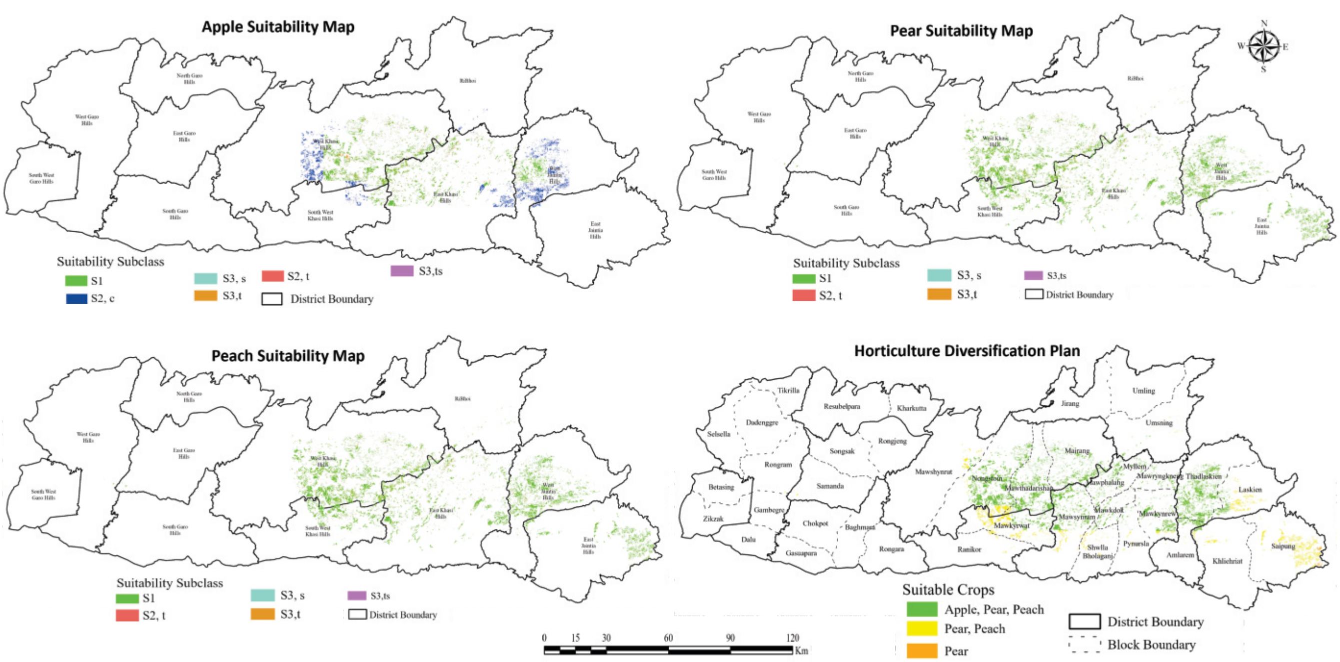

FIGURE 5 Suitable areas for apple, peach, pear and horticulture diversification plan

4 | CONCLUSIONS

This study successfully identifies significant untapped potential for horticultural diversification in Meghalaya, including apple, pear, and peach, across 64,485.92 ha of degraded and transitional land. Geospatial analysis delineates approximately 24,259 ha as highly suitable for all three species simultaneously — representing the most promising zones for intensive multi-crop orchard development and, critically, for landscape-scale soil stabilization in one of India's most erosion-vulnerable regions. The study demonstrates that the same biophysical conditions responsible for Meghalaya's land degradation challenge — steep slopes, high rainfall, and acidic shallow soils — can be turned into productive assets through the strategic placement of appropriate perennial fruit crops. The explicit integration of slope aspect as a microclimate modifier, the transparent parameterization of the FAO limitation scoring system, the field validation of suitability predictions across 785 locations, and the quantified soil conservation co-benefits of the diversification plan collectively strengthen the scientific and practical utility of this assessment. These findings provide policymakers, horticulture planners, and soil conservation practitioners with a common spatial evidence base for aligning crop promotion, nursery development, infrastructure investment, and watershed management priorities in Meghalaya. Future work should focus on farm-level economic validation, cultivar-specific chilling hour trials in identified S1 zones, and the integration of this suitability framework with real-time soil health monitoring networks to enable adaptive management of newly established orchards.

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CONFLICT OF INTEREST

The author declare there is no conflict.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available from the corresponding author upon reasonable request, subject to institutional permissions.

AUTHOR'S CONTRIBUTION

The first author conceptualized and designed the study. The second author performed data analysis and drafted the manuscript under the supervision of the first author. The first author reviewed and edited the manuscript. All authors approved the final version

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