



Comprehensive impact assessment of soil fertility enhancement strategies, economic viability, and yield performance of tomato (*Solanum lycopersicum*) in sub-tropical hill agroecosystems of Manipur

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ABSTRACT

The present study was carried out during winter (*rabi*) season of 2021–22 and 2022–23 at Krishi Vigyan Kendra, Churachandpur, (ICAR-Research Complex for NEH Region, Manipur), Manipur, to assess the yield, soil fertility, and economics of 'Arka Samrat' tomato (*Solanum lycopersicum* L.) variety compared to farmers' practices at six locations. The implementation of SSNM significantly enhanced soil fertility parameters, with marked improvements in soil organic carbon, SOC stock, N, P and K levels, whereas soil bulk density and pH remained unaltered. Agronomic performance was satisfactory, with yields averaging 20 t/ha across demonstration sites. Economic analysis revealed financial viability, with a mean gross return of ₹303,000/ha against a production cost of ₹97,800/ha, yielding an average net return of ₹210,500/ha. The benefit-cost ratio of 3.09 and return on investment of 2.15 accentuate the economic efficacy of the intervention. Additional economic indicators productivity per unit area (1,330), break-even point (8,150), marketable surplus (3,261), and marginal rate of return (222) further validate the financial reliability of the approach. This investigation establishes that SSNM-based tomato cultivation represents an agronomically viable and economically profitable enterprise for the sub-tropical hills of Manipur, offering a sustainable pathway to enhanced soil fertility, optimized yields, and improved agricultural livelihoods in this distinctive agroecological zone.

Keywords: Economics, Extension gap, Front line demonstration, Impact, Technology index, Tomato, Yield

Tomato (*Solanum lycopersicum* L.) is a globally important vegetable crop, valued for its economic and nutritional contributions, such as vitamins, antioxidants, and dietary fiber (Pandey *et al.* 2017). A subtropical environment, like that of Manipur, is characterized by high rainfall, warm temperatures, and distinct wet and dry seasons, where cultivation is further hampered by hilly terrain, acidic soils, and excessive precipitation that collectively contribute to soil erosion, nutrient leaching, and organic matter loss, while soil acidity reduces nutrient availability and increases Al toxicity, ultimately impairing crop growth (Kumar and Tripathi 2016).

The undulating terrain further accelerates erosion and limits mechanization, making sustainable farming challenging (Sahoo *et al.* 2016). These factors collectively

degrade soil health, reducing fertility and crop productivity in the region. These conditions demand a comprehensive evaluation of soil fertility management and yield optimization to improve tomato production in the region.

Soil fertility is critical for crop productivity, affecting nutrient availability and plant health (Bhattarai *et al.* 2018). The acidic soils in Manipur's hilly areas are often nutrient-deficient, especially in N, P and K, and may contain toxic elements like Al and Mn, which hinder nutrient uptake and root development (Singh *et al.* 2019). Improving soil fertility through organic amendments, lime application, and balanced fertilization can enhance soil pH and nutrient availability, contributing to better tomato yields (Jena *et al.* 2018). Research on these interventions under Manipur's conditions is necessary to understand their impact on both soil fertility and crop yield.

Despite extensive research on tomato cultivation and soil fertility, region-specific studies addressing the unique challenges of acidic soils and hilly terrains in the subtropical hills of north-eastern India, particularly Manipur, remain critically understudied, prompting this comprehensive assessment of soil fertility management, yield optimization, and economic viability in this agroecologically complex

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zone. Farmers in Manipur face limited access to resources, high input costs, and fluctuating market prices, which affect their profitability (Devi and Adhikary 2020). Economic assessments can help determine the cost-effectiveness of different soil fertility management practices and their impact on yield (Roy *et al.* 2017). In hilly areas, transportation and labour costs are higher, making profitability more challenging (Ghosh *et al.* 2019). Understanding the economic benefits of improved soil management can lead to support the financial sustainability of local farmers.

Tomato production in Manipur is constrained by sub-optimal growing conditions, with limited cultivable areas and sporadic yield variations (Singh *et al.* 2018). The state's production remains low, averaging 12 t/ha, primarily due to climatic limitations, pest challenges, and inadequate agricultural infrastructure (Devi and Adhikary 2020).

Tomato yield in Manipur's humid, monsoon-prone climate is influenced by soil fertility and pest pressures, necessitating resistant cultivars, integrated pest management, and proper nutrient strategies (Sharma *et al.* 2020), while localized research is needed to assess their combined impact on production.

This study seeks to integrate soil fertility and economic analyses to assess how targeted interventions improve tomato yield and profitability in Manipur's acidic, nutrient-deficient soils. Field trials using the improved tomato variety Arka Samrat under Front Line Demonstrations (FLD) aimed to showcase advanced cultivation practices that enhance yields, promote disease-resistant hybrids, and reduce input costs, offering region-specific solutions for sustainable farming.

MATERIALS AND METHODS

The region's soils, primarily acidic Inceptisols, are low in organic matter and moderate in fertility,

requiring effective nutrient management to improve productivity in crops like tomato. To assess site-specific nutrient management, KVK conducted a FLD during the winter (*rabi*) seasons of 2021–22 and 2022–23 across six villages, Siden (24°24'40.56"N, 93°44'12.67"E); Saihenjang (24°24'37.74"N, 93°42'48.20"E); Thingkangphai (24°19'17.19"N, 93°41'23.40"E); Vaojang (24°20'34.39"N, 93°39'11.82"E); Kangvai (24°26'31.76"N, 93°42'45.54"E); and Songpi (24°20'5.62"N, 93°39'13.87"E), covering 1 ha. Six farmers from each village were randomly selected for the demonstrations.

For this purpose, the Arka Samrat tomato variety, developed by the Indian Institute of Horticulture Research, Bengaluru, is a high-yielding (80–85 t/ha), disease-resistant (ToLCV, BW, EB) cultivar with large, firm fruits (90–110 g) (Reddy *et al.* 2023), making it ideal for challenging agricultural environments like Manipur was used to compare traditional farming practices (FP) with site-specific nutrient management (SSNM) (Table 1).

The data collection methodology followed a structured approach during the *rabi* season when tomato cultivation is predominant. The study involved field trials under FLD programmes comparing traditional FP with SSNM. Data were collected from selected farms in a phased manner, covering soil testing, seed rate, seed treatment, transplanting age, spacing, nutrient management, and pest control. Soil samples were collected before transplanting using standard protocols to assess fertility, followed by October transplanting and observations at vegetative, flowering, and fruiting stages. Nutrient application adhered to site-specific recommendations, neem-based pest control was monitored, and yield data were recorded at harvest. Adoption gaps were classified as full, partial, or none based on recommended practices, with all participating farmers

Table 1 Level of adoption and adoption gap of recommended technologies in tomato under FLD

Particulars	Farming practices (FP)	Site-specific nutrient management (SSNM)	Gap
Crop	Tomato		N.A.
Variety	Arka Samrat		
Soil testing	Partially done	Done in all locations	Partial gap
Seed rate /ha	300 g/ha	160 g/ha	Full gap
Treatment of seed before sowing	Not treated	Treated with <i>Rhizobium</i> at the rate of 5 ml/kg tomato seeds	Full gap
Age of transplanting of seedlings	No specified days	25 days	Full gap
Method of transplanting and spacing	Flatbed system with no spacing	Raised bed system with spacing of 75 cm × 75 cm	Full gap
Transplanting time	20 th October		Full gap
Nutrient management	No specified quantum of nutrients applied, however, locally made manures (composite mixture of composted crop residues, cow dung and poultry manure) were added	120 N:80 P ₂ O ₅ : 50 K ₂ O kg/ha and 10 t/ha FYM	Full gap
Intercultural operations	Weeding done @50 days after transplanting	Weeding done @30 and 60 days after transplanting	Partial gap
Plant protection	Spray of neem based solution on fruits @5 ml/L water		No gap

receiving pre-demonstration training from KVK experts on scientific cultivation of tomato. Table 1 details the adoption levels and gaps.

Seeds of the Arka Samrat variety were sown first fortnight of September on raised, well-drained seedbeds, with consistent moisture and an optimal temperature of 25–28°C for proper germination. Essential intercultural operations like weeding, watering, and roughing were performed as needed. After 25 days, seedlings were uprooted, root-treated with *Azotobacter* and *Azospirillum* for 40 min, and transplanted on 20th October in both years at 75 cm spacing. Fields were ploughed three times, incorporating FYM at 5 t/ha and *Trichoderma viride* at 2.5 kg/ha during the final ploughing. Tomato disease control involves spraying a neem-based solution at 5 ml/L of water. Neem acts as a natural biopesticide, preventing fungal, bacterial, and insect-related diseases. The FYM used had a pH of 6.5, OC of 14.4%, and essential nutrients: N (0.87%), P (0.40%), K (0.56%), Ca (0.83%), Mg (0.43%), S (0.35%), and Fe (0.24%). Group meetings in six villages informed the selection of participating farmers and identified local cultivation practices and market trends. The SSNM and FP (Table 1).

Laboratory analysis: Bulk density (BD) is measured by the core method (Blake and Hartge, 1986). Soil pH uses a 1:2.5 soil-to-water ratio (Thomas 1996). SOC is estimated with the Walkley-Black method (Walkley and Black 1934), and SOC stock is calculated based on BD and soil depth (Lal 2004). Available N is assessed via the alkaline permanganate method (Subbiah and Asija 1956), Available P by the Bray-1 method (Bray and Kurtz 1945), and available K through neutral ammonium acetate extraction (Jackson 1973).

Tomato quality analysis: Total soluble solids (TSS) was measured with a digital refractometer (Beckles 2012). Lycopene was spectrophotometrically analyzed using hexane-acetone-ethanol extraction (Fish *et al.* 2002). Ascorbic acid was quantified by the 2,6-dichlorophenolindophenol titrimetric method (AOAC 2000). Fruit firmness was assessed via a digital penetrometer (Tigist *et al.* 2013). Titratable acidity was determined by titration with 0.1 N NaOH and expressed as citric acid% (Sadler and Murphy 2010). The sugar-acid ratio, indicating taste balance, was calculated by dividing TSS by titratable acidity (Baldwin *et al.* 2008).

Indices: Studies on extension tools i.e. extension gap, technology gap, and technology index were worked out to evaluate the impact of FLD on tomato as suggested by (Bhupenchandra *et al.* 2022).

Technology gap = Potential yield - Demonstrated yield

Extension gap = Demonstrated yield - Yield under existing practice

Technology index = $\frac{\text{Potential yield} - \text{Demonstrated yield}}{\text{Potential yield}} \times 100$

Economic analysis: Key metrics include Gross Income (GI), calculated as yield per hectare times the market price, and Cost of Production (COP), covering inputs like

seeds, fertilizers, labour, and machinery, with both variable (TVC) and fixed costs (TFC). Net Returns (NR) indicate profit by subtracting COP from GI, while the benefit-cost ratio (BCR) shows profitability by dividing GI by COP. Return on Investment (ROI) reflects investment efficiency as a percentage of NR over COP. Productivity per hectare assesses land efficiency, while the break-even point (BEP) identifies the yield or price level where revenue equals costs. Marketable surplus (MS) is the portion of yield available for sale post-consumption, and the marginal rate of return (MRR) measures additional income generated per extra investment.

Production efficiency (PE) = $\frac{\text{Total fruit yield of tomato (kg/ha)}}{\text{Duration of the crop}}$

Monetary efficiency (ME) = $\frac{\text{Total net returns in SSNM or FP plot (₹/ha)}}{\text{Duration of the crop}}$

Data analysis: To assess statistical differences across demonstration sites, Duncan's Multiple Range Test (DMRT) was employed as a post-hoc analysis following Analysis of Variance (ANOVA) at a 5% significance level ($p < 0.05$) for precise identification of significant pairwise differences among treatment means. Additionally, an independent t-test was conducted using SPSS 24 to compare the means of Farmer Practices (FP) and Site-Specific Nutrient Management (SSNM), to determine statistically significant variations between the two treatment groups.

RESULTS AND DISCUSSION

Soil properties: Statistical analysis of data (Table 2) revealed improvements in soil properties under site-specific nutrient management (SSNM) compared to farmers' practices (FP). Results (Table 2) indicated that BD decreased by 3.12% under SSNM (1.24 vs. 1.28 Mg/m³) and pH increased nominally by 3.49% (5.63 vs. 5.44), and these changes were not statistically significant ($p > 0.05$). However, SSNM significantly ($p < 0.05$) enhanced SOC by 10.91% (1.83% vs. 1.65%, $p = 0.034$) and SOC stock by 7.57% (45.5 vs. 42.3 Mg/ha, $p = 0.047$), indicating improved C sequestration. Nutrient availability also showed significant ($p < 0.05$) improvements, with N increasing by 9.89% (244.6 vs. 222.6 kg/ha, $p = 0.037$), P by 13.75% (18.2 vs. 16.0 kg/ha, $p = 0.041$), and K by 4.94% (337.8 vs. 321.1 kg/ha, $p = 0.038$).

The reduction in BD under SSNM compared to FP indicates that soil structure and aeration were improved. Similar observations have been made, where organic amendments and balanced fertilization were found to enhance soil porosity and reduce compaction (Sharma *et al.* 2022). A nominal increase in soil pH under SSNM suggests that a liming effect might have occurred due to improved nutrient balance and organic matter decomposition. Integrated nutrient management has been shown to counteract soil acidity in highly weathered soils (Singh *et al.* 2022). A significant increase in SOC under SSNM indicates improved soil organic matter accumulation, enhancing fertility, microbial activity, and long-term carbon storage through balanced nutrient applications and increased root

Table 2 Effect of FP and SSNM technology on soil properties under tomato farming

Demonstration sites	BD (Mg/m ³)		pH		SOC (%)		SOC stock (Mg/ha)		Available N		Available P		Available K	
	FP	SSNM	FP	SSNM	FP	SSNM	FP	SSNM	FP	SSNM	FP	SSNM	FP	SSNM
Siden	1.28 ^a	1.23 ^a	5.62 ^a	5.75 ^a	1.66 ^{ab}	1.85 ^b	42.0 ^a	45.1 ^a	220.7 ^b	239.7 ^{ab}	16.7 ^{ab}	19.6 ^{bc}	335.0 ^{bc}	347.2 ^{bc}
Saihenjang	1.28 ^a	1.24 ^a	5.54 ^a	5.71 ^a	1.66 ^{ab}	1.83 ^b	42.0 ^a	45.4 ^a	221.4 ^a	240.4 ^{ab}	16.6 ^{ab}	19.3 ^{bc}	331.2 ^{bc}	344.0 ^{bc}
Thingkangphai	1.28 ^a	1.24 ^a	5.42 ^a	5.69 ^a	1.65 ^{ab}	1.84 ^b	42.2 ^a	45.4 ^a	221.7 ^a	240.7 ^{ab}	16.4 ^{ab}	18.7 ^{bc}	322.1 ^{cd}	342.3 ^{bc}
Vaojang	1.28 ^a	1.24 ^a	5.45 ^a	5.56 ^a	1.64 ^{ab}	1.83 ^b	42.3 ^a	45.5 ^a	222.4 ^b	248.4 ^a	15.9 ^c	17.4 ^{bc}	310.4 ^c	329.5 ^c
Kangvai	1.29 ^a	1.25 ^a	5.32 ^a	5.53 ^a	1.64 ^{ab}	1.83 ^b	42.5 ^a	45.6 ^a	223.5 ^b	248.5 ^a	15.7 ^c	17.1 ^d	292.7 ^{ef}	316.3 ^{cd}
Songpi	1.28 ^a	1.24 ^a	5.30 ^a	5.53 ^a	1.64 ^{ab}	1.82 ^b	42.5 ^a	45.8 ^a	225.8 ^a	249.8 ^a	14.8 ^d	16.8 ^c	335.0 ^{bc}	347.2 ^{bc}
Mean	1.28	1.24	5.44	5.63	1.65	1.83	42.3	45.5	222.6	244.6	16.0	18.2	337.8	321.1
t-test	0.624		0.572		0.547		0.687		0.25		0.587		0.985	
p-value	0.124		0.087		0.034		0.047		0.037		0.041		0.038	

Duncan's Multiple Range Test indicated significant differences among treatments, as shown by the varying alphabetical superscripts. Treatments with the same superscript letter are not significantly different at the 5% level.

BD, Bulk density; SOC, Soil organic carbon; FP, Farmer's practice; SSNM, Site-specific nutrient management.

biomass (Li *et al.* 2023). Higher N availability under SSNM indicate improved nutrient-use efficiency through better synchronization with crop demand, aligning with findings on SSNM's precision in meeting plant needs (Zhao *et al.* 2023). A significant increase in available P suggest that P solubilization was enhanced, possibly due to microbial inoculation and organic amendments, as previously demonstrated (Meena *et al.* 2021). SSNM increases available K by enhancing microbial activity, soil organic matter, and nutrient interactions, while reducing fixation through organic amendments and balanced fertilization (Zhang *et al.* 2023).

In overall, the mean values indicate that SSNM improved soil properties compared to FP by reducing BD (1.24 Mg/m³), enhancing aeration, increasing SOC (1.83%) and SOC stock (45.5 Mg/ha) for better C sequestration, and improving available N, P, and K, thereby supporting soil fertility and plant nutrition.

Tomato quality parameters: Results indicated that

under SSNM, TSS increased by 17.14% over FP with t-test showing a significant difference ($p = 0.0034$) (Table 3). Lycopene content was 33.17% higher, with a significant difference ($p = 0.0011$). Ascorbic acid augmented by 28.32%, and the t-test confirmed a significant difference ($p = 0.0045$). Firmness improved by 27.09%, with a significant difference ($p = 0.0022$). Titratable acidity increased by 27.27%, with t-test indicating a significant difference ($p = 0.0097$). The sugar-acid ratio was 26.56% higher, with a significant difference ($p = 0.0017$).

A significant increase in TSS under SSNM indicated enhanced sugar accumulation, improving fruit sweetness and consumer preference (Sharma *et al.* 2020). Lycopene content also increased, likely due to improved N and K availability, which promoted carotenoid biosynthesis (Kumar *et al.* 2019). Ascorbic acid content was higher under SSNM, suggesting improved vitamin C synthesis due to better nutrient availability and reduced oxidative stress

Table 3 Effect of FP and SSNM technology on fruit quality parameter of tomato

Location	TSS (%)		Lycopene (mg/100g)		Ascorbic acid (mg/100 g)		Firmness (kg/cm ²)		Titratable acidity (%)		Sugar: Acid ratio	
	SSNM	FP	SSNM	FP	SSNM	FP	SSNM	FP	SSNM	FP	SSNM	FP
Siden	5.56 ^a	4.67 ^b	4.75 ^{ab}	3.73 ^b	24.42 ^{ab}	19.35 ^b	3.05 ^a	2.37 ^b	0.44 ^{ab}	0.34 ^b	12.54 ^a	9.23 ^b
Saihenjang	6.12 ^a	4.89 ^b	5.83 ^a	4.29 ^b	26.53 ^a	21.47 ^b	3.41 ^a	2.65 ^b	0.48 ^a	0.39 ^b	13.11 ^a	10.25 ^b
Thingkangphai	5.78 ^a	5.12 ^b	4.99 ^a	4.12 ^b	29.61 ^a	22.98 ^b	2.98 ^{ab}	2.44 ^b	0.35 ^{ab}	0.29 ^b	14.22 ^a	11.34 ^b
Vaojang	5.21 ^{ab}	4.75 ^b	5.25 ^a	3.95 ^b	23.77 ^{ab}	18.62 ^b	3.14 ^a	2.53 ^b	0.42 ^a	0.36 ^b	11.98 ^a	9.87 ^b
Kangvai	5.47 ^a	4.62 ^b	5.68 ^a	3.99 ^b	28.13 ^a	20.54 ^b	3.22 ^a	2.38 ^b	0.46 ^a	0.33 ^b	12.87 ^a	10.12 ^b
Songpi	6.29 ^a	5.34 ^b	5.79 ^a	4.18 ^b	27.35 ^a	23.19 ^b	3.36 ^a	2.71 ^b	0.39 ^a	0.28 ^b	14.11 ^a	11.45 ^b
Mean	5.74	4.90	5.38	4.04	26.64	21.03	3.19	2.51	0.42	0.33	13.14	10.38
t-test	5.12		6.47		4.89		5.77		3.93		6.02	
p-value	0.003		0.001		0.005		0.0022		0.0097		0.0017	

Duncan's Multiple Range Test indicated significant differences among treatments, as shown by the varying alphabetical superscripts. Treatments with the same superscript letter are not significantly different at the 5% level.

FP, Farmer's practice; SSNM, Site-specific nutrient management.

Table 4 Effect of SSNM technology on economics, yield performance and technology gaps under SSNM under tomato farming

Demonstration village	GR	COP	NR	BCR	ROI	PUA	BEP	MS	MRR	ME	PE	Yield (t/ha)		% Increase in yield	TG	EG	TI
												FP	SSNM				
Siden	216000	98700	117000	2.18	1.18	1200	8225	2964	213	975	150	13	18	35	18	5	50
Saihenjang	252000	97800	154200	2.57	1.57	1400	8150	3448	205	1285	175	14	21	50	15	7	41
Thingkangphai	328500	97600	228000	3.36	2.33	1266	8133	3100	214	1900	158	15	19	27	17	4	47
Vaojang	337500	96500	276000	3.49	2.86	1533	8041	3728	246	2300	192	17	23	35	13	6	36
Kangvai	346500	98200	248300	3.52	2.52	1113	8183	2778	209	2069	142	13	17	31	19	4	52
Songpi	337500	98000	239500	3.44	2.44	1466	8166	3548	242	1996	183	15	22	47	14	7	39
Mean	303000	97800	210500	3.09	3.31	1330	8150	3261	222	1754	167	14.5	20	37.5	16	5.5	44.2

GR, Gross return; COP, Cost of production; NR, Net Return; BCR, Benefit Cost Ratio; ROI, Return on Investment; PUA, Productivity per Unit Area; BEP, Break Even Point; MS, Marketable Surplus; MRR, Marginal Rate of Return; ME, Monetary efficiency; PE, Production efficiency; FP, Farmer's practice; SSNM, Site-specific nutrient management; TG, Technology gap (t/ha); EG, Extension gap (t/ha); TI, Technology index (%).

(Singh *et al.* 2018). Fruit firmness increased, attributed to enhanced Ca and K uptake, which strengthened cell wall integrity (Duret *et al.* 2025). Titratable acidity was also higher, indicating improved organic acid metabolism, which contributed to better postharvest quality (Das *et al.* 2022). The sugar-acid ratio increased, enhancing overall fruit taste and acceptability (Meena *et al.* 2020).

Economic analysis yield performance and technology gaps under SSNM: The agricultural performance across demonstration villages under SSNM shows yield, GR, and economic variability (Table 4). Results demonstrated that the SSNM practices implementation across six demonstration villages revealed significant variations in yield and economic performance. Vaojang emerged as the leading demonstration site with 23 t/ha yield, generating the highest net return (₹276,000/ha) and an remarkable benefit-cost ratio (BCR) of 3.49. With exceptional efficiency metrics- including the lowest break-even point (8,041), highest marketable surplus (3,728), and strongest MRR (246) this village demonstrated optimal resource utilization. Songpi and Kangvai demonstrated that market factors can significantly influence economic outcomes. Despite contrasting yields (22 t/ha and 17 t/ha), both achieved remarkable BCRs (3.44 and 3.52). Kangvai's case is particularly noteworthy, achieving the highest BCR despite the lowest yield, highlighting the importance of market engagement. The remaining villages (Saihenjang, Thingkangphai, and Siden) showed varying degrees of success, with yields between 18–21 t/ha and BCRs ranging from 2.18–3.36.

The PE (Table 4) varied considerably from 142 kg/ha (Kangvai) to 192 kg/ha (Vaojang), reflecting differences in input utilization effectiveness. ME metrics further differentiated performance, with Vaojang (₹2,300) and Kangvai (₹2,069) leading, while Siden recorded the lowest (₹975). The consistently high BCRs across all villages validate SSNM's effectiveness in enhancing agricultural viability. The results suggested potential for additional investment in SSNM technologies to further improve productivity and economic outcomes in tomato cultivation across Manipur's subtropical hills.

Cluster heatmap: The clustered heatmap (Fig. 1) illustrates relationships among soil properties and nutrient availability under FP and SSNM across six sites. Parameters like BD, SOC, SOC stock, and nutrients (N, P, K) cluster by similarity, with colour gradients from low (purple) to high (yellow). SOC, available K, and N form one cluster, while available P and pH group separately, with SOC stock and BD slightly apart. Kangvai and Songpi showed lower BD and SOC stock, whereas Saihenjang and Siden exhibit higher SOC and nutrient levels, particularly N and P. The heatmap indicated SSNM enhances available N, K, and SOC, aligning with Fageria (2009), who highlighted SOC's role in N and K availability. The P-pH association corresponds with Richardson *et al.* (2009), linking pH to P bioavailability. Variations in BD and SOC stock are influenced by site-specific factors, aligning with long-term soil changes (Lal 2004, Bhupenanchandra *et al.* 2022 and

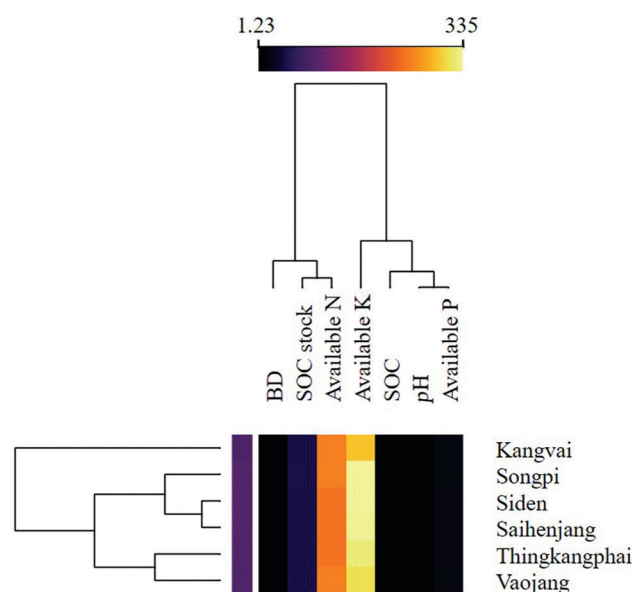


Fig. 1 Clustered heatmap representation of soil physical, chemical, and nutrient parameters under FP and SSNM across six demonstration sites.

2024). Lower nutrient availability in Kangvai and Songpi suggests tailored strategies are needed (Roberts 2008), while higher levels in Saihenjang and Siden under SSNM confirm its effectiveness in improving nutrient dynamics in acidic soils of north-east India.

In overall, the clustered heatmap analysis indicated that SSNM improves soil nutrient availability, especially N, K, and SOC, highlighting its effectiveness in enhancing soil fertility across diverse sites.

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