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RESEARCH ARTICLE

Strategic mapping of agroclimate vulnerability and carbon emissions for India's net zero transition

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Abstract

India's dual challenge of achieving net zero emissions by 2070 while enhancing climate resilience demands integrated policy tailored regional contexts. This study presents a novel framework that simultaneously evaluates agroclimatic vulnerability and sector specific carbon emissions at the state level to present targeted climate action. We constructed Climate Vulnerability Index (CVI) by normalizing nine indicators across biophysical dimensions, socioeconomic factors and institutional capacities using Principal Component Analysis (PCA) on state level data (2011-2023) a period marked by multiple climate policy reforms and agricultural transitions in India. PCA was initially applied to assign indicator weights, but due to limited variance among components, equal weighting was adopted to maintain robustness and transparency. Concurrently, we quantified carbon emissions across primary, secondary and tertiary sectors using standardized national datasets. Due to the lack of a centralized, sector disaggregated emissions database, estimates are indicative rather than exhaustive. Now by overlaying CVI scores with sectoral emissions, we developed a regional prioritization matrix that classifies states into four categories for policy interventions. Our findings reveal significant interstate disparities with CVI scores ranging from 0.421 (Sikkim) to 0.782 (Manipur). Analysis of emission patterns across sectors indicates that tertiary sector contributes the largest share of national emissions (~42 %), followed by secondary (~30 %) and primary (~28 %) sectors. Contrary to typical national patterns where primary and secondary sectors (e.g., agriculture, manufacturing and energy) are dominant emitters, our analysis suggests that tertiary sector emissions appear more prominent, though these are primarily indirect emissions. Based on these insights, we recommend tailored interventions that include scaling up climate smart agriculture and enhancing financial inclusion in high vulnerability states. In regions identified as emissions hotspots, focus on precision farming and water efficient technologies. For low vulnerability regions, conservation agriculture and agroforestry can play a key role. This framework offers data driven study for designing region specific strategies that simultaneously support India's decarbonization efforts and strengthen agricultural resilience, thereby ensuring inclusive pathway to achieve net zero emissions.

Keywords: agriculture; carbon emissions; CVI; India; regional prioritization matrix

Introduction

Climate change is no longer a distant threat, it is the defining crisis of our century, reshaping economies, ecosystems and everyday lives with alarming speed. From scorching heatwaves to rising sea levels and melting glaciers, its fingerprints are visible across the globe. Driven predominantly by human induced greenhouse gas emissions, this global emergency poses an existential risk to both nature and humanity. The urgency to act has never been greater yet climate negotiations must uphold global equity and the principle of Common but Differentiated Responsibilities (CBDR), recognizing that countries like India face the dual challenge of building climate resilience while supporting inclusive growth. As the Intergovernmental Panel on Climate Change (IPCC) warns, without immediate and large-scale reductions in emissions, limiting global warming to 1.5 °C or even 2 °C will be beyond reach, so every fraction of a degree matters and so does every policy, investment and collective action we take today (1).

Recognizing this growing urgency, India has committed to reach net zero carbon emissions by 2070. Announced at COP26 in Glasgow, this is a landmark move for an economy that ranks third in total CO_2 emissions but remains well below the global average on a per capita and historical basis. India's target is aligned with a broader set of climate goals, including reducing the carbon intensity of its GDP by 45 % from 2005 levels by 2030, achieving 500 GW of non-fossil energy capacity and meeting half of its energy requirements through renewables (2). These goals aim to strike a balance between the need for economic growth and the responsibility to reduce climate risks.

Beyond global responsibility, India's urgency is rooted in its domestic vulnerability. Its vast and diverse geography makes it prone to a range of climate related hazards, including floods, droughts, heatwaves, cyclones and changing monsoon patterns. Climate Vulnerability Assessment (CVA) is a systematic approach to evaluating the degree to which a country is susceptible to the adverse impacts of climate change. CVAs help quantify this risk analysing three key components such as exposure to climate hazards, sensitivity of systems to those hazards and the adaptive capacity to cope with or recover from them (1). The conceptual definition of climate vulnerability discussed so far is depicted in Fig. 1.

Several studies have emphasized the importance of such assessments. For instance, a CVI was developed for Indian states, though it did not address the emissions dimension (3, 4). Another study quantified emissions from agriculture and livestock but did not assess regional resilience (5). More recent efforts have attempted to integrate emissions and vulnerability in the Himalayan regions yet lacked applicability across the entire country (6). These limitations point to a clear gap in the literature.

At the same time, formulating effective climate policy requires robust emissions data at disaggregated levels. While understanding sector-wise emissions is vital, India lacks a single, reliable database that maps emissions across sectors and states. Existing studies often rely on fragmented or modelled estimates. This underscores the need for analytical frameworks that combine vulnerability and emissions insights while acknowledging data limitations.

To address these gaps, this study develops an integrated framework that overlays state level carbon emissions with CVI scores across India's agricultural zones. We first normalized nine indicators spanning biophysical, socio-economic and institutional dimensions then applied PCA across the 2011-2023 panel to explore weighting structures. As the first three PCA components explained less than 45 % of the variance, equal weighting was adopted for transparency and interpretability.

Building on this, we constructed a regional prioritization matrix that classifies states by their CVI and sectoral emissions. This allows us to identify clusters of states requiring differentiated interventions such as climate smart agriculture and irrigation investments in vulnerable regions and decarbonization pathways in high emission states.

By integrating emissions and vulnerability into a single decision support tool, this framework offers a novel study for policymakers. Also, by addressing both the drivers of emissions and the vulnerabilities, India can pave the way for a resilient, low carbon future that ensures prosperity for farmers while contributing to global climate goals. India's climate journey is not only a national challenge but a global concern, where the stakes are high and timely, data driven action is imperative.

Materials and Methods

The methodology used in this research outlines an interdisciplinary approach to evaluate the vulnerability of Indian agriculture to climate change, analyse sector wise carbon emissions and prioritize regions for targeted interventions. This research is guided by the IPCC's conceptual framework for climate vulnerability, which offers high level principles on exposure, sensitivity and adaptive capacity rather than a prescriptive step by step methodology (1). The results not only identify state wise climate vulnerable regions but also tie them to sectoral emission profiles, offering a dual lens for adaptation and mitigation strategies.

The foundation of this study lies in an interdisciplinary design that blends statistical rigor with contextual insights, ensuring a holistic understanding of climate vulnerability and carbon emissions. It adopts the IPCC's exposure, sensitivity and adaptive capacity framework, which defines vulnerability as the interplay of three dimensions exposure to climatic shifts (e.g., erratic rainfall, rising temperatures), sensitivity of agricultural systems (e.g., crop yield declines, soil degradation) and adaptive capacity to cope with these changes (e.g., access to irrigation, institutional support) (1). To ensure PCA

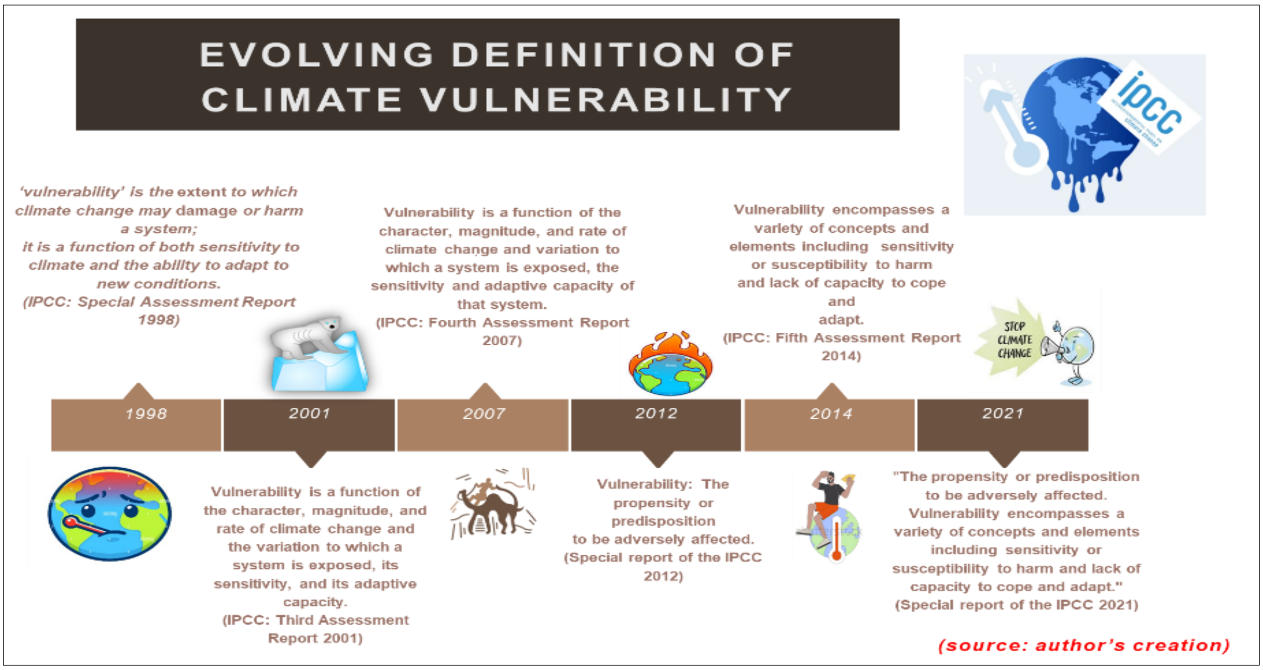

Fig. 1. Evolving definitions of climate vulnerability.

suitability, we computed the Kaiser Meyer Olkin index (0.72) and Bartlett's test of sphericity ($p < 0.01$), confirming sufficient sampling adequacy. The widely accepted model underpins the development of a CVI, which is calculated using advanced statistical tools like PCA (3).

It focuses on state level analysis for climate vulnerability across India from 2011 to 2023, a period reflecting diverse climatic and socio-economic trends. Inspired by Smit and Wandel's contextual approach, it assesses climate vulnerability based on current conditions before climate hazards fully manifest, providing a proactive baseline (4). Rather than treating vulnerability as a future scenario, this study recognizes that extreme weather events such as record heat waves and unprecedented monsoon variability are already reshaping India's agricultural landscape, underscoring the need for real time vulnerability assessment. This conceptual grounding sets the stage for the detailed vulnerability assessment that follows, linking theoretical rigor to practical application.

CVA methodology

CVA methodology translates the conceptual framework into actionable insights by following a structured, multi-step process. Each step is designed to ensure replicability and clarity. These sources vary in reporting frequency and accuracy administrative PMFBY figures differ from survey-based workforce data, so we interpret cross indicator comparisons cautiously.

Step 1: Indicator selection

The assessment hinges on carefully chosen indicators that mirror the IPCC's three dimensions (1). First, biophysical indicators include yield variability of food grains, which reflects sensitivity to climate fluctuations like erratic rainfall or temperature extremes, area under rainfed agriculture, which highlights dependency on unpredictable rainfall, increasing drought risks and forest area as a percentage of geographic area, which enhances resilience through ecosystem services like soil protection and water retention (1, 5, 7). Second, socio-economic Indicators include percentage of BPL population, implying that poverty limits financial capacity to adapt to climate impacts, share of horticulture in agriculture, indicating that diversified income from resilient crops improves adaptive capacity, marginal and small landholdings, highlighting risks small farmers face due to limited resources and women's workforce participation, suggesting that higher participation strengthens household resilience through income diversification also it is an institutional indicator that can enhance household adaptive capacity, though high participation may also reflect economic necessity in informal sectors. Hence, we interpret this metric alongside income-security indicators (8-11). Third, institutional indicators include crop insurance coverage (PMFBY), which mitigates financial losses from climate shocks, enhancing recovery and MGNREGA employment, which provides income security during climate-induced agricultural downturns (11, 12).

Data sources for indicators:

1. Poverty rate (% BPL population) - Planning Commission of India (now NITI Aayog), based on the Tendulkar committee methodology.

2. Share of horticulture in NSA (Net Sown Area) - Ministry of Agriculture and Farmers Welfare, Government of India.

3. Percentage of marginal and small operational holdings - Agriculture Census, Ministry of Agriculture and Farmers Welfare, Government of India.

4. Coefficient of variation/ yield variability of food grains - Directorate of Economics and Statistics, Ministry of Agriculture and Farmers Welfare.

5. Area under PMFBY and RWBCIS crop insurance- Pradhan Mantri Fasal Bima Yojana (PMFBY) and Restructured Weather Based Crop Insurance Scheme (RWBCIS), Ministry of Agriculture and Farmers Welfare.

6. Proportion of area under rainfed agriculture - Ministry of Agriculture and Farmers Welfare, Government of India.

7. Forest area as a percentage of geographical area (GA) of state - India State of Forest Report (ISFR), Forest Survey of India (FSI).

8. Labour force participation rate for women - Periodic Labour Force Survey (PLFS), Ministry of Statistics and Programme Implementation (MoSPI).

9. Average days of employment provided per household – Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA), Ministry of Rural Development.

The nine indicators such as Poverty rate (% BPL population), share of horticulture in NSA, percent of marginal and small operational holdings, coefficient of variation/ yield variability of food grains, area under PMFBY and RWBCIS crop insurance, proportion of area under rainfed agriculture, forest area as a percentage of GA of state, labour force participation rate for women and average days of employment provided per household were selected, each rooted in literature and tailored to India's agricultural context.

Step 2: Normalization of indicators

To enable comparison across diverse indicators, each was normalized to a 0-1 scale, where 0 indicates the least vulnerable state and 1 the most vulnerable. The formulas vary by indicator type as shown below:

For positive relationships with vulnerability (e.g., yield variability)

$$\frac{x - xmin}{xmax - xmin} \qquad \text{(Eqn. 1)}$$

For negative relationships (e.g., forest cover)

$$\frac{xmax - x}{xmax - xmin} \qquad \text{(Eqn. 2)}$$

This normalization eliminates unit disparities, preparing the data for aggregation into the CVI, a critical link to the next step.

Step 3: Weighting and index calculation

Initially, PCA was explored to assign weights to indicators, leveraging its ability to distill complex datasets (3). However, due to minimal variation in explanatory power, equal weights were adopted for simplicity and robustness. Because the first three PCA components explained only 45 % of total variance indicating a weak factor structure. We elected equal weighting as a transparent strategy rather than risk over interpreting unstable loadings. We then conducted sensitivity checks using expert opinion weights, state rankings remained within 5 % of the equal weight results, affirming index robustness. The CVI for each state was computed by averaging the normalized indicator scores, with higher values indicating greater climate vulnerability. This straightforward approach ensures transparency while maintaining statistical integrity.

Step 4: Ranking and driver analysis

After calculating CVI, states were ranked by their CVI scores, pinpointing the most vulnerable regions. A deeper dive into each state's highest scoring indicators revealed key vulnerability drivers, such as reliance on rainfed farming or weak institutional support, offering actionable insights. This ranking not only identifies at risk areas but also connects directly to the emissions analysis, enriching the study's scope.

Carbon emissions analysis

This methodology incorporates a detailed analysis of carbon emissions to explore their interplay with agricultural risk (13). Emissions data were sourced from the India Climate & Energy Dashboard and Council on Energy, Environment and Water (CEEW) reports, covering three sectors; primary sector (agriculture, forestry and fishing), secondary sector (manufacturing, construction and mining) and tertiary sector (services like transportation and trade) (14, 15). This step aligns with UNFCCC reporting standards and complements the CVI, an essential precursor to the prioritization matrix (7).

The methodology culminates in a regional prioritization matrix, merging vulnerability and emissions data for policy relevant insights.

Regional prioritization matrix

To tabulate the matrix, states are grouped into four quadrants based on the calculated CVI and emission data:

1. Low vulnerability - Low emissions
2. Low vulnerability - High emissions
3. High vulnerability - Low emissions
4. High vulnerability - High emissions

A sensitivity analysis, testing alternative thresholds (e.g., quartiles), confirms the matrix's robustness (16). This approach highlights states needing urgent adaptation (high vulnerability) and mitigation (high emissions), linking the study's dual objectives seamlessly. We note that some states lie near quadrant boundaries (e.g., moderate emissions & moderate vulnerability). Policy makers should therefore view the matrix as a decision support guide examining trade-offs such as balancing low carbon technology adoption with resilience investments rather than a rigid categorization.

The methodologies used above offer a clear, interconnected framework to assess Indian agriculture's vulnerability, analyse carbon emissions and prioritize regions for action. By linking vulnerability drivers to emission profiles through a prioritization matrix, it provides a powerful tool for researchers and policymakers. The research's interdisciplinary design, rooted in recent literature and data, paves the way for informed climate strategies in India.

Results

Analysis of state wise climate vulnerability in India is done to identify the most and least vulnerable states with respect to specific indicators. The regional patterns and drivers of vulnerability are also assessed and presented below. Sectorial carbon emissions analysis is mapped with calculated CVI scores through the regional prioritization matrix.

State wise CVA

The nine indicators identified is normalized to find the contribution of these indicators in the climate vulnerability. CVI was calculated for each Indian state by averaging the normalized scores of nine indicators (Table 1).

Analysis of specific indicators

Analysis of specific indicators with respect to the Actual (AC) and Normalized Values (NV) of key indicators across the states is revealed to identify the disparities (Table 1, Fig. 2-6).

Poverty rates

It is one of the important factors that does not directly influence climate change but significantly reduces adaptive capacity, limiting the ability of communities to cope with or recover from climate induced shocks. The states such as Chhattisgarh (AC = 39.93 %, NV = 1.000) and Bihar (AC = 33.74 %, NV = 0.822) exhibit the highest normalized poverty rates, reflecting severe economic constraints. In contrast, Goa (AC = 5.09 %, NV = 0.000) and Kerala (AC = 7.05 %, NV = 0.056) show significantly lower rates, indicative of better socio-economic resilience (Fig. 2). *BPL: Below Poverty Line is defined as households classified by the Government of India as living below the minimum income necessary for basic sustenance.*

Share of horticulture in NSA

Share of horticulture in NSA have a considerable impact on the climatic changes. A higher share of horticulture in NSA indicates income diversification and climate resilient cropping patterns, improving adaptive capacity but not directly influencing emissions (Fig. 3). The States such as Mizoram (AC = 0.74, NV = 0.00) and Sikkim (AC = 0.48, NV = 0.35) lead in horticulture share, suggesting diversification that enhances resilience. But Punjab (AC = 0.05, NV = 0.94) and Rajasthan (AC = 0.01, NV = 0.99) rely heavily on non-horticultural crops, increasing their exposure to climate risks (Fig. 3). *NSA: The total area sown with crops in a given agricultural year, excluding fallow lands.*

Marginal and small holdings

Marginal and small holdings impact the climatic factors particularly marginal and small farms. The prevalence of marginal and small landholdings reflects structural vulnerabilities in Indian agriculture, which increase exposure to climate risks due to limited capital, technology and institutional support .The states such as Kerala (AC = 0.99, NV = 1.00), West Bengal (AC = 0.96, NV = 0.96) and Bihar (AC = 0.97, NV = 0.98) have the highest normalized values, reflecting a predominance of small-scale farming that limits mechanization and adaptation. Punjab (AC = 0.33, NV = 0.18) and Nagaland (AC = 0.19, NV = 0.00) show lower values, aligned with larger, more mechanized operations (Fig. 4).

Table 1. State wise AC and NV of indicators

States	Poverty rate (% BPL population)		Share of Horticulture in NSA		% of marginal and small operational holding		Coefficient of variation/ Yield variability of food grains		Area under PMFBY and RWBCIS crop insurance	
	AC	NV	AC	NV	AC	NV	AC	NV	AC	NV
Andhra Pradesh	9.2	0.118	0.13	0.83	0.89	0.88	0.05	0.261	76.85	0.902
Arunachal Pradesh	34.67	0.849	0.14	0.81	0.45	0.33	0.02	0.061	000	1.000
Assam	31.98	0.772	0.11	0.85	0.86	0.84	0.06	0.348	25.45	0.967
Bihar	33.74	0.822	0.08	0.89	0.97	0.98	0.06	0.319	46.09	0.941
Chhattisgarh	39.93	1.000	0.02	0.97	0.83	0.80	0.15	0.965	163.83	0.791
Goa	5.09	0.000	0.61	0.18	0.91	0.90	0.03	0.118	0.01	1.000
Gujarat	16.63	0.331	0.14	0.82	0.68	0.61	0.03	0.122	112.33	0.856
Haryana	11.16	0.174	0.02	0.97	0.69	0.63	0.04	0.189	130.58	0.833
Himachal Pradesh	8.06	0.085	0.30	0.60	0.89	0.88	0.04	0.222	77.06	0.902
Jharkhand	36.96	0.915	0.09	0.88	0.84	0.81	0.07	0.399	19.4	0.975
Karnataka	20.91	0.454	0.09	0.89	0.80	0.76	0.09	0.520	138.82	0.823
Kerala	7.05	0.056	0.21	0.71	0.99	1.00	0.08	0.505	3.08	0.996
Madhya Pradesh	31.65	0.762	0.03	0.96	0.76	0.71	0.10	0.581	782.35	0.000
Maharashtra	17.35	0.352	0.13	0.82	0.81	0.78	0.12	0.762	485.73	0.379
Manipur	36.89	0.913	0.21	0.72	0.83	0.80	0.16	1.000	0.36	1.000
Meghalaya	11.87	0.195	0.36	0.51	0.79	0.75	0.14	0.840	0.03	1.000
Mizoram	20.4	0.439	0.74	0.00	0.81	0.78	0.02	0.093	0	1.000
Nagaland	18.88	0.396	0.18	0.76	0.19	0.00	0.11	0.650	0	1.000
Orissa	32.59	0.789	0.00	1.00	0.93	0.93	0.10	0.613	91.67	0.883
Punjab	8.26	0.091	0.05	0.94	0.33	0.18	0.04	0.215	0	1.000
Rajasthan	14.71	0.276	0.01	0.99	0.62	0.54	0.04	0.210	683.19	0.127
Sikkim	8.19	0.089	0.48	0.35	0.85	0.83	0.01	0.000	0.01	1.000
Tamil Nadu	11.28	0.178	0.15	0.80	0.93	0.93	0.03	0.137	96.19	0.877
Telangana	9.2	0.118	0.05	0.94	0.88	0.86	0.07	0.413	37.83	0.952
Tripura	14.05	0.257	0.36	0.52	0.96	0.96	0.03	0.157	1.48	0.998
Uttar Pradesh	29.43	0.699	0.09	0.89	0.93	0.93	0.04	0.237	283.56	0.638
Uttarakhand	11.26	0.177	0.08	0.90	0.92	0.91	0.05	0.251	55.31	0.929
West Bengal	19.98	0.427	0.34	0.55	0.96	0.96	0.03	0.149	55.85	0.929

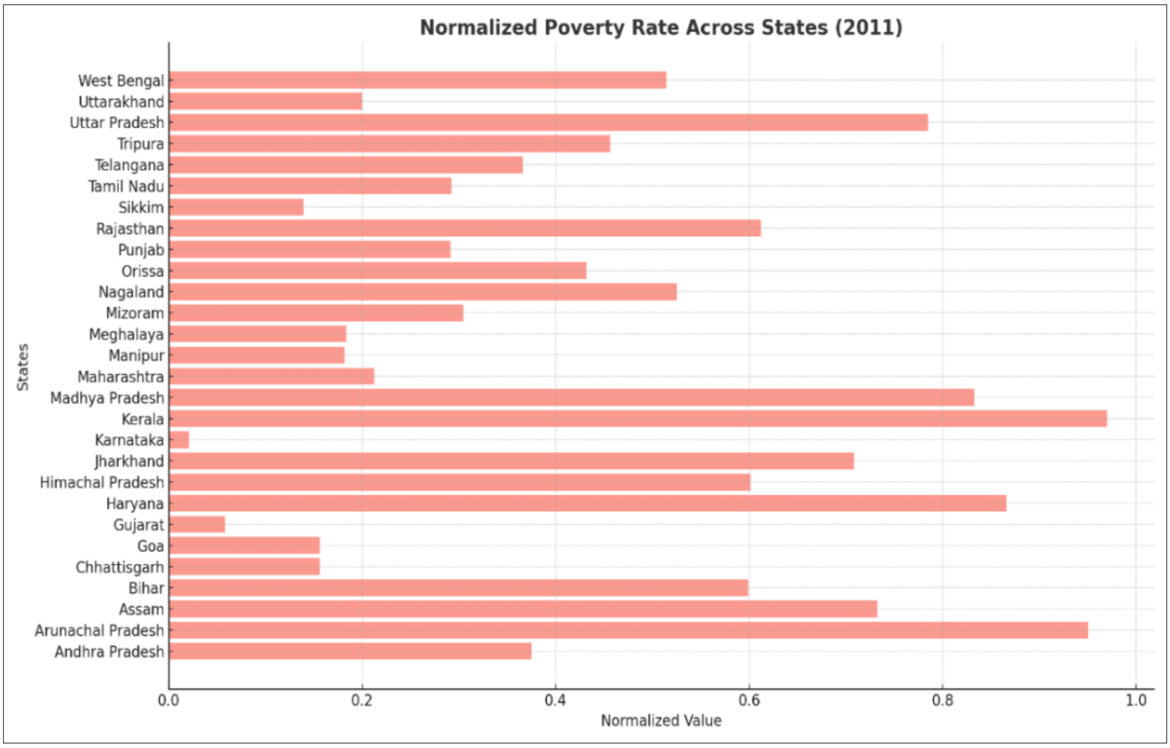

Fig. 2. Normalized poverty rates.

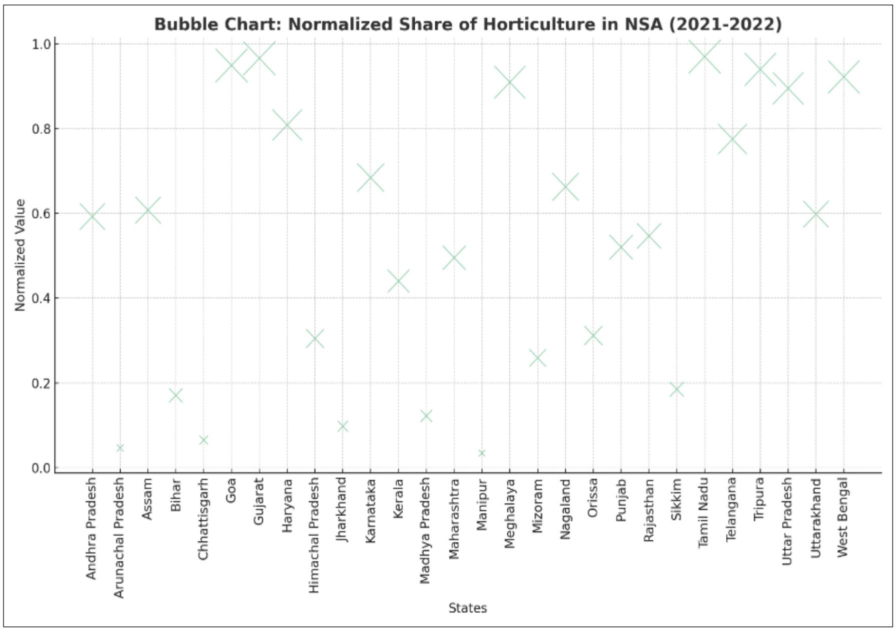

Fig. 3. Normalized share of horticulture in NSA.

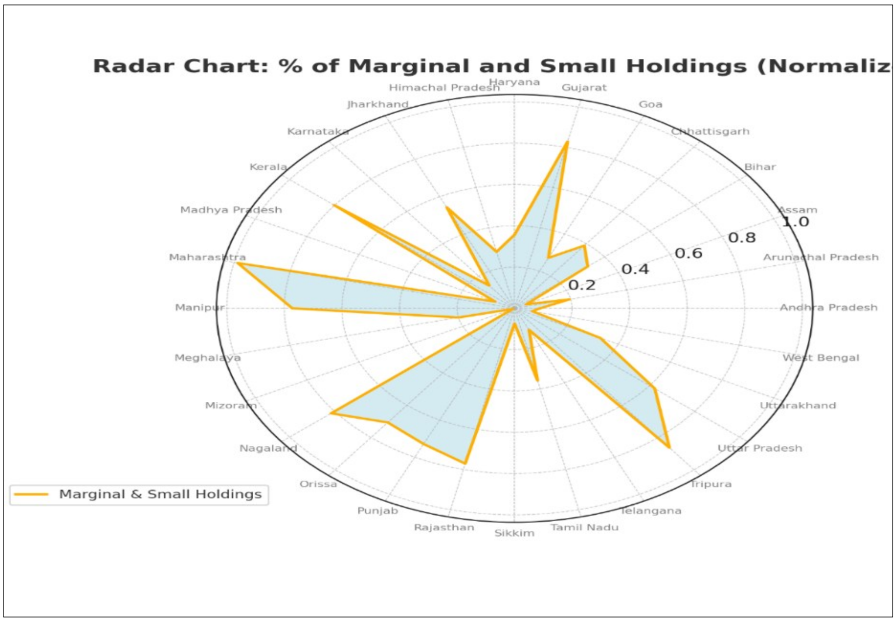

Fig. 4. Normalized values of marginal and small holdings.

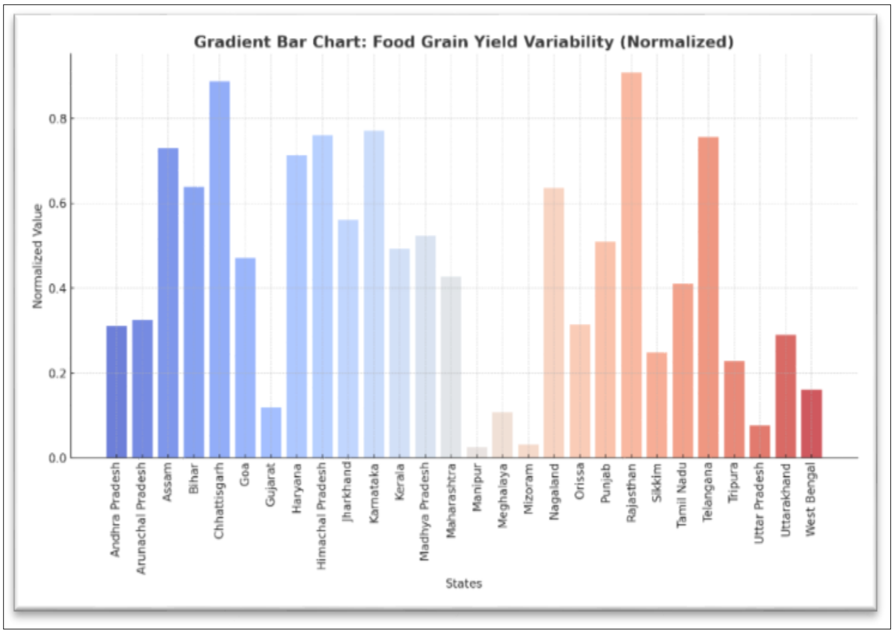

Fig. 5. Normalized values of food grain yield variability.

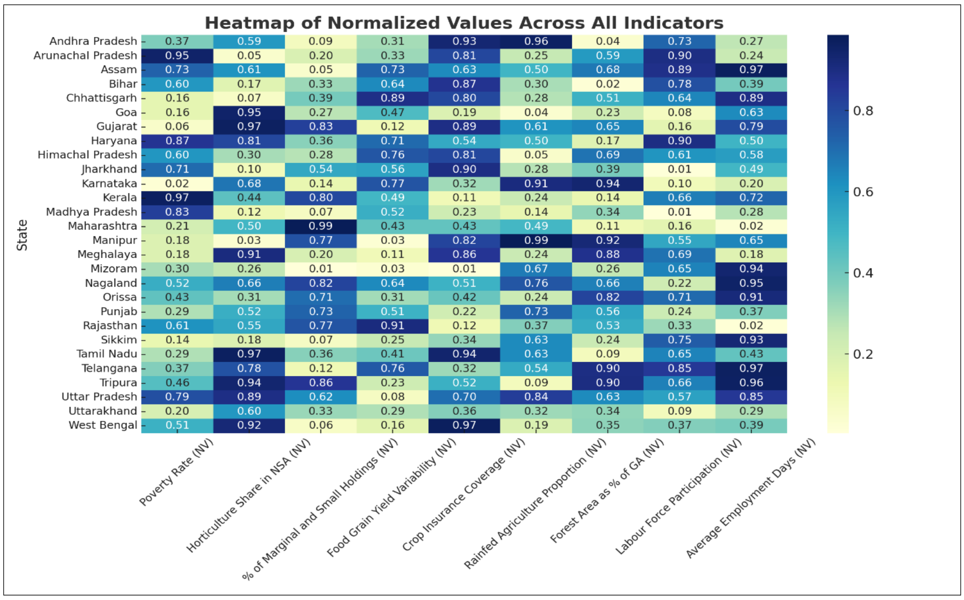

Fig. 6. Heat map of indicators.

Food grain yield

Food grain yield uses the inputs in inappropriate rate the level of yield also plays an important role. The states such as Manipur (AC = 0.16, NV = 1.000) and Meghalaya (AC = 0.14, NV = 0.840) exhibit the highest variability, indicating unstable yields due to climatic and technological factors. Sikkim (AC = 0.01, NV = 0.000) and Tamil Nadu (AC = 0.03, NV = 0.137) show greater stability, supported by irrigation and modern practices (Fig. 5).

Patterns across multiple indicators

The heat map here illustrates normalized scores across all indicators (Fig. 6), revealing consistent patterns. States like Kerala and Goa perform well, with low vulnerability scores in poverty rate, forest area and women's labour participation rate, reflecting better socio-economic and environmental conditions. While low poverty rates may enhance adaptive capacity, overall climate vulnerability also depends heavily on geographic exposure and systemic sensitivity such as proximity to coasts or dependence on monsoon linked cropping systems conversely, Bihar, Jharkhand and Odisha consistently show high scores, facing multiple challenges including poverty, low agricultural productivity and limited economic opportunities (Fig. 6).

Notably, northeastern states such as Arunachal Pradesh and Mizoram have low vulnerability in terms of forest cover (high AC, low NV), indicating strong natural resource endowments, but lag in economic and agricultural indicators like crop insurance coverage and employment days. This contrast highlights the complex interplay between environmental assets and socio-economic development.

The heatmap identifies states needing holistic interventions, with northeastern regions requiring economic development alongside leveraging natural assets and eastern states needing agricultural and social support. While the analysis reveals strong spatial and dimensional associations, the study does not test for causality, interpretations should be viewed as correlational rather than deterministic.

State wise CVI in India

The CVI rankings reveal significant variation across states (Table 2).

Table 2. State wise CVI in India

States	CVI	Ranking
Manipur	0.782	1
Bihar	0.780	2
Assam	0.757	3
Orissa	0.739	4
Chhattisgarh	0.730	5
Jharkhand	0.717	6
Karnataka	0.683	7
West Bengal	0.668	8
Maharashtra	0.643	9
Uttar Pradesh	0.638	10
Kerala	0.629	11
Haryana	0.627	12
Telangana	0.620	13
Goa	0.602	14
Gujarat	0.592	15
Meghalaya	0.582	16
Arunachal Pradesh	0.581	17
Andhra Pradesh	0.577	18
Uttarakhand	0.570	19
Madhya Pradesh	0.565	20
Tripura	0.560	21
Tamil Nadu	0.556	22
Nagaland	0.546	23
Punjab	0.539	24
Rajasthan	0.501	25
Mizoram	0.492	26
Himachal Pradesh	0.481	27
Sikkim	0.421	28

Manipur (CVI = 0.782), Bihar (0.780) and Assam (0.757) ranks as the most vulnerable, driven by high poverty, reliance on rainfed agriculture and limited adaptive capacity. Conversely, Sikkim (CVI = 0.421) and Himachal Pradesh (0.481) exhibit the lowest vulnerability, benefiting from diversified agriculture, high forest cover and stronger socio-economic conditions. The disparities highlight the influence of socio-economic factors and agricultural dependence on vulnerability, with northeastern and eastern states facing greater risks due to natural and institutional challenges, while hilly and southern states leverage adaptive advantages.

Regional patterns and drivers of vulnerability

The CVI map illustrates regional vulnerability patterns. North-eastern and eastern states (e.g., Assam, Bihar, Manipur) exhibit high vulnerability due to heavy rainfall, landslide risks and socio-economic challenges like poverty and limited infrastructure.

These regions reliance on rainfed agriculture (e.g., Assam: AC = 0.009, NV = 1.000) amplifies their sensitivity to climate variability. Southern states like Kerala and Tamil Nadu show lower vulnerability, supported by diversified agriculture, better irrigation (e.g., Kerala: AC = 0.800, NV = 0.889, mitigated by infrastructure) and higher insurance coverage (e.g., Tamil Nadu: AC = 96.190, NV = 0.877). Key drivers include small landholdings, yield variability, low insurance penetration and socio-economic barriers (Fig. 7).

Once CVI scores were calculated for each state, we performed driver analysis by examining the normalized indicator values contributing most significantly to each state's CVI. For each state, we identified the top three indicators with the highest normalized scores, reflecting areas of greatest vulnerability. These indicators were then tagged as 'key drivers' and thematically grouped by dimension (e.g., biophysical, institutional).

Sector wise carbon emission in India

India's total annual CO_2 emissions are estimated at 2.83 billion tonnes (7), disaggregated into three sectors. Sector wise carbon emission in India needs to be assessed to provide a clear picture of carbon emission contributions. Among the sectors in India, energy and industry contribute the maximum, to an extent of 40 %, followed by energy in buildings, transport, etc. However, the agriculture sector contributes a marginal share of 14 % (14). Agriculture contributes approximately 14 % of India's total emissions primarily from methane and nitrous oxide. When forestry and fishing are included, the entire primary sector contributes roughly 28 % (17). These estimates come from distinct inventory methods and time frames (Fig. 8).

Primary sector contributes roughly 28 % of overall emissions (17). This figure is largely attributable to the carbon footprint of agricultural practices such as soil management, crop burning and methane emissions from livestock (6). For instance, emissions from agricultural soils constitute approximately 15 % of the total, while crop burning contributes an additional 6 % (18) (Fig. 9).

Secondary sector contributes about 30 % of India's emissions through industrial activities (14). This includes energy intensive industries like steel, cement and chemical production. The iron and steel sector, in particular, accounts for nearly 19 % of emissions in this category (18, 19). Industrial reliance on coal and other fossil fuels remains a critical driver of high carbon intensity. In addition, the chemical and petrochemical industries, contributing around 20 % to emissions, continue to depend on traditional processes that lack the energy efficiency seen in more advanced economies (Fig. 10).

Tertiary sector is the largest contributor, responsible for about 42 % of total emissions (17). While the tertiary sector appears to have a high share of emissions, this is largely due to indirect emissions particularly from electricity consumption, transport and service linked energy use rather than direct emissions from production activities. Within this sector, the generation of electricity, which still predominantly relies on coal, accounts for roughly 30 % of national emissions (20). The transportation sub-sector, covering road, rail, air and water transport, contributes about 20 %. The rapid urbanization of India has led to increased vehicular traffic and rising energy demands in cities, further intensifying the emission load (Fig. 11) (14).

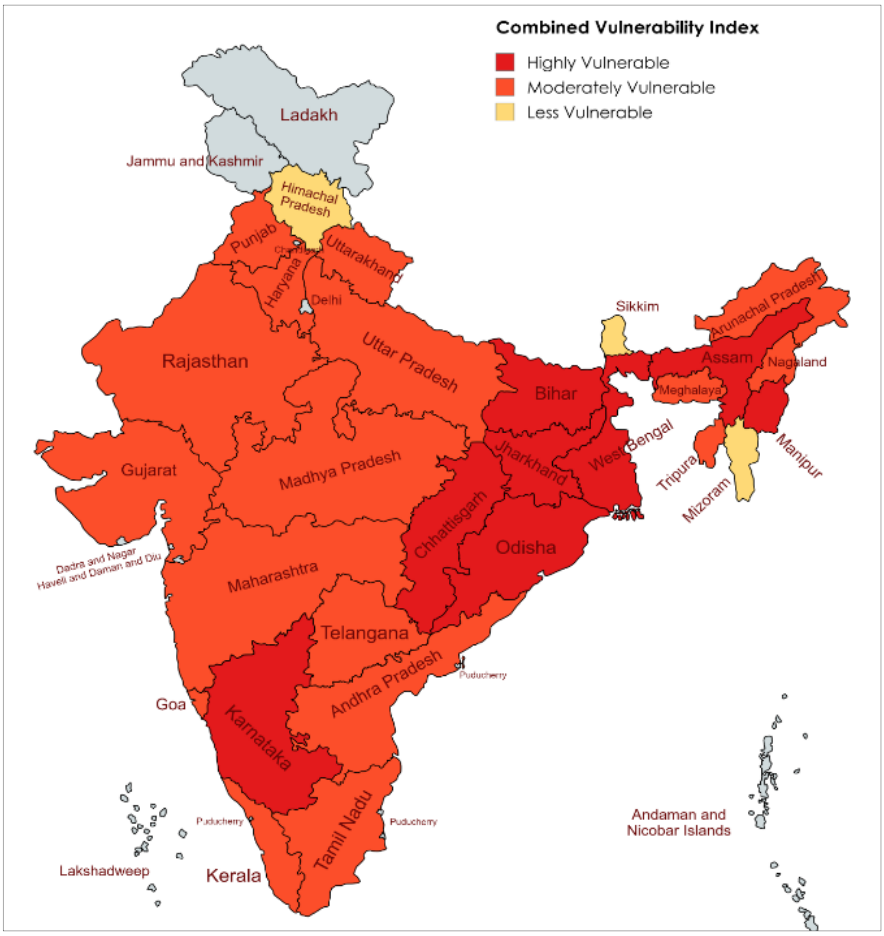

Fig. 7. Map of the CVI of all states in India.

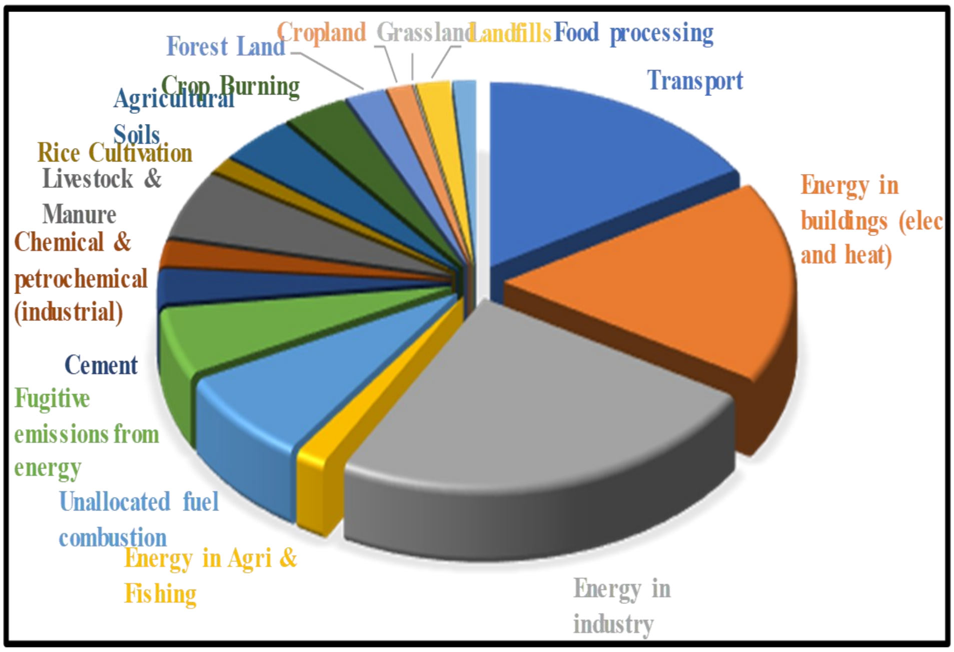

Fig. 8. Sector wise carbon emission in India.

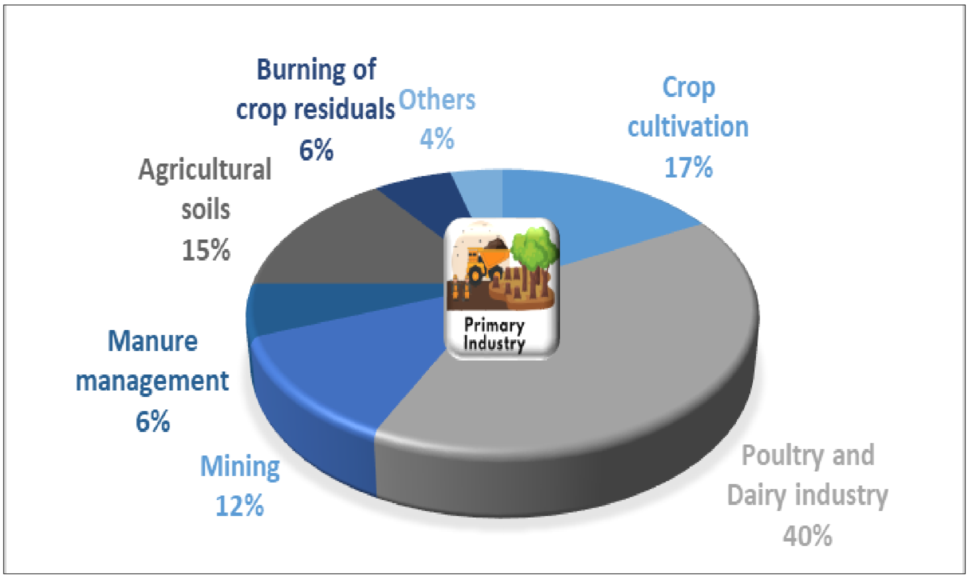

Fig. 9. Primary sector emission.

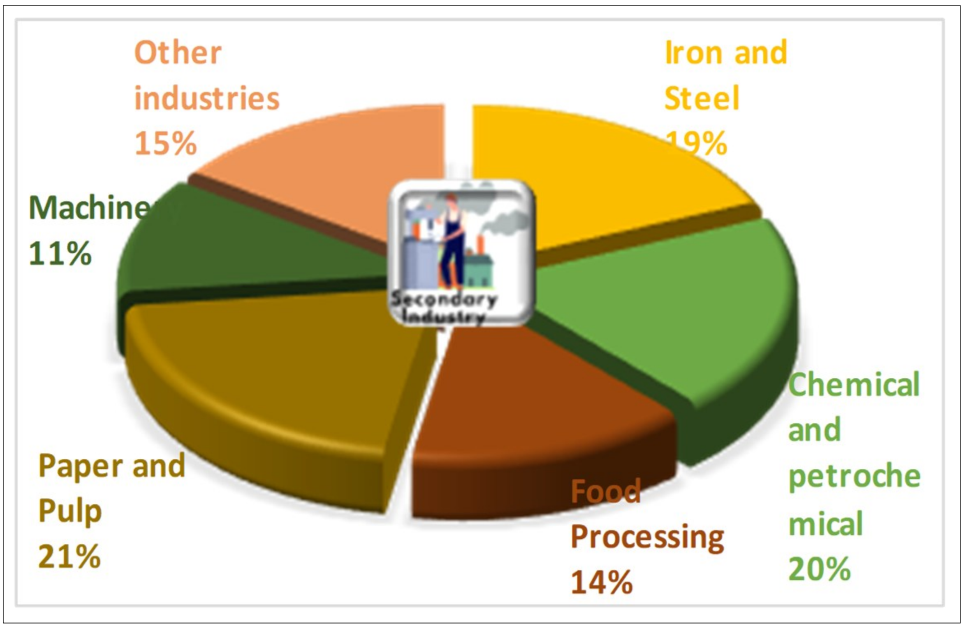

Fig. 10. Secondary sector emission.

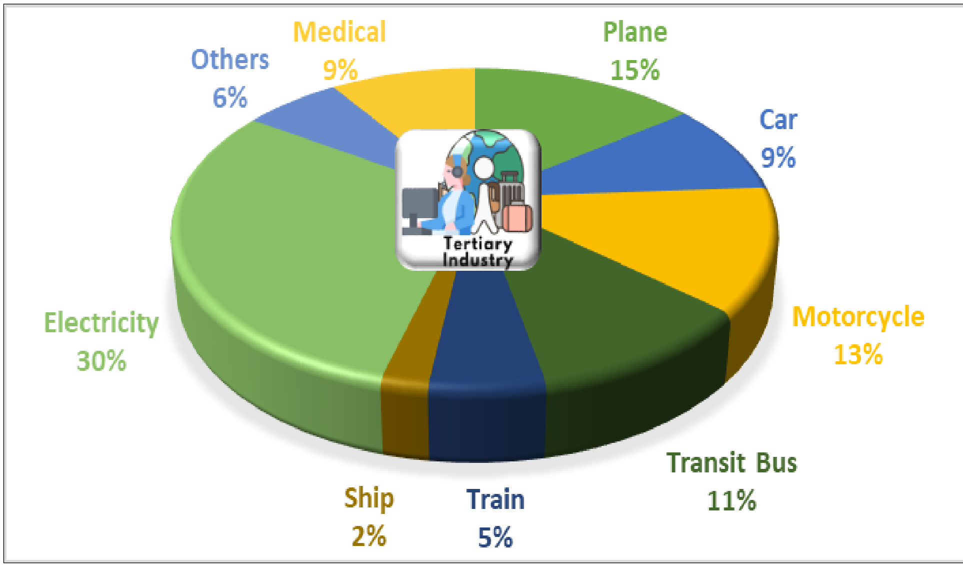

Fig. 11. Tertiary sector emission.

Agriculture's significant emissions, particularly from traditional practices, link directly to vulnerability, while industrial and service sectors reflect broader energy challenges, necessitating sector specific mitigation strategies. Sectoral emissions underscore agriculture's role (28 %), with methane from livestock and soil management, consistent with MoEFCC estimates (7). The tertiary sector's 42 % share highlights energy challenges from coal-based electricity, while the secondary sector's 30 % contribution, led by steel, suggests mitigation potential through climate-smart practices (19-21). The prioritization matrix informs tailored policies: high emission, high vulnerability states need climate-smart technologies, while low emission, low vulnerability states should sustain organic farming, aligning with India's climate goals (7).

Regional prioritization matrix

This study integrates CVI and emissions data into a prioritization matrix, categorizing states into four clusters with respect to emission rate and vulnerability level (Table 3).

This matrix provides a strategic framework for prioritizing interventions, balancing emission reduction with vulnerability mitigation across diverse state profiles. The states such as Uttar Pradesh, Punjab, Madhya Pradesh, Bihar, Assam, Odisha and Chhattisgarh have high emissions & high vulnerability. Also, emissions in populous states like Uttar Pradesh and Madhya Pradesh are high in absolute terms, but not necessarily on a per capita or per hectare basis. Future research should incorporate intensity adjusted metrics to refine prioritization.

Discussion

Our findings suggest a mutually reinforcing association between emissions and vulnerability, high emission practices such as crop residue burning degrade soil health and reduce adaptive capacity, while limited resilience driven by poverty and weak institutional support can perpetuate reliance on carbon intensive techniques (22, 23). While our integrated framework highlights a strong link between emission intensity and vulnerability, other studies report divergent patterns. For example, a study in Maharashtra's irrigated districts found no clear correlation between emissions and social vulnerability. Such discrepancies may reflect differences in spatial scale, indicator selection or temporal scope. Our broader state-level approach and inclusion of institutional factors may account for these contrasts, underscoring the importance of methodological context in vulnerability research. Although causal pathways were not formally tested here, these patterns align with feedback loops documented in regional case studies (24). In high vulnerability states like Bihar (CVI = 0.780) and Assam (CVI = 0.757), socio-economic pressures drive unsustainable practices, amplifying environmental stress, aligning with a study on the feedback loop between emissions and vulnerability (9). Conversely, low vulnerability states like Sikkim (CVI = 0.421) leverage diversified agriculture and high forest cover (AC = 82.310 %), suggesting that reducing emissions can enhance resilience, while building adaptive capacity may lower emission intensive practices. It is important to note that emission reduction efforts support long term climate stabilization but may not yield immediate resilience benefits particularly in low income, resource scarce regions.

Table 3. Regional prioritization matrix

Category	States	Strategic Interventions
High Emissions & High Vulnerability	Uttar Pradesh, Punjab, Madhya Pradesh, Bihar, Assam, Odisha, Chhattisgarh	Implement climate-smart technologies, enhance carbon credit accessibility, promote afforestation and introduce agroforestry.
High Emissions & Low Vulnerability	Haryana, Gujarat, Maharashtra andhra Pradesh, Rajasthan	Scale up precision agriculture, improve irrigation systems and incentivize reduced fertilizer use.
Low Emissions & High Vulnerability	Manipur, West Bengal, Jharkhand, Arunachal Pradesh, Meghalaya	Strengthen rural financial support systems, increase climate insurance coverage and diversify livelihood options.
Low Emissions & Low Vulnerability	Sikkim, Himachal Pradesh, Mizoram, Nagaland	Promote conservation agriculture, support organic farming and enhance ecosystem resilience.

Conversely, certain adaptive strategies like expanded irrigation or mechanization may increase emissions unless designed with low carbon safeguards. Therefore, integrated planning must explicitly address potential mitigation adaptation trade-off.

Regional disparities highlight the interplay of natural and human factors. Northeastern and eastern states face higher vulnerability due to climatic risks and institutional gaps, such as low insurance penetration (e.g., Manipur: NV = 1.000), corroborating IPCC findings on regional climate sensitivity (1). Southern states like Kerala benefit from adaptive infrastructure, reflecting NITI Aayog insights on regional capacities (14). The heatmap presented underscores multidimensional challenges in states like Jharkhand, where poverty and yield variability converge, contrasting with northeastern states' natural endowments underutilized due to socio-economic lags (Fig. 6).

Primary sectoral emissions underscore agriculture's role, with methane from livestock and soil management, consistent with MoEFCC estimates (7). The tertiary sector's 42 % share highlights energy challenges from coal-based electricity, while the secondary sector's 30 % contribution, led by steel (19, 20), suggests mitigation potential through climate smart practices (21, 25). The prioritization matrix informs tailored policies high emission, high vulnerability states need climate-smart technologies, while low emission, low vulnerability states should sustain organic farming, aligning with India's climate goals (26). The quadrant analysis enables context specific strategies. In high emission/ high vulnerability states like Bihar and Chhattisgarh, policymakers should prioritize climate smart irrigation paired with microfinance schemes to reduce crop burning and bolster adaptive capacity. For high emission/ low vulnerability states such as Gujarat and Maharashtra, emphasis should be on scaling renewable energy microgrids and incentivizing low carbon industrial clusters. Low emission/ high vulnerability regions like Manipur and Jharkhand require investments in decentralized weather index insurance and agroforestry to diversify livelihoods, while low emission/ low vulnerability states like Sikkim and Himachal Pradesh can serve as test beds for organic horti-clusters and carbon-credit partnerships (27).

Limitations include state level data aggregation, potentially masking district variations and emissions data granularity constraints, as noted in IPCC (1). Also, equal weighting and normalization assume indicator comparability but may overlook dynamic interactions among variables. Future research should incorporate localized data and longitudinal studies to refine assessments, enhancing policy precision and weighting of our nine Indica variables. Additionally, our nine indicator CVI does not account for geophysical hazards such as glacial melt and landslide risk, which may lead to an underestimation of vulnerability when applied to Himalayan states. Integrating remote sensing-based hazard data in future assessments could significantly enhance the accuracy of vulnerability estimates in these regions.

Conclusion

The study disaggregates carbon emissions by sector, identifying agriculture, industry and services as significant contributors to India's overall carbon footprint. The regions such as Manipur, Bihar and Assam are characterized by high poverty levels, extensive rainfed agriculture and limited access to modern adaptive measures are the most vulnerable. While states like Manipur and Bihar exhibit high overall CVI scores, indicator level variation reveals important nuance. For instance, Manipur has high forest cover and moderate insurance coverage, which enhance resilience in some dimensions. This dual analysis not only highlights the environmental and socio-economic challenges but also underscores the intricate interplay between carbon emissions and agricultural vulnerability, providing a data driven basis for targeted interventions. The importance of the agricultural sector in India's net zero transition cannot be overstated. While employing a significant portion of the population and serving as the foundation for rural economies, the sector stands at a crossroads being both a contributor to the nation's carbon footprint and among the most adversely affected by climate variability. This dichotomy underscores the urgency of integrating carbon mitigation strategies with adaptive measures that enhance agricultural resilience. Such integration requires technological and infrastructural interventions alongside a revaluation of existing agricultural practices and policies. Modernizing agriculture through climate smart practices can mitigate emissions and enhance resilience but demands concerted efforts to address socioeconomic inequities and build local capacities.

For implementing these policies, instead of one-size-fits-all targets, India needs policies tailored to each region's needs. High emission areas must slash emissions but also protect farmers' incomes. Vulnerable regions need help adapting like promoting hardy crops or restoring forests. In conclusion, the net-zero transition in India is not only an environmental imperative but also a transformative challenge that demands systemic changes in agricultural systems, industrial practices and governance structures (28-30). The recommendations outlined for agricultural sector ranging from implementing climate-smart technologies (e.g., zero-tillage), afforestation, precision agriculture, enhanced crop insurance, improved water management practices, institutional reforms, diversifying livelihoods to bolster resilience, promoting organic farming, etc., to offer a pathway toward achieving a resilient, sustainable future. While practices like organic farming, conservation agriculture and zero tillage offer potential alignment with low emission pathways, they are not formally specified within India's Long Term Low Emission Development Strategy (LT-LEDS) or current Nationally Determined Contribution (NDC) targets. Their integration into national planning will require formal inclusion in future iterations of policy instruments. These strategies align with India's climate goals, offering a region-specific roadmap.

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Authors' contributions

MPP and SA conceived the concept and wrote the manuscript. MPP designed the diagrams and tables. SS, MT and RR gave ideas for the design of the diagrams and tables. All authors read, revised and approved the final manuscript.

Compliance with ethical standards

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