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RESEARCH ARTICLE

Integrated assessment of environmental and economic sustainability in natural and conventional vegetable farming systems in the Indian Himalayas

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Abstract

Natural farming (NF) is gaining global attention as an agroecological farming approach to address the dual aspects of ecological benefit and maintaining food security. The present study examined the impact of NF compared to conventional farming (CF) among vegetable growers in the hilly region of India. The study was performed with 300 actively engaged farmers selected through a multi-stage sampling technique to quantify various environmental indicators like Greenhouse Gas (GHG), acidification, eutrophication, ecotoxicity and ecoefficiency with TEBA-TCA and IPCC Tier 1 framework. In particular, NF significantly reduced environmental footprints, with net GHG emissions decreasing from 8215.6 kg CO_2 eq./ha in conventional farming to just 69.2 kg CO_2 eq./ha, while eco-efficiency improved from ₹36.6–₹7163/kg CO_2 eq. Findings further revealed that NF-based crop combination achieved a higher benefit-cost ratio of 7.51, reflecting its strong economic viability. Comparing the composite sustainability impact with aggregation, suggested NF combinations significantly reduce the average emission value (e.g., 69.2 kg CO_2 eq./ha in NF vs. 8215.6 kg CO_2 eq./ha in CF for tomato). While the other indicators of ecotoxicity, eutrophication and acidification, reported no evidence through their eco-friendly farm management practices, remarking on the resilient balancing between mitigating climate change and ensuring farm profitability. Overall, the enhanced eco-efficiency observed in NF supports a higher sustainability index, demonstrating that integrating environmental externalities into economic assessments can guide sustainable farming strategies in alignment with the Sustainable Development Goals (SDGs).

Keywords: agroecology; carbon sink; food security; organic farming; sustainable agricultural practices

Introduction

India is an agriculture-dominated nation known for its diverse agro-climatic zones and the globally second-largest arable land, presenting a strong comparative advantage for diversified farming (1). The country is intricately rooted in its traditional farming practices that have historically adapted to environmental changes, contributing to the conservation of natural resources and agroecosystems from the landscape to the farm level. From ancient times, agriculture was a major livelihood source for its population, contributing significantly to rural Gross Domestic Product (GDP) in several states. With the introduction of the green revolution, the traditional diverse farming system has been replaced by the monocropping of rice-wheat, which largely contributes to the staple food diets of people (2, 3). However, in recent decades, a sharp rise in demand for fruits and vegetables has been witnessed owing to changes in consumers' income level, buying patterns, food habits, faster returns and market prices. The expanding demand, particularly in urban, peri-urban areas, has driven many rural farmers to engage in intensive vegetable farming to improve their livelihoods. In India, small and marginal farmers cultivate about 44 % of the total agricultural land (4, 5). They are generally recognised for their high level of efficiency with higher cropping intensity (6). Vegetable farming has largely impacted these farm categories, making a remarkable contribution to total food security. However, the intensification of vegetable farming has led to an increase in the dependency on synthetic inputs, particularly hybrid seeds, fertilisers and plant protection, thereby escalating the total cost, economic burden and ecosystem degradation. Long-term use of chemical pesticides not only poses risks to human health due to increased pesticide residues, but also degrades the soil organic matter, thereby exacerbating the impact of climate change (7, 8). According to the FAO, on-farm activities, particularly land use changes, contributed approximately 9.3 billion tonnes of CO_2 equivalent emissions globally showing an increase in GHG contribution [carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)] (9). The synthetic nitrogen production and consumption have far greater global warming potential than CO_2, with FAO projections estimate that global consumption of synthetic nitrogen fertilizers could surge by 50 % from 2012 levels by 2050 (10), posing serious challenges to the climate goals of Paris Agreement to limit global temperature rise from 1.5 °C or well below 2 °C (11). To tackle this issue, agroecological and regenerative farming practices are being promoted globally amidst increasingly direct and interconnected challenges of chemical-based farming on soil degradation and biodiversity loss (12, 13). The global agroecology movement, La Vía Campesina (14) and the European Green Deal have gained momentum in transforming food systems worldwide by promoting reduced pesticide and fertilizer use, alongside Food and Agriculture Organization's (FAO) Scaling Up Agroecology Initiative (15). In India, attention has shifted towards similar initiatives under the NF system, an indigenous agroecological approach that eliminates the use of chemicals and emphasises the restoration of soil health, biodiversity, farmers' livelihood and climate change (16-18). While NF was practised in small pockets of Indian states, the traction gained momentum after the successful results of the large-scale implementation of NF in Andhra Pradesh.

NF is an integrated, chemical-free farming approach similar to the agroecology model. It integrates livestock inputs (cow dung and cow urine), diversified cropping systems, soil-moisture conservation through mulching, legume-based cropping for nitrogen fixation and bio-formulations that catalyse soil microbial growth (19).

The basic pillar of NF is:

I. Jeevamrit application: Liquid manure is used to enhance soil fertility and microbial activity
II. Beejamrit application: Liquid seed treatment is applied before sowing to protect from diseases and enhance germination
III. Ghanajeevamrit application: It's a fermented microbial powder to enhance soil health and crop production
IV. Acchadana (Mulching): This involves covering the soil surface with organic materials like straw, crop residues or even live plants (cover crops).
V. Whapasa: It refers to a condition in NF where the soil contains both air and water molecules, creating a favourable microclimate for plant roots and soil organisms.

The details of the elements used to prepare (a) Jeevamrit, (b) Beejamrit, (c) Ghanajeevamrit are presented in Fig. 1.

Understanding the real-world trade-offs within farming systems requires in-depth integration of economic and environmental metrics. Given the growing global concerns of climate change, there is a lack of evidence that connects environmental and economic sustainability in the agricultural system, especially the vegetable farming sector. The existing literature mostly focuses on assessing the productivity, cost-benefit analysis and adoption impact of NF vs. CF across different regions of India. The widely known acronym of NF as an eco-friendly farming approach lacks the scientific studies to support the argument. The trade-off between NF over CF for maintaining livelihood security at positive environmental externalities, particularly in the context of climate change, remains unclear and unexplored. This serves as a basis for the present study, as hilly regions are typically more vulnerable to climate change at a higher rate than the average global levels (20, 21).

Sustainable farming practices are essential for maintaining ecosystem services and supporting small and marginal farmers. Himachal Pradesh was selected for the present study owing to its diverse agroclimatic zones, which offer immense opportunities to empower the small and marginal farmers in vegetable farming. Therefore, the present study was conducted with dual assessment of environmental and economic sustainability in Indian regenerative natural farming vs. conventional vegetable farming in the Indian Himalayas.

Materials and Methods

Study area

Himachal Pradesh is a hilly region located in the North Western Himalayas, well known for its tourism, agriculture, cultural diversity and temperate crops. The sub-climatic conditions vary widely across the state and are known for their four sub-agro-climatic zones (Fig. 2).

1. **Zone I** - Sub-mountainous low hills, subtropical (up to 1100 m).
2. **Zone II** - Mid-hills, sub-humid (1100 -2000 m).
3. **Zone III** - High hills, temperate wet (2000 -2999 m).
4. **Zone IV** - High hills, temperate dry (>3000 m).

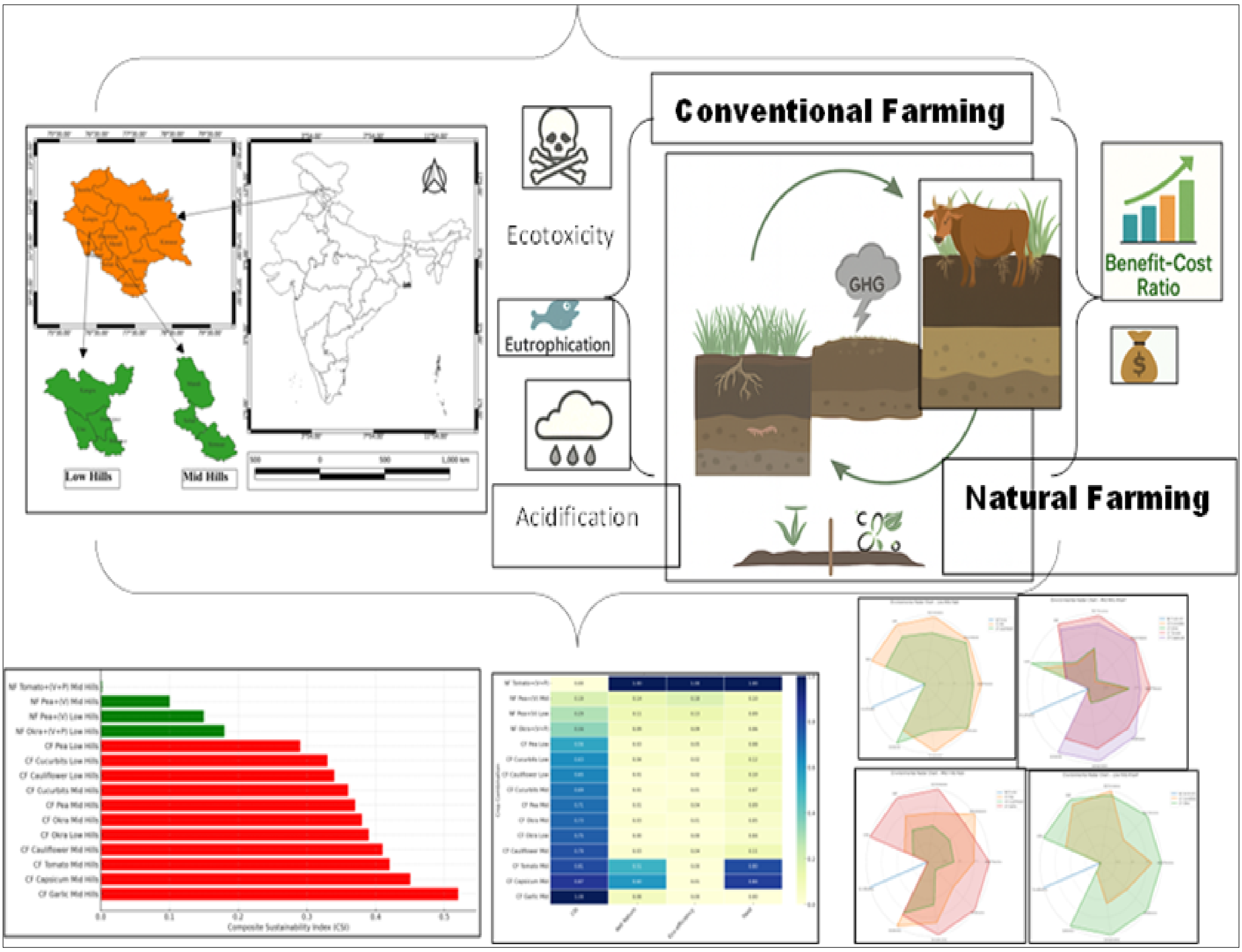
Himachal Pradesh was purposefully selected due to its abundance of natural resources, spanning 51 blocks, covering a total cropped area of 8.91 lakh hectares (22). Vegetable farming in Himachal Pradesh gained significant space due to high market value and favourable climatic conditions. The majority of the population resides in rural areas with marginal and small land holdings and relies on agriculture for their livelihood (23). However, input-intensive vegetable farming burdens capital-intensive farmers, driving interest in shifting to NF practices.

Sampling strategy

The secondary data, including a list of NF and CF vegetable growers, was collected from the Agriculture Department. The primary data about crop choices, input use and net earnings were collected through face-to-face interview schedules. A stratified random sampling approach was adopted to select the representative farmers from the study area. In the first stage, two zones were selected based on total cultivated area. In the second stage, five blocks were selected from each zone and in third stage three panchayats were selected from each block. In last stage, 10 farmers (5 NF and 5 CF) were randomly selected from each panchayat, resulting in a total representative of 300 farmers (Fig. 3). Data covering both the kharif and rabi seasons were collected between 2023 and 2024.

Environmental metrics

The environmental impacts of NF and CF systems were quantified using data on fertilisers (N, P, K), diesel and plant protection chemicals (herbicides, fungicides, insecticides). Emissions and pollutant loads were estimated using the TEBA-TCA, IPCC Tier 1 and UseTox frameworks, selected for their suitability in data-constrained, smallholder hill systems. Carbon emissions were calculated by multiplying the quantity of each input by its corresponding emission factor (kg CE/ha), as per IPCC Tier 1 guideline (24, 25). N_2O emissions were measured using a default nitrogen emission factor of 0.01 and expressed in CO_2 equivalents with global warming potential (GWP) values (26). Total GHG emissions included contributions from CO_2, N_2O and CH_4 sources. GHG intensity was calculated as a quotient of GHG emissions and crop yield in kg CO_2 eq./kg yield. The Grey Water Footprint method was utilised for assessing water pollution based on nitrogen leaching-runoff fraction of 0.10 and Phosphorus fraction of 0.03 (27).



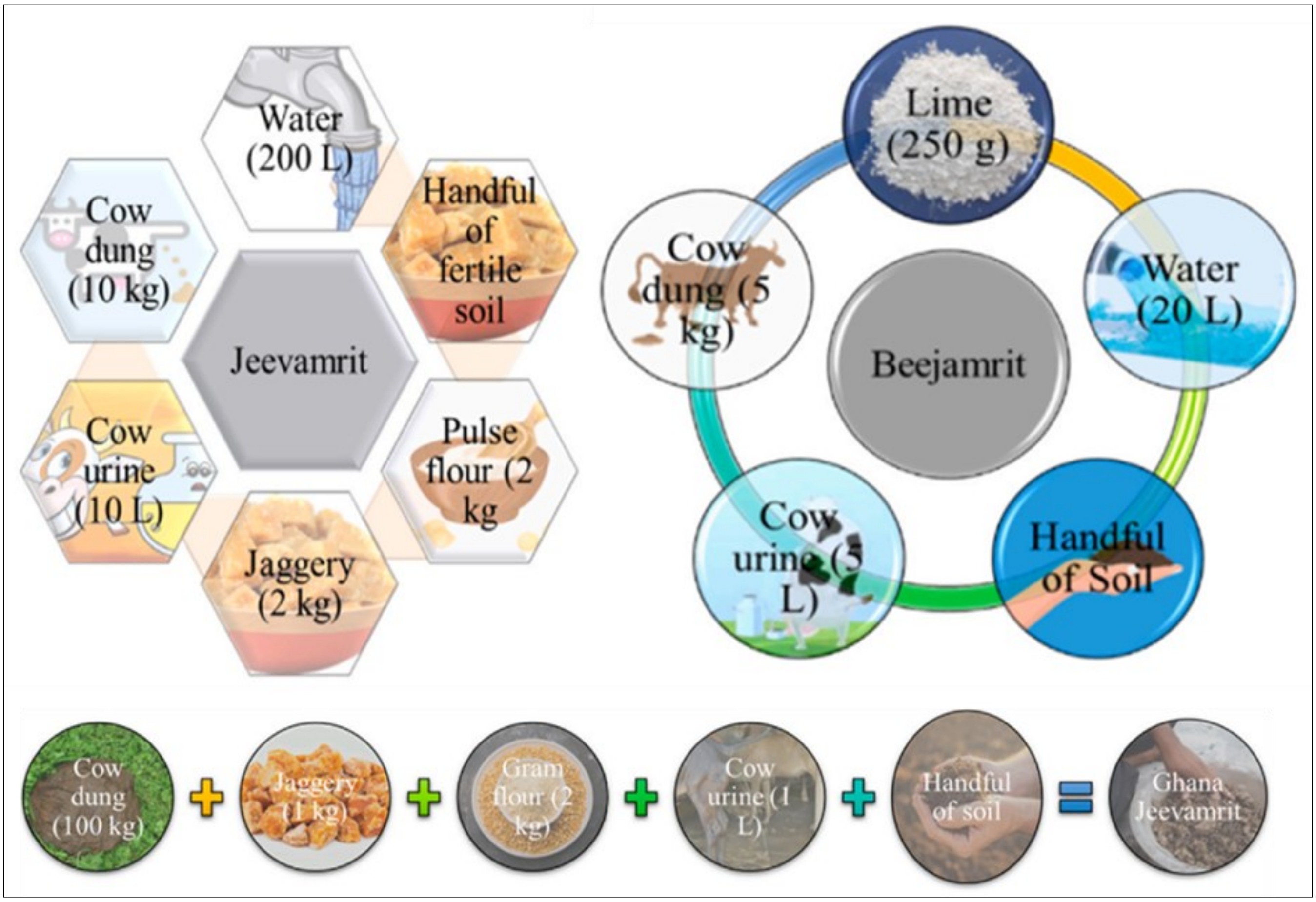


Fig. 1. Elements used for preparation of (a) Jeevamrit, (b) Beejamrit, (c) Ghanajeevamrit.

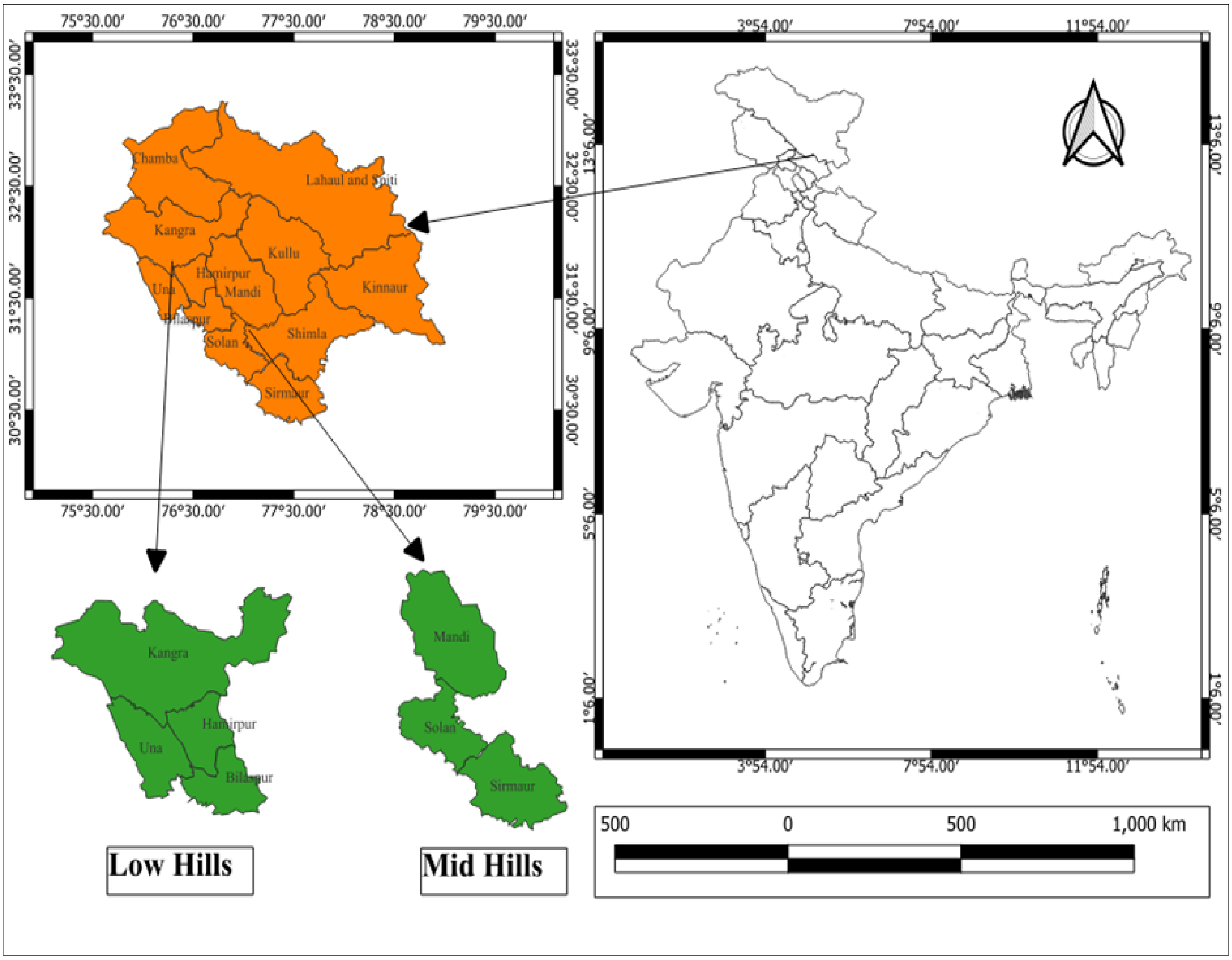


Fig. 2. Location of the study regions in India.

Source : QGIS software, Version 3.42.3.

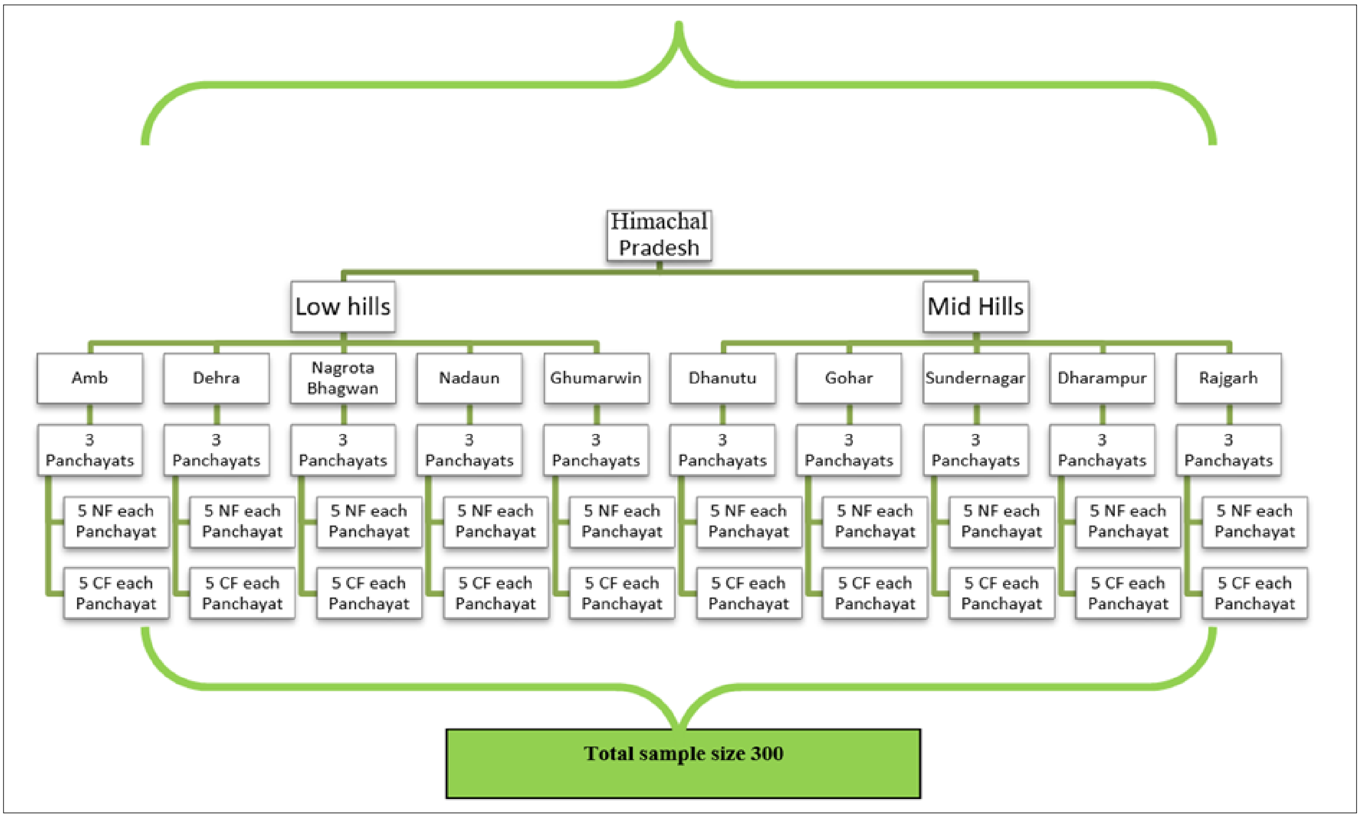


Fig. 3. Sampling frame of the selected farmers.

Eutrophication and acidification impacts were quantified by multiplying pollutant quantities by respective impact factors expressed in PO_4^{3-} equivalents and SO_2 equivalents respectively. Pesticide use ecotoxicity was approximately estimated using the UseTox model, which assesses potential harmful effects on biodiversity and non-target organisms somewhat globally. Eco-efficiency was ultimately figured out as ratio of net economic returns in ₹/ha and total GHG emissions in kg CO_2 eq./ha. Sustainable agriculture aims to increase its eco-efficiency by lowering the environmental impacts like energy use and GHG emissions of agriculture, while increasing the economic output (28). The emission parameters of input used in both farming system is provided in Table 1 & 2.

Equations

Water pollution

Water pollution = amount of N applied (kg) × leaching-runoff of N + amount of P applied (kg) × leaching-runoff of P (Eqn. 1)

Ecotoxicity

Ecotoxicity = Use of substance i (kg) × Toxicity impact of use of substance i (kg Cu equivalent/kg)

N_2O emission

N_2O emission (kg/year) = N contributed by N sources × 0.01 × 44/28 (Eqn. 2)

N_2O-CO_2 eq = N_2O emission × 265

Global warming potential (GWP)/Total GHG

GWP = N_2O-CO_2 eq. + CO_2 emission (Eqn. 3)

For rice

GWP = total CH_4 emission × 25 + N_2O-CO_2 eq. + CO_2 emission (Eqn. 4)

Greenhouse intensity (GHGI)

GHGI= TGHG/Yield (Eqn. 5)

Eutrophication (Eu)

Eu = Use of substance i × Eutrophication potential of substance i (kg PO_4 eq./unit) (Eqn. 6)

Acidification (Ac)

Ac = Use of substance i × Acidification potential of substance i (kg SO_2 eq./unit (Eqn. 7)

Eco-efficiency

Eco–efficiency (₹/kg CO_2 eq.) = Net Return (₹/ha)/GHG emission (kg CO_2 eq./ha) (Eqn. 8)

Table 1. Emission factors used to quantify GHG emissions

Inputs	Equivalent carbon emission (kg CE/kg)	Reference
Diesel	0.94	(28)
Nitrogen	1.3	(28)
Phosphorous	0.2	(28)
Potassium	0.15	(28)
Herbicide	6.3	(28)
Fungicide	3.9	(28)
Insecticide	5.1	(28)
FYM	0.00509	(29)
	N_2O emission	
Inputs	**Emission factor**	**References**
Urea	0.7 kg N_2O per kg Urea	(30)
FYM	0.2 × (N of FYM applied)	(31)
Diesel	0.6 kg N_2O/TJ	(32)

Table 2. Specific weighting factor of pollution with unit of measure

Potential	NO_x	NH_3	PO_4	References
Acidification Potential (Kg SO_2 eq)	0.7	1.88	-	(33, 34)
Eutrophication Potential (Kg PO_4^{3-} eq)	0.13	0.35	1.00	
		Nutrients		
Inputs	**N (%)**	**P (%)**	**K (%)**	**References**
Jeevamrit	0.25	0.13	0.16	(35)
Beejamrit	0.72	0.14	0.23	(35)
Ghanajeevamrit	1.05	0.87	0.68	(35)
Emission factor	**Wet climate**	**Dry climate**	**Units**	**References**
Cow dung	0.0013	0.0007	Kg N_2O kg^{-1}	(26, 36)
Cow urine	0.0077	0.0032	Kg N_2O kg^{-1}	(26, 36)

Farmyard manure (FYM) is a decomposed mixture of dung, urine, litter and leftover materials from roughages and fodder fed to animals. A well-decomposed FYM contains 1.2 % N, 0.4 % P_2O_5 and 1.0 % K_2O (37).

Economic indicators

The key parameters such as cost, market price, gross returns and net return were evaluated alongside benefit-cost ratio. Crop equivalent yield (CEY) was calculated as the sum of equivalent principal and intercrop yields (16). The differing yields of intercrops were transformed into the equivalent yield of any crop depending on the commodity price. Additionally, income metrics about labour requirements, labour charges, were also taken to calculate the farm business income, family labour income and farm investment income to have insights into financial performance across NF and CF systems. The Composite Sustainability Index (CSI) was constructed by normalisation of values of all indicators and assigned the inverted value for negatively associated ones. Equal weights were assigned for all indicators in the geometric mean aggregation:

$$CSI = \prod_{j=1}^{n} \left(x'_{(j)}\right)_j^{w}$$

Where:

x_j = normalised value of the j^{th} indicator

w_j = equal weight (1/n)

n = number of indicators

Methodological boundaries

The TEBA-TCA and IPCC Tier 1 methods were considered for the assessment of small and marginal vegetable growers. This framework enables the direct calculation of ecological expenses associated with the quantity of input uses. This approach evaluates the effectiveness of a farm without upstream or downstream data inventory as required for the ISO framework of Life Cycle Assessment (LCA). The United Nations – The Economics of Ecosystems and Biodiversity (UN-TEEB) Agrifood framework was selected to comprehensively capture farm-level environmental externalities. The analysis of the results was done using Excel and R software.

Results and Discussion

The present study conducted a comprehensive study on the sustainability aspects of vegetables grown under both farming systems. The findings revealed a more diverse cropping pattern among NF vegetable growers, who integrated main crops with sub-legume crops, compared with their counterparts. The details of the choice of crop grown are shown in Fig. 4, providing a clear profile of crop diversification concerning sustainability, soil health and agroecosystem integrity.

Environmental sustainability indicators: NF vs. CF across agro-climatic zones

The environmental impact assessment provides valuable insights into the agroecological aspect of the NF system over CF footprints. Across all parameters, NF consistently outperformed in environmental parameters by cutting down the GHG emissions, N_2O emissions, GWP, eutrophication, acidification, ecotoxicity, water pollution and GHGI (Fig. 5). However, the extent of the gains significantly varied across different crop combinations under the NF system (Table 3).

GHG emissions and GWP

GHG Emission estimates were significantly lower under all NF crop combinations. In low hills, the NF crop combination pea + (vegetables) [P + (V)] emitted about 24.23 kg CO_2 eq./ha in contrast to CF pea and okra (1040 and 4429.8 kg CO_2 eq./ha). Similarly, the NF crop combination in mid hills had also lower emission, i.e., 7.12 kg CO_2 eq./ha in tomato + (vegetables + pulses) [T+ (V + P)] while the contrast CF tomato had emission of 3148.79 kg CO_2 eq./ha, indicating reductions exceeding 95–98 %. Tomato, capsicum and garlic under CF recorded the highest emissions in the entire dataset, with 8215.6, 7595 and 7126.90 kg CO_2 eq./ha respectively. However, when the same crops were grown under NF, emissions dropped to 69.2 and 23.89 kg CO_2 eq./ha respectively.

This reduction in GHG was attributed to the exclusion of synthetic inputs and eco-friendly livestock-based farm inputs (38, 39). The finding further highlighted that conventional farmers engaged in high-value vegetables intensively pose a severe threat to the environment, while NF farmers offer scalable, low-emission results.

N_2O emissions and GHGI emissions

Nitrous oxide contributed largely to agricultural climate change, exhibiting significant differences in both farming approaches. Across both zones, NF crop combination consistently recorded lower emissions. In low hills, NF pea + (vegetables) [P + (V)] had emission of 24.23 kg N_2O-CO_2 eq./ha to maximum of 27.97 kg N_2O-CO_2 eq./ha in okra + (vegetables + pulses) [O + (V + P)] whereas, in conventional farming the lowest emission was recorded as 576 kg N_2O-CO_2 eq./ha in cucurbits to maximum of 1143 kg N_2O-CO_2 eq./ha in okra. In mid hills, NF pea + (vegetables) [P + (V)] emitted about 19.74 kg N_2O-CO_2 eq./ha to a maximum of 62.09 kg N_2O-CO_2 eq./ha, in tomato + (vegetables + pulses) [T + (V + P)], while in CF garlic emissions exceeded 6558.37 kg N_2O-CO_2 eq./ha. The GHGI accounts for the trade-off between yield and GHG emissions and reinforces the unsustainable nature of the conventional farming system. In low hills, the highest GHGI in NF was recorded to 0.02 kg CO_2 eq./kg yield in okra + (vegetables + pulses) [O + (V + P)] vs 1.70 kg CO_2 eq./kg yield in okra. Whereas in the mid-hills, the maximum intensity of 0.01 kg CO_2 eq./kg yield was observed in pea + vegetables [P + V], compared with 3.80 kg CO_2 eq./kg yield in the CF garlic crop, demonstrating efficiency gains of more than 100-fold. The exclusion of synthetic inputs combined with bio-organic fertilisers reduced N_2O and NO emissions (40-42). This highlights that NF has potential to reduce the GHG emission at low-cost productivity.

Eutrophication and Acidification

Nutrient runoff is a key indicator linked to eutrophication and

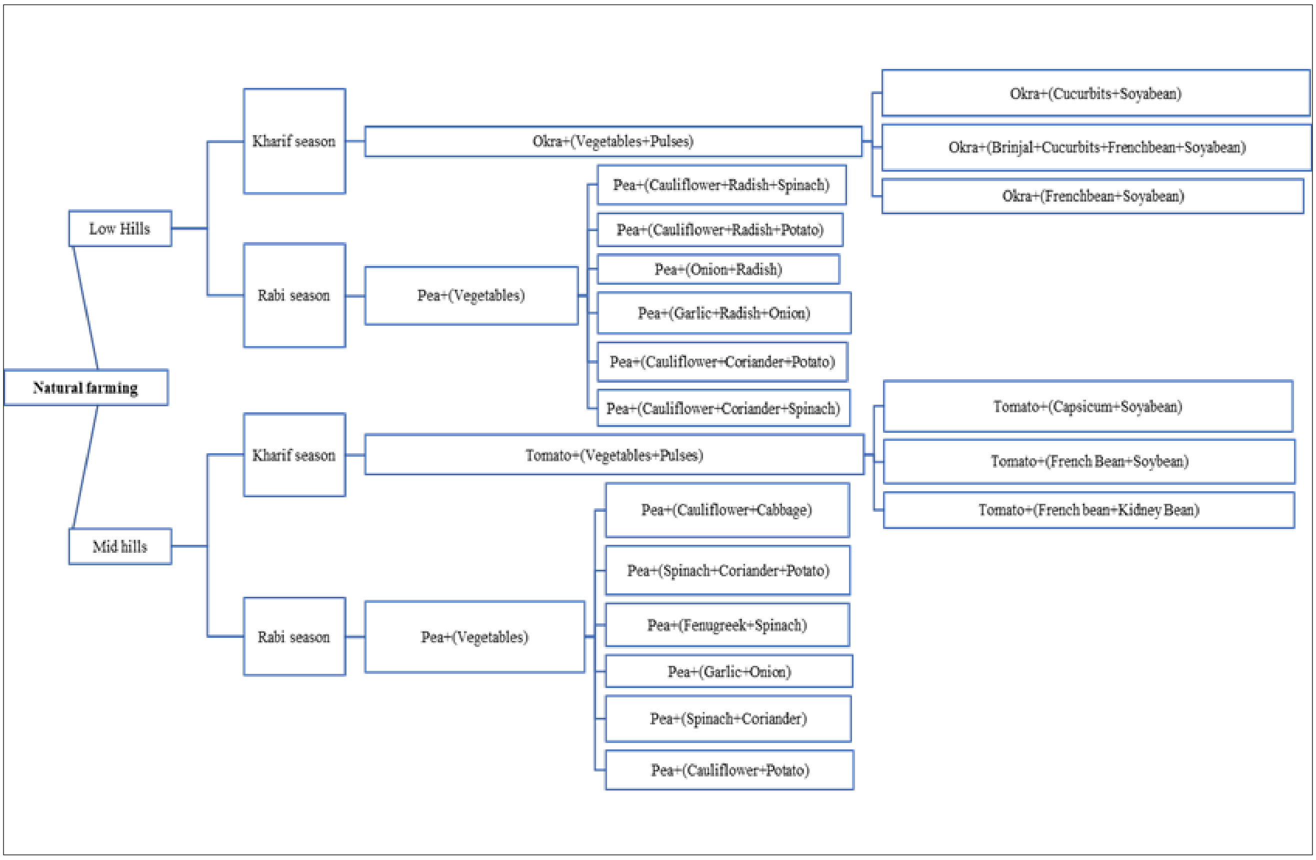


Fig. 4. Diverse intercropping combinations grown by Natural farmers across hills.

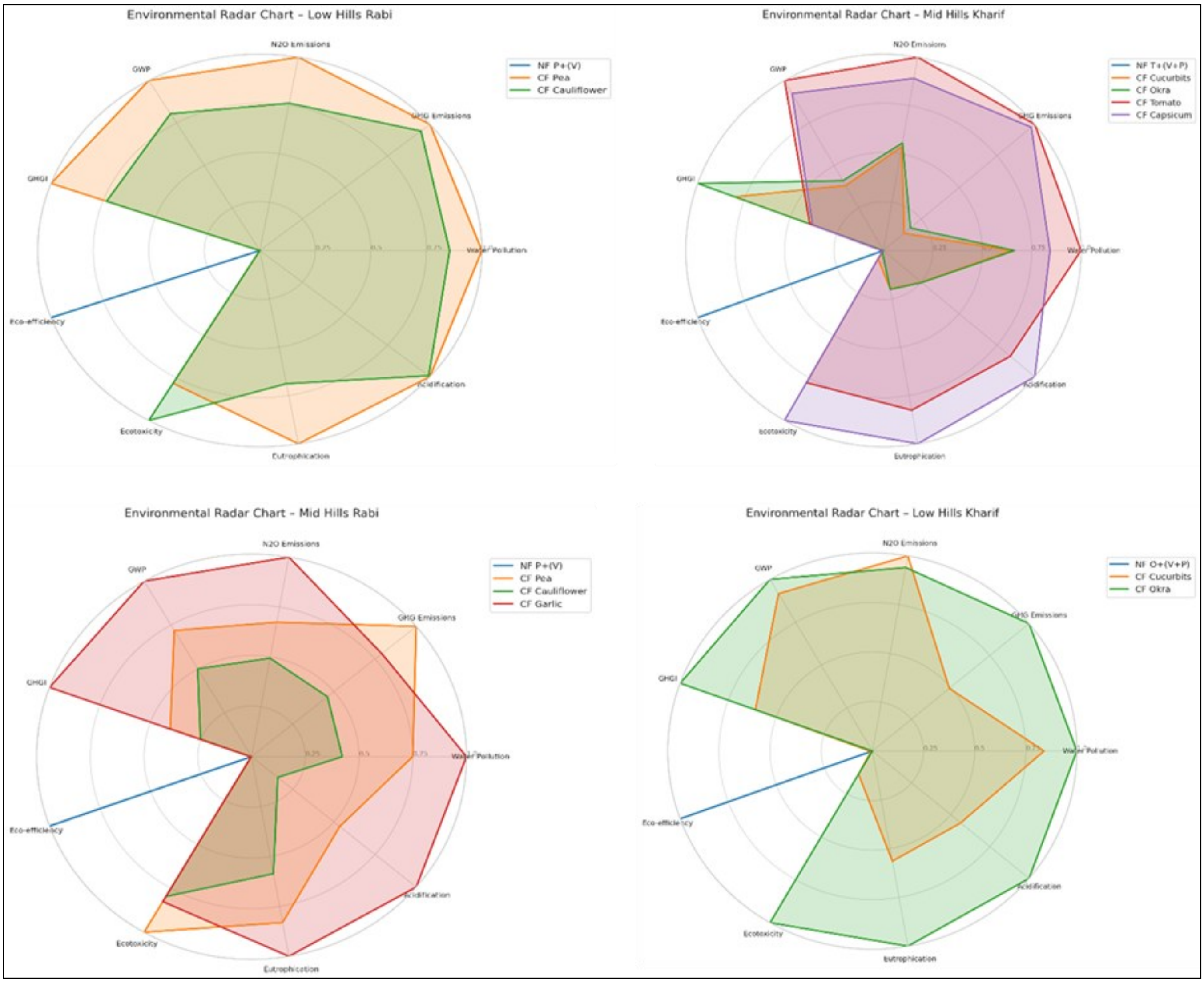


Fig. 5. Environmental impact assessment of NF and CF practices across hills.

Table 3. Environmental impact assessment of Natural and Conventional farming systems

Regions	Seasons	Cropping system	Water pollution (kg/ha)	GHG emissions (kg CO_2 eq./ ha)	N_2O emissions (kg N_2O-CO_2 eq./ha)	GWP (kg CO_2 eq./ha)	GHGI (kg CO_2 eq./ kg yield)	Eco-efficiency (₹/kg CO_2 eq.)	Ecotoxicity (PAF. m^3 kg^{-1} /ha)	Eutrophication (Kg PO_4 eq./ ha)	Acidification (Kg So_2 eq./ ha)
					Natural farming						
Low hills	**kharif**	O + (V + P)	0.16	27.97	39.62	67.59	0.02	736	-	-	-
	rabi	P + (V)	0.16	24.23	24.07	48.29	0.01	1305	-	-	-
Mid hills	**kharif**	T + (V + P)	0.19	7.12	62.09	69.20	0.03	7163	-	-	-
	rabi	P + (V)	0.34	23.89	19.74	43.64	0.01	1719	-	-	-
					Conventional farming						
Low Hills	**kharif**	Cucurbits	6.44	576	3491.73	4068.61	1.04	7.28	51113	6.64	37.84
		Okra	7.64	1143	3286.04	4429.78	1.70	1.85	378747	11.77	67.08
	rabi	Pea	11.65	1040	3393.18	4433.97	1.33	4.70	521637	83.3	115.65
		Cauliflower	9.98	986	2590.13	3576.03	0.98	3.49	667928	57.39	114.77
Mid Hills	**kharif**	Cucurbits	6.54	436.40	2746.41	3182.81	1.01	4.59	121877	50.28	42.00
		Okra	6.70	569.61	2846.86	3416.47	1.27	6.14	25808	50.94	42.32
		Tomato	10.00	3148.79	5066.81	8215.60	0.51	36.59	1839477	209.2	139.86
		Capsicum	8.46	3076.25	4518.80	7595.05	0.49	34.09	2365500	253.23	166.85
	rabi	Pea	11.39	712.42	4423.02	5135.44	1.54	2.28	224214	74.34	85.65
		Cauliflower	6.57	341.17	3245.91	3587.08	0.97	6.19	178481	52.44	25.42
		Garlic	15.08	568.52	6558.37	7126.90	3.80	6.95	185047	89.5	159.94

*O + (V + P): Okra + (Vegetables + Pulses), P + (V): Pea + (Vegetables), T + (V + P): Tomato + (Vegetable + Pulses) acidification effects, which were calculated based on their weightage potential of the nutrients and quantity applied (Table 2). NF combinations show no leaching due to use of organic, non-synthetic nutrient sources. In contrast, the significant environmental load was observed from mid-hills CF crops in capsicum and garlic, exceeding 250 kg PO_4 eq./ha and acidification potential nearing 160 kg SO_2 eq./ha, often linked to high application of chemical inputs on the farming system. In low hills, the eutrophication and acidification were highest in pea (83.30 kg PO_4 eq./ha; 115.65 kg SO_2 eq./ha), followed by cauliflower (57.39 kg PO_4 eq./ha; 114.77 kg SO_2 eq./ha). These findings are critical for agriculture in hilly regions, where nutrient leaching from CF is greater than that from livestock-based natural farming and can adversely affect adjoining regions through downstream water quality degradation, heavy metal accumulation and threats to biodiversity (43-46).

Ecotoxicity and Water pollution

To quantify the pesticide impact on the ecosystem, the UseTox model was used based on type of chemical input used (fungicide, insecticide and herbicides) in crop management by CF and NF farmers (Table 4). The findings demonstrated the ecotoxicity exceeding 2 million PAF·m^3·kg^{-1}/ha in capsicum and 1.8 million PAF·m^3·kg^{-1}/ha in tomato from mid-hills regions. While in low hills, the value reaches 0.6 million PAF·m^3·kg^{-1}/ha in cauliflower and 0.5 million PAF·m^3·kg^{-1}/ha in pea. All NF crop combinations recorded zero or negligible ecotoxicity with traditional plant protectants such as neem-based formulations and fermented botanicals (47, 48).

Water pollution estimates based on the Grey Water Footprint (GWF) approach showed that NF practices emerged safer, as it recorded water pollution 0.16 kg/ha in low hills, while in mid hills it was recorded as 0.19-0.34 kg/ha. In contrast to conventional farming, a significant water pollution gap was recorded with a minimum of 6.44 kg/ha in cucurbits to a maximum of pea (11.65 kg/ha) in low hill regions while in the mid hills, the water pollution ranged from 6.54 kg/ha in cucurbits to a maximum of 15.08 kg/ha in garlic highlighting the effectiveness of NF in the sustainable ecosystem in life below water (43).

Table 4. Ecotoxicity effect factor of the inorganic substances

Plant Protection	Chemical substance	Ecotoxicity effect factors
Insecticides	Chlorpyrifos methyl	2.08E+04 PAF.m^3. kg^{-1}
	Cypermethrin	2.78E+06 PAF.m^3. kg^{-1}
	Deltamethrin	1.75E+05 PAF.m^3. kg^{-1}
	Dimethoate	9.55E+02 PAF.m^3. kg^{-1}
	Endosulfan	5.03E+04 PAF.m^3. kg^{-1}
	Imidacloprid	5.94E+01 PAF.m^3. kg^{-1}
	Malathion	3.33E+03 PAF.m^3. kg^{-1}
Fungicides	Captan	1.59E+03 PAF.m^3. kg^{-1}
	Carbendazim	1.90E+04 PAF.m^3. kg^{-1}
	Pararquat	3.88E+03 PAF.m^3. kg^{-1}
	2,4-D	2.20E+01 PAF.m^3. kg^{-1}

Operational efficiency of NF and CF

While considering environmental outcomes for long-term sustainability, farm profitability remains a critical concern and a primary objective. The economic assessment of the NF system over CF gives valuable insights based on the input costs incurred, productivity and profitability to see broad aspects of NF to sustain the future needs (Fig. 6 & 7). Economic analysis is a crucial component of farm decision-making as it directly impacts the livelihood and financial stability of farmers. Farmers, being profit-driven decision-makers, often prioritise practices and crops that maximise their income while minimising costs. Their choice of inputs, cropping patterns and farming techniques is heavily influenced by economic returns.

Yield and gross/net returns

During kharif season, NF in low hills had yield of 29.80 q/ha in okra + (vegetables + pulses) [O + (V + P)] with gross returns of ₹119192/ha and net returns of ₹49719/ha. In contrast, mid hills NF had achieved staggering yield of 190.65 q/ha in tomato + (vegetables + pulses) [T + (V + P)] with gross returns of ₹571945/ha and net returns of ₹495744/ha. The NF system showed superiority over CF crops; even capsicum and tomato recorded respectable yields (156.25 and 162.50 q/ha respectively) with net returns of ₹186913/ha and ₹209837/ha. During the rabi season, NF farmers in both low and mid hills adopted the same cropping pattern: pea + (vegetables) [P + (V)]. Yet, regional differences in yield and profitability were observed. In mid hills, the combinations yielded 36.00 q/ha generating gross returns of ₹144000/ha and net returns of ₹75010/ha, while in low hills, it provided 33.76 q/ha, with gross returns of ₹135033/ha and net returns of ₹63007/ha. These values were still significantly higher than the average CF pea and CF cauliflower yields (33.13 and 36.50 q/ha respectively), with net returns of ₹16266/ha and ₹17258/ha respectively, resulting in marginal profits or break-even outcomes due to high input costs (Supplementary Table 1 & 2).

Benefit-Cost Ratio (BCR) and farm income metrics

NF has outperformed CF in benefit-cost analysis across both zones due to low cost incurred with higher gross returns (market value of yield) in NF combinations. In NF, the total cost ranged from ₹69473/ha to ₹76201/ha, with the highest cost in tomato + (vegetables + pulses) [T + (V + P)] and the lowest in okra + (vegetables) [O + (V)]. In contrast, the cost of conventional cropping ranged from ₹86646/ha (okra) to ₹209837/ha (tomato), highlighting a significant difference in net investment for crop cultivation by farmers. The tomato + (vegetables + pulses) [T + (V + P)] combinations of mid hills achieved the BC ratio of 7.51, while pea + (vegetables) [P + (V)] combination achieved the BC ratio of 2.09. Whereas in low hills, pea + (vegetables) [P + (V)] combination has achieved the BC ratio of 1.87 while okra + (vegetables + pulses) [O + (V + P)] achieve 1.72 ratio. In contrast to CF, mostly crops fell in a narrow BCR range of 1.09–2.23, comparatively lower to their NF counterparts. The other key income metrics such as farm business income, family labour income and farm investment income, were considerably higher in the NF crop combinations compared to the counterpart CF crops (Supplementary Table 3, 4 & 5). The outperformance of NF in terms of economic and environmental parameters supports the long-term viability to combat climate change and supports the farmer's income, livelihood and nutritional security (17).

Eco-efficiency: bridging economics and environment

Eco-efficiency is expressed as economic net return per kg of GHG emission. It demonstrated the divergence of economic profitability from environmental sustainability between the systems. NF tomato + (vegetables + pulses) [T + (V + P)] in the mid hills achieved ₹7163/kg CO_2 eq. of eco-efficiency compared to its CF counterpart, i.e., ₹36.59 in tomato indicated a 195-fold increase in eco-efficiency. Similarly, in the low hills, NF pea + (vegetables) [P + (V)] yielded ₹1305/kg CO_2 eq. in comparison to CF pea ₹4.70 reflecting a 99-fold increase. These results underscore the integrity of climate-resilient agriculture that

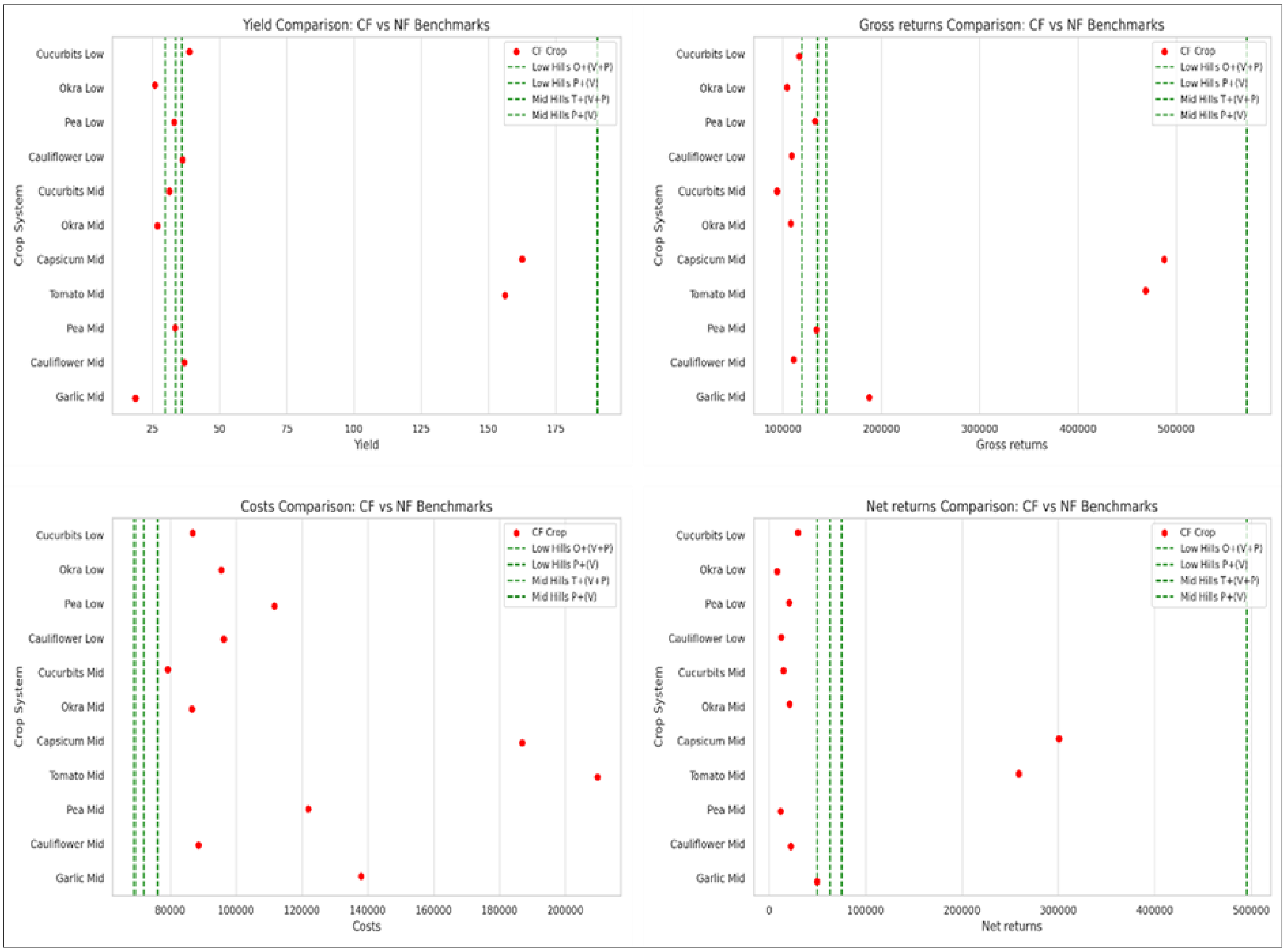


Fig. 6. Economic footprint assessment of NF and CF practices across hills.

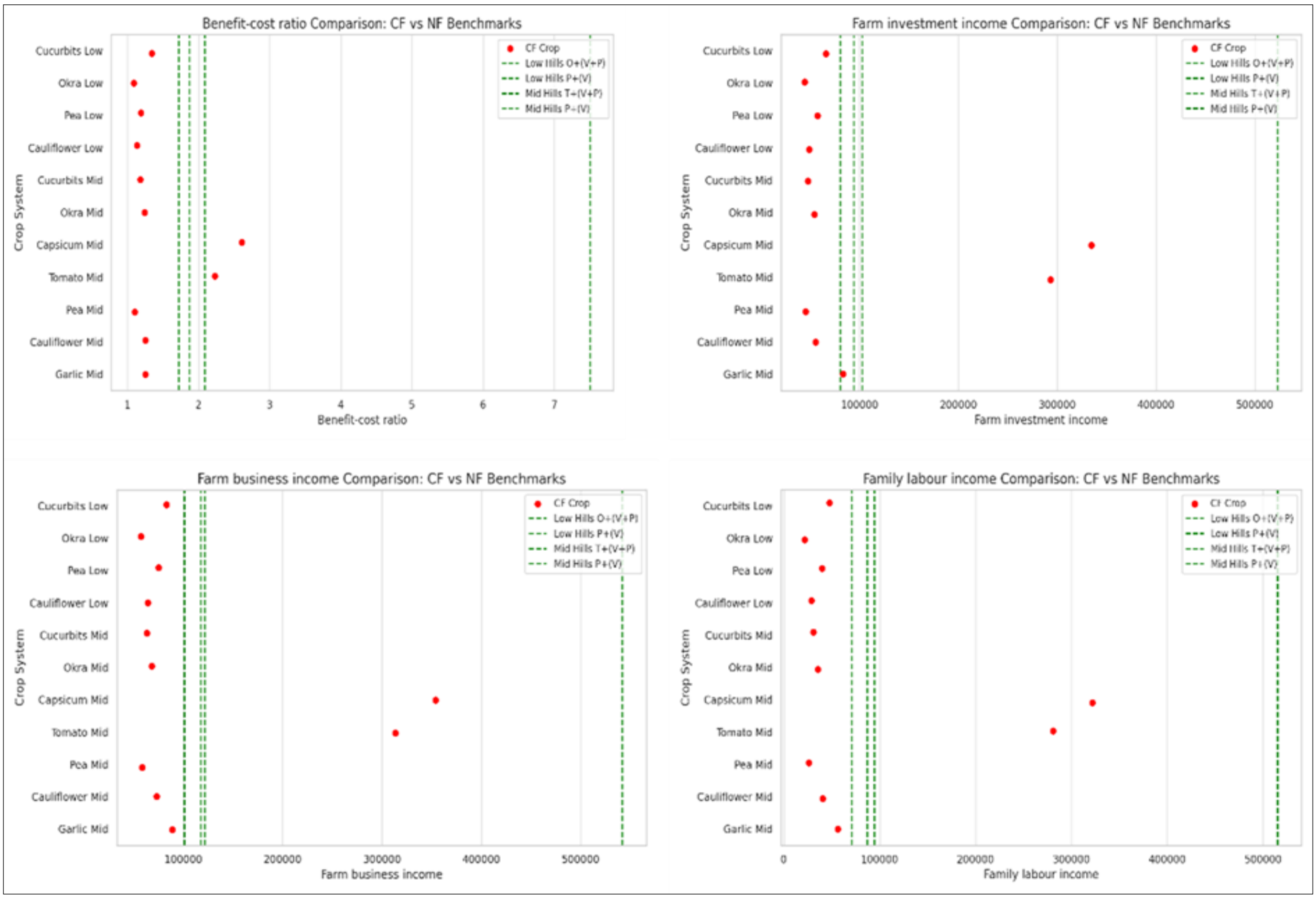


Fig. 7. Economic footprint assessment of NF and CF practices across hills.

does not compromise profitability (23, 49, 50). These variations in environmental and economic metrics were primarily due to the cropping pattern choice of the NF and CF farmers, linked to chemical -free input use and land management practices.

Sustainability ranking and income trade-off mapping

To evaluate the clear comparative and multidimensional assessment of all crops/crop combination across both zones, the CSI was evaluated based on weight assigned (Fig. 8). Assigning equal weight ensures equal weightage to give a balanced assessment of overall sustainability (51). The lower values indicate the greater overall sustainability of the crop choices. Further, a comparative assessment with data normalization was carried out, as shown in Fig. 9. Out of all crops, the tomato + (vegetables + pulses) [T + (V + P)] crop combination had highest sustainability spectrum, with the lowest CSI value of (0.001) and maximum net return, eco-efficiency and yield (normalised to value 1.00), reflecting it as an ecological and economical balance. The other NF crop combinations such as pea + (vegetables) [P + (V)] across both low and mid hills and okra + (vegetables + pulses) [O + (V + P)] also maintain the higher level of sustainability with normalised returns (0.09-0.14), eco-efficiency (0.09-0.18) and yield (0.06-0.10), indicating the ecological and economic sustainability. In contrast, the CF crops display a higher level of divergence between economic and ecological sustainability. The CF capsicum and CF tomato of mid hills outperformed with normalised value of yield (0.84 and 0.80 respectively), net return (0.60 and 0.51) and very low eco-efficiency (0.01 and 0.00). This indicates that these systems operate at the edge of profitability while imposing a higher ecological burden, as reflected by high CSI values (0.87 and 0.81). More critically, the CF garlic of mid hills emerges as highly unsustainable with a normalised CSI value of 1.00, including net returns of 0.8 and eco-efficiency and yield falls at level zero. Other CF crops also show a lower sustainability level with high CSI value and lower economic and environmental efficiency (Supplementary Table 6). Overall, the analysis highlights that NF systems offer a more consistent and cohesive sustainability profile over the conventional farming system, as shown in Fig. 9. This stresses the importance of adopting on-farm bio-inputs, which are eco-friendly and simultaneously economical to farmers.

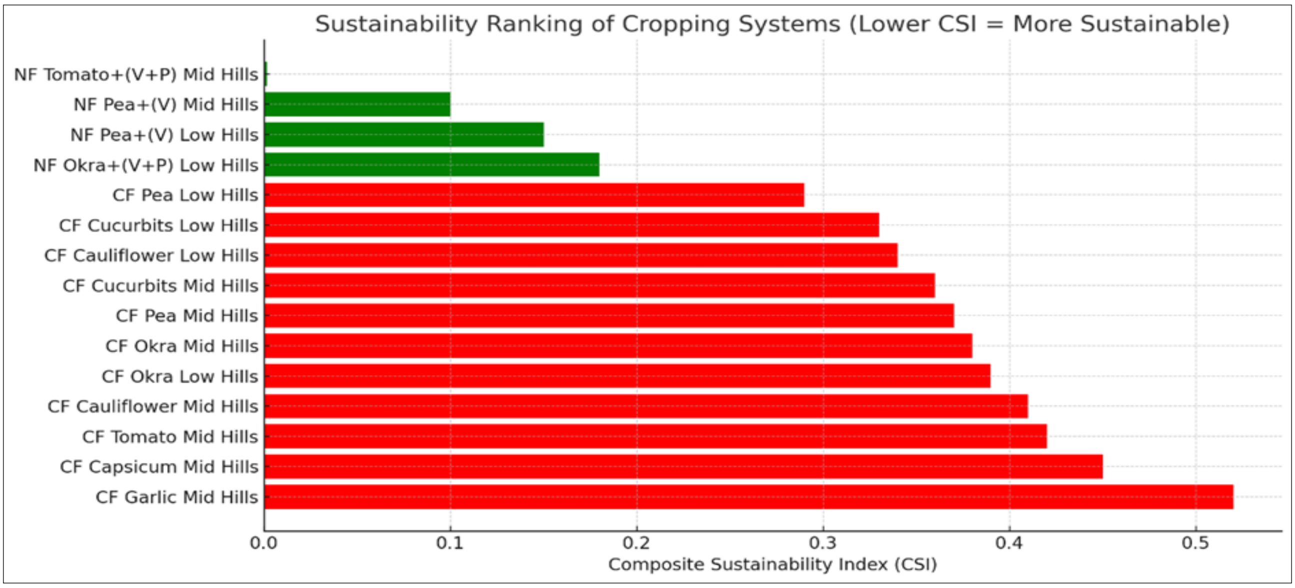


Fig. 8. Multi-Indicator benchmarking of crop combinations under NF and CF across hills.

Crop Combination	CSI	Net Return	Eco-efficiency	Yield
NF Tomato+(V+P)	0.00	1.00	1.00	1.00
NF Pea+(V) Mid	0.19	0.14	0.18	0.10
NF Pea+(V) Low	0.29	0.11	0.13	0.09
NF Okra+(V+P)	0.34	0.09	0.09	0.06
CF Pea Low	0.56	0.03	0.05	0.08
CF Cucurbits Low	0.63	0.04	0.02	0.12
CF Cauliflower Low	0.65	0.01	0.02	0.10
CF Cucurbits Mid	0.69	0.01	0.01	0.07
CF Pea Mid	0.71	0.01	0.04	0.09
CF Okra Mid	0.73	0.03	0.01	0.05
CF Okra Low	0.75	0.00	0.00	0.04
CF Cauliflower Mid	0.79	0.03	0.04	0.11
CF Tomato Mid	0.81	0.51	0.00	0.80
CF Capsicum Mid	0.87	0.60	0.01	0.84
CF Garlic Mid	1.00	0.08	0.00	0.00

Fig. 9. Multi-Indicator benchmarking of crop combinations under NF and CF across hills.

Conclusion

The study compared NF and CF systems in the hilly regions of India using data taken from 300 farmers. NF reduced GHG emissions by 99 %, with levels between 7.12–27.97 kg CO_2 eq./ha, compared to 576–3148 kg CO_2 eq./ha in CF. CF showed high eutrophication (up to 253.23 kg PO_4 eq./ha), acidification (up to 166.86 kg SO_2 eq./ha) and ecotoxicity, all absent in NF due to minimal synthetic input use. NF matched or exceeded CF in productivity and significantly improved economic outcomes, with 27–44 % lower costs and over 190 % higher net earnings. Eco-efficiency gains under NF reached over 23000 % in low hills and 32000 % in mid hills. These results highlighted NF as a climate-resilient, economically viable alternative aligned with the Paris Agreement and SDGs, offering a sustainable pathway for transforming hill agriculture. However, the present study did not capture the impact of NF vs CF on other parameters of the TEEB framework, such as social capital and human capital. At a broader and more widespread level, future studies should incorporate these parameters alongside the economic and environmental parameters currently used. Additionally, gathering insights on soil health parameters from farmers' Soil Health Cards, wherever available and observing biodiversity, such as microbial counts and pollinators, would significantly strengthen the scope of future studies.

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Authors' contributions

RT contributed to the conceptualisation of the study, methodology design, investigation and data collection, formal data analysis, visualisation and assisted in drafting the manuscript. SS provided methodological supervision, guidance on the analytical framework, support in formal analysis and critically reviewed and edited the manuscript. AN supported data collection and field surveys, contributed to formal data analysis and participated in writing the original draft, including review and editing. PVS critically reviewed the manuscript and provided intellectual feedback. N contributed to results preparation and the methodology section. AK[1] and AK[2] contributed to results preparation and the literature review. All authors read and approved the final manuscript. [AK[1] stands for Akanksha Klate and AK[2] stands for Anurita Kharayat]

Compliance with ethical standards

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

Ethical issues: None

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