



Research article

Strategies for climate resilience in Indian states: Addressing innovation-vulnerability mismatch

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Abstract: Climate change poses uneven risks across Indian states and amplifies exposure to climate hazards. In this study, we examined climate-related regional risk by analyzing data from eight representative Indian states to capture the mismatch between climate vulnerability and innovation capacity. For the study, the Dynamic Adaptive Pathway Modeling for Climate Resilience (DAPM-CR) framework was proposed as an integrated analytical framework for assessing climate resilience. The analysis drew on secondary data from the NITI Aayog India Innovation Index, the Department of Science and Technology's Climate Vulnerability Assessment, Human Development Index indicators, and state-level R&D statistics. We integrated climate vulnerability, innovation, human development, and R&D indicators to assess regional disparities in climate resilience across eight representative Indian states. The DAPM-CR framework was developed to integrate climate vulnerability and innovation capacity and identify adaptive pathways for strengthening state climate resilience. The study contributes to the literature by providing evidence on the spatial mismatch between climate vulnerability and innovation capacity. The findings revealed that Bihar, Jharkhand, Chhattisgarh,

Assam, and Odisha exhibit low climate resilience, low innovation capacity, and low human development. In contrast, Karnataka, Maharashtra, and Tamil Nadu demonstrated stronger innovation ecosystems for climate resilience. The study demonstrates how integrating innovation capacity with climate vulnerability assessment can strengthen adaptive climate resilience. The Composite Resilience Index revealed that states like Tamil Nadu and Karnataka benefit from large-scale renewable energy projects to enhance resilience. Thus, the proposed framework can be extended to other Indian states to provide insights into the requirement for spatially equitable resilience strategies.

Keywords: climate resilience; climate vulnerability; climate resilience framework; innovation capacity; climate change

JEL Codes: Q54, Q56, O33, R11, R58

1. Introduction

India remains at the forefront of climate change and faces increasingly frequent extreme weather events such as droughts, heatwaves, floods, and cyclones. More than 60% of the population depends on climate-sensitive sectors such as agriculture, fisheries, and forestry for their livelihoods, making the nation highly vulnerable to climate-related disruptions. The vulnerability is further compounded by rapid urbanization, population density, socio-economic inequality, and gaps in critical infrastructure, especially in developing economies. In the context of climate resilience and sustainable transitions, innovation capacity plays a crucial role. It determines how effectively regions can adopt and diffuse climate-smart technologies, policy frameworks, and institutional reforms (Archibugi & Coco, 2005). In India, capacity needs to be strengthened through capacity-building, comprehensive governance, and integrated planning to reduce regional disparities. India also needs to anticipate, plan for, and adapt to climate risks, and build resilience through technology to ensure sustainable and equitable development across the country.

Technology and innovation are key drivers of change, offering transformative solutions to climate change while supporting sustainable economic development. In India, they play a twofold role as regional inequality and environmental susceptibility intersect. It can mitigate environmental impacts and enable adaptive resilience. Innovation capability plays a significant role in estimating how different regions can adopt and diffuse climate-smart technologies, institutional reforms, and policy frameworks (Archibugi & Coco, 2005). Scientific research provides critical insights into climate systems, risk forecasting, and impact modeling, which are essential for evidence-based policymaking. Innovation, particularly through digital platforms, clean-tech startups, and frugal technologies, can democratize access to sustainability solutions across socio-economic segments. Government initiatives such as the National Innovation Council, Atal Innovation Mission, and the National Mission on Strategic Knowledge for Climate Change (under NAPCC) demonstrate India's commitment to harnessing technology and innovation for sustainable development (Ramanan, 2016). Nevertheless, the effectiveness in driving change depends on its affordability, diffusion, and contextual relevance,

especially in vulnerable areas. Adaptive pathways are conceptualized through foresight-informed strategies to navigate uncertainty and support adaptive policymaking in the face of climate change and technological disruption (Sovacool & Hess, 2017). The mismatch between technological development and regional adaptation can be reduced, but it must be translated into realistic, region-level resilience measures. Thus, a foresight-informed strategy is vital to support India's evolution toward a reduced-carbon, climate-resilient future. The gap in India's pathway to climate resilience lies in the mismatch between innovation capacity and climate vulnerability across states and regions (WIPO, 2022). The weak innovation capacity in susceptible states can be attributed to limited investment in technology, insufficient digital infrastructure, inadequate knowledge networks, and weak links among academia, industry, and government. Furthermore, studies emphasize that policies in India often neglect states' specific requirements, resulting in the underutilization of several schemes for innovation advancement (Mehta et al., 2020). This divide weakens the nation's aim of comprehensive and climate-resilient growth and green technologies, failing to reach those at risk. Hence, focusing on the innovation-vulnerability mismatch is important for guiding technology investments, developing region-specific strategies, and designing unbiased pathways. A foresight-informed approach is required to document this discrepancy and recommend adaptive models to address the innovation gap in the country's most climate-susceptible regions. Many researchers (Zupancic, 2022; Tran et al., 2025) have examined climate vulnerability, innovation capacity, and resilience as separate dimensions. Chapagain et al. (2025) and Ran et al. (2020) highlight the need for more integrated assessment approaches, as few researchers integrate these dimensions into a unified assessment framework. This study bridges this gap by proposing the DAPM-CR framework to integrate these dimensions.

A substantial body of literature exists on climate resilience and innovation systems, but we address the limited understanding of the mismatch between innovation capacity and climate vulnerability, particularly in emerging economies. We integrate selected Indian state-level innovation indicators to understand climate resilience. Our main innovation is the development of a Dynamic Adaptive Pathway Modeling for Climate Resilience (DAPM-CR) framework that integrates climate vulnerability, innovation capacity, human development, and state-level R&D indicators. This helps us analyze the climate resilience of selected Indian states. The framework adopted in this study is a modified, data-driven interpretation for comparing selected Indian states. It provides foresight-informed strategies and adaptive pathways to strengthen resilience in emerging economies.

Against this background, we aim to assess the spatial mismatch between climate vulnerability and innovation capacity across selected Indian states using secondary data. To achieve this, we propose the DAPM-CR framework, which integrates technology readiness, innovation capacity, resilience assessment, adaptive pathway planning, and composite resilience evaluation into a sequential analytical process. The study contributes by providing an integrated framework for identifying regional innovation-vulnerability mismatches and supporting evidence-based adaptive climate resilience planning at the state level.

2. Literature review

The association of technology, climate resilience, and innovation disparities among Indian states has gained attention in academic and policy discourse. The research focuses on innovation capacity to recover from climate shocks and build climate resilience, with regional differences playing a significant

role (IPCC, 2022). In India, this unevenness is intensified by socio-economic inequalities, unequal infrastructure, and environmental sensitivity. Northeastern and eastern states such as Assam, Bihar, and Odisha are highly vulnerable due to persistent floods, socio-economic instability, and droughts (Dasgupta et al., 2021; CEEW, 2021). Climate resilience is a fundamental concept related to climate change adaptation and sustainable development, enabling planning, response, and recovery from climate-related instabilities. Climate resilience can be defined as the capacity of economic, social, and environmental systems to cope with risks and instabilities (IPCC, 2022). India's susceptibility to climate change, spanning from glacial melting to coastal floods and agricultural concerns, requires adaptive strategies that are locally relevant and technologically robust (Dasgupta et al., 2021). It goes beyond immediate disaster response to incorporate long-term strategies for reducing risk, systemic transformation, and adaptive governance (IPCC, 2022). The resilience framework combines sociological and socio-economic elements through underlying social disparities and environmental exposure (Adger, 2006). Human capacity plays a significant role in enhancing climate resilience through adaptive capacity. This is possible by enhancing knowledge, skills, and institutional support systems to respond to climate vulnerability (Adger, 2006), along with technological advancement, which plays a major role (Al-Maadid et al., 2025). In India, climate resilience is relevant given the country's high sensitivity to climate extremes, ranging from irregular monsoon rainfall to glacial melt and sea-level rise along coastal areas (Roy et al., 2022). The Indian government has introduced many policy tools, such as the State Action Plans on Climate Change (SAPCCs) and the National Adaptation Fund for Climate Change. However, gaps in institutional capacity across states have led to uneven execution (TERI, 2021). A study (Bahadur et al., 2015) emphasized that climate resilience should be defined in context, especially in a country like India, where rural farming communities and urban areas face distinct climate threats. Likewise, urban resilience is gaining attention due to infrastructure strain, flooding, and extreme heatwaves in metro cities such as Chennai, Mumbai, and Delhi (Revi et al., 2014). Researchers (Béné et al., 2012; Tanner et al., 2015) differentiate adaptive, transformative, and absorptive resilience from reactive to anticipatory resilience strategies. Resilience is also linked to institutional flexibility, innovation systems, and data-powered foresight tools to anticipate and manage uncertainty. This is especially relevant in the Global South, where capacity constraints and development challenges complicate conventional models of resilience building (Nelson et al., 2007; Pelling, 2011).

Another focus is transitions, emphasizing reduced-carbon economies through behavioral, policy, and technological changes (OECD, 2011). These transformations are possible through increased R&D expenditure, climate-resilient infrastructure, and the scaling of renewable energy. Though India has made progress through national initiatives such as the Smart Cities Mission, advanced technology, innovation, and the National Solar Mission, further progress is required. Government initiatives such as the National Mission on Strategic Knowledge for Climate Change (under NAPCC), the National Innovation Council, and the Atal Innovation Mission reveal India's commitment to developing technology for sustainable development (Ramanan, 2016). However, the successful implementation of technology and innovation depends on its affordability, contextual relevance, and institutional support.

Innovation capacity is another area of focus, referring to the ability to generate and diffuse new technologies and knowledge. It is often measured using indicators such as industrial diversification, patent filings, R&D investment, and the availability of human capital. In the Indian context, innovation capacity is highly uneven across states, shaped by differences in institutional strength,

infrastructure, and economic specialisation. The India Innovation Index, issued by NITI Aayog (2021), classifies states based on enablers such as investment, human capital, business environment, and knowledge workers, as well as performance metrics such as start-ups and patents. Studies (Balachandra, 2011) reveal that India's innovation ecosystem is focused on tech-centric industries and cosmopolitan states, creating sectoral and spatial imbalances. The Global Innovation Index (WIPO, 2022) highlights India's strengths in Information and Communication Technology (ICT) services exports and knowledge diffusion. However, it has limitations in goods production, environmental sustainability, investment, and scaling local innovation. Alharbi et al. (2023) demonstrated that green finance significantly promotes renewable energy production, enhancing long-term climate resilience. Similarly, Cheng and Jiang (2024) provided empirical evidence from China that carbon markets can support the development of the renewable energy sector, demonstrating how market-based environmental mechanisms can facilitate the transition toward cleaner energy systems. These findings highlight the importance of financial and market-based policy instruments in strengthening renewable energy development and supporting broader climate-resilience strategies. Furthermore, the DST R&D Statistics (2020) show that nearly 75% of R&D funding and activity is concentrated in just five states, exacerbating the innovation divide. This discrepancy in innovation capacity limits the reach of climate-smart technologies and hinders efforts to drive green change and build climate resilience. Studies highlight the need for area-specific innovation strategies and the development of region-specific innovative systems aligned with environmental and socio-economic priorities. These insights confirm the relevance of reviewing innovation-vulnerability mismatches and developing foresight-informed strategies that are spatially equitable and state-specific. Adaptive pathway approaches have emerged as risk management tools that enable decision-makers to respond under deep uncertainty.

An extensive literature exists on climate resilience and innovation, independently and in integrated assessments. However, empirical applications linking innovation capacity directly to sub-national climate vulnerability remain limited, particularly in emerging economies such as India. In this study, we focus on innovation capacity, human development, climate vulnerability, and research and development as a framework. We assess the interaction between innovation systems and resilience outcomes in eight selected states in India. We also propose the DAPM-CR framework by comparing selected states to assess each state's resilience. The proposed DAPM-CR framework integrates established concepts from multiple research domains into a sequential analytical process. Integrated analytical frameworks have increasingly been recognized as effective tools for evaluating the interactions among related factors (Shehadeh et al., 2024). The framework begins by assessing technology readiness and innovation capacity, then evaluates their interaction with climate vulnerability. It then estimates the likelihood of future technological transitions, identifies adaptive pathways for long-term planning, and concludes by constructing a Composite Resilience Index to quantify regional resilience. We aim to address this gap through the following research objectives.

3. Research objectives

To analyze the spatial mismatch between innovation capacity and climate vulnerability among selected Indian states, focusing on innovation index score, R&D intensity (measured using R&D expenditure), Human Development Index (HDI), and climate vulnerability.

DAPM-CR to develop foresight-informed, state-specific strategies that improve innovative capacity for climate resilience among selected Indian states. A modified DAPM-CR framework that adapts well to the framework is used with the following steps: Technology Readiness Assessment, Innovation Diffusion Index, Resilience-Innovation Coupling Matrix, Transition Likelihood Assessment, Adaptive Pathway Mapping, and Composite Resilience Index.

4. Methodology

Two methods are adopted to examine the mismatch between representative Indian states: comparison and correlation analysis. The second method is to develop a DAPM-CR framework.

In this study, we used comparative analysis of secondary data to assess the spatial mismatch between innovation capacity and climate vulnerability across eight representative Indian states. The proposed analytical framework assessed climate risk at the state level by distinguishing risk exposure and risk mitigation capacity. Climate vulnerability indicators derived from the DST and XDI datasets represented exposure to physical climate risks. Innovation capacity indicators, including innovation index scores, R&D intensity, and diffusion potential, reflect adaptive risk-mitigation capacity. The spatial mismatch between these dimensions was interpreted as an indicator of state climate risk. The variables considered for this study were based on their theoretical relevance and the availability of reliable secondary data. Climate vulnerability was incorporated to understand states' adaptive capacity to climate-related risks. Innovation capacity was included to understand its role in supporting climate-resilient development. The Human Development Index represents the socio-economic capacity of states to respond to climate challenges. With these variables, the proposed DAPM-CR framework is considered to assess selected state-level climate resilience.

Key pointers were extracted from resources like the Markard, Raven and Truffer (2012) Council on Energy, Environment and Water (CEEW), Department of Science and Technology (DST), India Innovation Index (NITI Aayog) for innovation capacity, Indian Council of Agricultural Research (ICAR) (2021), International Energy Agency (IEA) (2022), Ministry of New and Renewable Energy (MNRE) (2024), The Energy and Resources Institute (TERI), XDI (Climate Change Exposure Index), and the Climate Vulnerability Assessment Report by the Department of Science and Technology (DST) for climate risk profiling.

Further, Pearson's correlation analysis was performed to examine the relationships among R&D intensity, Innovation Index, Human Development Index (HDI), and Climate Vulnerability. The analysis considered eight representative Indian states. SPSS was used to calculate the strength and direction of the linear relationships.

We included only eight Indian states: Assam, Bihar, Chhattisgarh, Jharkhand, Karnataka, Maharashtra, Odisha, and Tamil Nadu. These states were selected to represent the country's climatic,

geographical, socio-economic, and innovation contexts. Secondary data for these states were also available, enabling their selection.

The DAPM-CR framework was designed to provide a systematic analytical process. This framework integrated multiple dimensions of resilience into a single assessment. It also helped identify innovation-vulnerability relationships and supported adaptive planning for climate resilience. The proposed DAPM-CR framework integrated concepts into a unified analytical framework for regional resilience assessment. The concepts included climate vulnerability assessment, innovation evaluation, adaptive pathway planning, and composite indicator methodology. Researchers have examined climate vulnerability, innovation, and resilience independently. However, they have provided limited insight into their interrelationships.

The framework's sequential six-stage analytical process began with Technology Readiness Assessment, followed by the Innovation Diffusion Performance Index (IDPI) and the Resilience-Innovation Coupling Matrix (RICM). This was followed by estimating technology transition through Dynamic Transition Probability, developing state-specific Adaptive Pathways, and finally integrating the outputs into a Composite Resilience Index (CRI) to provide an overall assessment of climate resilience across the selected states. The six analytical stages were organized to reflect the logical progression of climate resilience assessment. The six steps of the framework included: technology readiness assessment, innovation diffusion index, resilience-innovation coupling matrix, transition likelihood assessment, adaptive pathway mapping, and composite resilience index.

These methodological approaches enabled the identification of innovation-vulnerability mismatch zones and the formulation of framework-to-foresight-informed adaptive strategies Figure 1.

The model of the study was as follows:

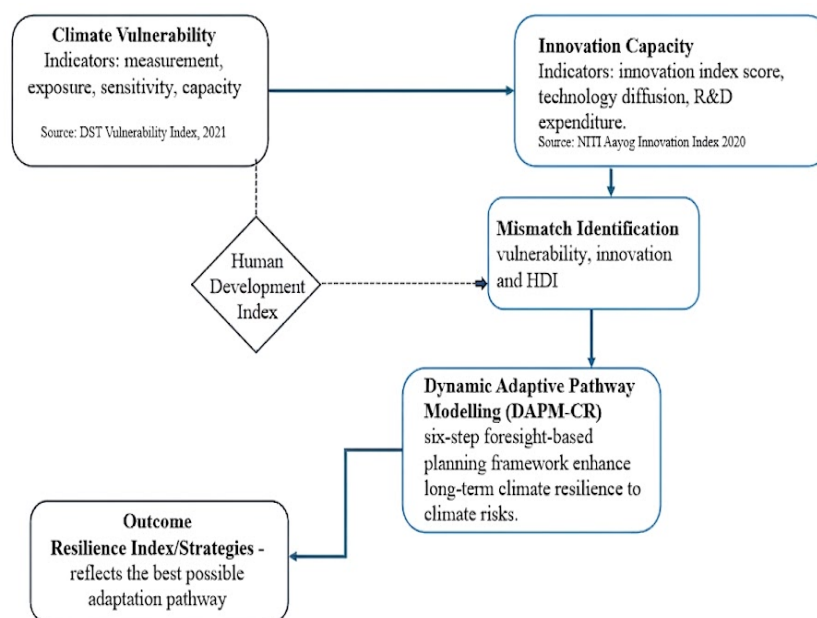


Figure 1. Model of the study-foresight-informed strategy for climate resilience in India.

The eight states selected for the study, Assam, Bihar, Chhattisgarh, Jharkhand, Karnataka, Maharashtra, Odisha, and Tamil Nadu, are represented in Figure 2.



Figure 2. Map of India highlighting the states considered for the study.

5. Results

The analysis addressed Objectives 1 and 2.

5.1. Objective 1

In response to Objective 1, two analyses were conducted based on the secondary data (refer to Table 1) that include: 1. Comparative analysis of innovation capacity and climate vulnerability across selected Indian states; and 2. Conducting correlation analysis using R&D intensity, climate vulnerability, innovation index score and HDI.

Table 1. Data sources and variable definition.

Variable	Definition	Source
Climate vulnerability	DST vulnerability index	DST
Innovation capacity	Innovation Index Score	NITI Aayog
R&D intensity	R&D expenditure/GSDP	RBI
Human development	HDI score	Global Data Lab Subnational Human Development Database

5.1.1. Comparative analysis-innovation capacity and climate vulnerability among Indian states

In this section, we outline different Indian states in terms of climate vulnerability and innovation capacity. By mapping these two dimensions together, we aim to identify broad patterns and highlight states that are either well-positioned for climate resilience or at greater risk due to innovation deficits.

While the broader comparison (Table 2) provides an initial understanding of the relationship between innovation and vulnerability across Indian states, a closer examination of select states offers deeper insights into critical mismatches and emerging patterns.

Table 2. Innovation index scores and climate vulnerability rankings of Indian states.

State	Innovation Index Score (2020)	Climate Vulnerability Ranking (Global)
Karnataka	42.50	Moderate (XDI Report)
Maharashtra	38.03	Moderate (XDI Report)
Tamil Nadu	37.91	Moderate (XDI Report)
Chhattisgarh	15.77	High (XDI Report)
Bihar	14.48	High (XDI Report)
Assam	16.38	High (XDI Report)
Jharkhand	17.12	High (XDI Report)
Odisha	18.94	High (XDI Report)

Source: NITI Aayog, 2020. India Innovation Index (2020). XDI (Climate Change Exposure Index), (2020). XDI Report: India Climate Vulnerability Rankings.

5.1.2. Innovation-resilience dynamics: Study on selected Indian states

Table 3. Climate vulnerability vs innovation capacity; selected Indian states.

State	Climate Vulnerability (DST, 2021)	Innovation Index Score (NITI Aayog, 2020)	Innovation Rank	Mismatch Category
Bihar	High	14.48	17/17	High vulnerability, Low innovation
Jharkhand	High	17.12	13/17	High vulnerability, Low innovation
Chhattisgarh	High	15.77	15/17	High vulnerability, Low innovation
Assam	High	16.38	14/17	High vulnerability, Moderate innovation
Odisha	High	18.94	12/17	High vulnerability, Moderate innovation
Karnataka	Low	42.50	1/17	Low vulnerability, High innovation
Maharashtra	Moderate	38.03	2/17	Moderate vulnerability, High innovation
Tamil Nadu	Low	37.91	3/17	Low vulnerability, High innovation

Source: Climate Vulnerability Data: DST (2021), National Climate Vulnerability Assessment Report, available at dst.gov.in; Innovation Index Scores: NITI Aayog (2020), India Innovation Index Report, available at niti.gov.in

Building upon the comparative overview, in this section, we narrow the focus to a subset of states representing contrasting profiles. We examine how the interaction between innovation ecosystems and climate risks varies across regions, offering deeper insights into the resilience challenges faced by specific Indian states.

Table 3 shows the spatial mismatch between climate vulnerability and innovation capacity across selected Indian states. To better understand the structural drivers behind these mismatches, it is important to analyze how states invest in innovation through R&D expenditure relative to their climate resilience needs.

5.1.3. Linking R&D expenditure, climate vulnerability, and innovation capacity among Indian states

Table 4. R&D expenditure vs climate vulnerability vs innovation capacity.

State	R&D Expenditure (₹ Crore, FY 2020-21)	Climate Vulnerability Ranking (Global)	Innovation Index Score (2020)
Jharkhand	89.76	Among the top 8 most vulnerable states	17.12
Chhattisgarh	227.02	Among the top 8 most vulnerable states	15.77
Odisha	269.24	Not specified	18.94
Bihar	379.32	22nd (XDI Report)	14.48
Maharashtra	663.42	Not specified	38.03
Tamil Nadu	609.72	Not specified	37.91
Assam	390.59	28th (XDI Report)	16.38
Karnataka	394.42	Among the top 5 most vulnerable states (CEEW, 2021)	42.5 (Rank 1 among major states)

Source: R&D Expenditure: Reserve Bank of India, State Finances: A Study of State Budgets 2024. Climate Vulnerability Rankings: Cross Dependency Initiative (XDI), Gross Domestic Climate Risk Report 2023, Innovation Index Scores: NITI Aayog, India Innovation Index 2020, CEEW Report (2021): Mapping India's Climate Vulnerability

In this section, we explore the relationship between R&D investment, climate vulnerability rankings, and innovation index scores across Indian states. By statistically linking these indicators, we seek to understand how financial commitments to innovation align (or misalign) with actual climate adaptation needs.

Innovation Index Scores indicate that states such as Maharashtra, Tamil Nadu, and Karnataka are at the forefront of innovation, with scores above 30 (Table 4). Furthermore, Climate Vulnerability Rankings indicate that states such as Bihar, Uttar Pradesh, and Assam are among the most vulnerable to climate change impacts, underscoring the need for targeted adaptation strategies.

Beyond innovation efforts and vulnerability rankings, resilience is also closely linked to broader human development indicators, necessitating a more holistic exploration of the links among innovation, climate risks, and social outcomes.

5.1.4. Interlinkages of climate vulnerability, innovation capacity, and human development among Indian states

In this final analytical section, we integrate human development indicators to provide a more holistic view. The analysis highlights how innovation and climate resilience are interconnected with broader socio-economic factors, underlining the multifaceted nature of sustainable development pathways.

States like Bihar, Jharkhand, and Chhattisgarh face a triple challenge of high climate vulnerability, low innovation capacity, and low human development (Table 5). However, Assam and Odisha exhibit high climate vulnerability but have moderate innovation scores. Furthermore, states like Karnataka, Maharashtra, and Tamil Nadu are better positioned to leverage innovation for climate resilience due to their low to moderate vulnerability, high innovation capacity, and higher human development levels.

Figure 3, a scatter plot, shows that states in the top-left (High vulnerability, Low innovation) are critical hotspots. States in the bottom-right (Low vulnerability, High innovation) are resilient leaders, and those in the middle are transition zones.

The correlation (Table 6) reveals a statistically significant, strong positive relationship between R&D intensity and the innovation index ($r = 0.804$, $p < 0.05$). Furthermore, R&D intensity and HDI are not significant ($r = 0.600$, $p > 0.05$). R&D intensity and climate vulnerability are also not significant ($r = 0.365$, $p > 0.05$). The relationship between the Innovation Index and HDI is statistically significant ($r = 0.839$, $p < 0.05$). The relationship between the Innovation Index and climate vulnerability is positive but not statistically significant ($r = 0.490$, $p = 0.218$). In contrast, HDI and climate vulnerability exhibit a statistically significant positive relationship ($r = 0.776$, $p = 0.024$).

Table 5. Climate vulnerability vs innovation capacity vs human development.

State	Climate Vulnerability (DST, 2021)	Innovation Index Score (NITI Rank Aayog, 2020)	Innovation Index (NITI Rank)	HDI (2019)	HDI Rank ³⁶	Mismatch Category
Bihar	High	14.48	17/17	0.574	36/36	High vulnerability, Low innovation, Low HDI
Jharkhand	High	17.12	13/17	0.599	34/36	High vulnerability, Low innovation, Low HDI
Chhattisgarh	High	15.77	15/17	0.617	31/36	High vulnerability, Low innovation, Low HDI
Assam	High	16.38	14/17	0.613	30/36	High vulnerability, Moderate innovation, Low HDI
Odisha	High	18.94	12/17	0.608	32/36	High vulnerability, Moderate innovation, Low HDI
Karnataka	Low	42.5	1/17	0.679	19/36	Low vulnerability, High innovation, High HDI
Maharashtra	Moderate	38.03	2/17	0.701	15/36	Moderate vulnerability, High innovation, High HDI
Tamil Nadu	Low	37.91	3/17	0.709	11/36	Low vulnerability, High innovation, High HDI

Sources: Innovation Index: NITI Aayog India Innovation Index 2020

Climate Vulnerability: DST's Climate Vulnerability Assessment for Indian States 2021

HDI: Global Data Lab Subnational Human Development Database (latest update around 2019)

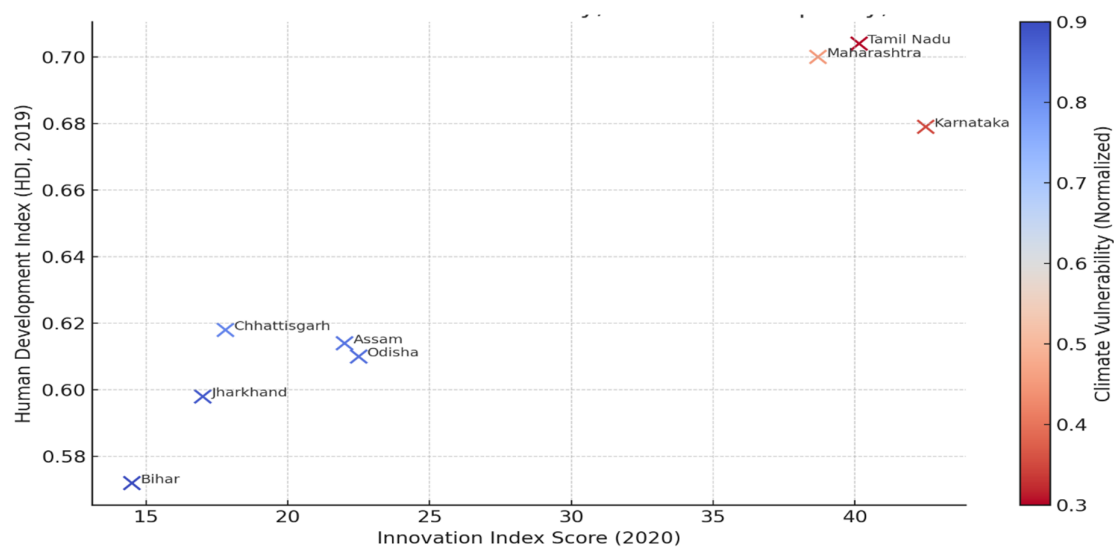
**Figure 3.** Mismatch-climate vulnerability, innovation capacity, and human development index (HDI).

Table 6. Correlation analysis of the variables considered.

		R&D Intensity ¹	Innovation Index Score ²	HDI	Climate Vulnerability
R&D Intensity ¹	Pearson Correlation	1			
	Sig. (2-tailed)				
	N	8			
Innovation Index Score ²	Pearson Correlation	0.804*	1		
	Sig. (2-tailed)	0.016			
	N	8	8		
HDI	Pearson Correlation	0.600	0.839**	1	
	Sig. (2-tailed)	0.116	0.009		
	N	8	8	8	
Climate Vulnerability	Pearson Correlation	0.365	0.490	0.776* ¹	
	Sig. (2-tailed)	0.374	0.218	0.024	
	N	8	8	8	8

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

5.2. Objective 2

The analysis for Objective 2 is conducted using DAPM-CR, an approach to manage complexity and uncertainty in climate change. In this study, secondary data-driven interpretation is considered to enable comparative analysis of the selected Indian states. Accordingly, the modification adapts the DAPM-CR framework.

The following step-by-step methods are utilized to integrate technology and innovation indicators with climate-resilience metrics and forecast transitions.

The six steps of DAPM-CR include:

- Step 1 Technology readiness assessment
- Step 2 Innovation diffusion index
- Step 3 Resilience-innovation coupling matrix
- Step 4 Transition likelihood assessment
- Step 5 Adaptive pathway mapping
- Step 6 Composite resilience index

5.2.1. Step 1: Technology readiness assessment

The first step assesses the readiness of different technologies that contribute to climate resilience. This assessment includes multiple dimensions such as policy support, technical maturity, scalability, and economic viability. Secondary data is utilized to understand India's progress in implementing climate-resilient technologies.

The scores for each technology (Table 7) are determined based on an assessment of Indian-specific factors, including technological development, government policies, market conditions, and scalability potential. Data sources include reports from the Indian Ministry of New and Renewable Energy (MNRE, 2024), NITI Aayog (2020), DST (2021), and other government and industry publications related to energy transition and technology readiness in India.

Table 7. Multi-dimensional technology readiness assessment; energy transition technologies in India.

Technology	Technical Maturity	Policy Support	Economic Viability	Scalability
Renewable Energy (Solar/Wind)	High	Strong	Improving	High
Electric Vehicles (EVs)	Moderate	Strong	Improving	Moderate
Climate-Resilient Agriculture	Moderate	Strong	Variable	Moderate
Energy Efficiency Technologies	High	Strong	High	High
Green Hydrogen	Low-Moderate	Emerging	Low	Low-Moderate
Smart Grids	Moderate	Moderate	Improving	Moderate
Biogas/Waste-to-Energy	Moderate	Moderate	Variable	Moderate

Sources: Ministry of New and Renewable Energy (MNRE, 2024), NITI Aayog (2020), the Department of Science and Technology (DST, 2021), and relevant government publications.

5.2.2. Step 2: Innovation diffusion index (IDPI)

This step focuses on a subset of states representing contrasting profiles. It examines how the interaction between innovation ecosystems and climate risks varies regionally, offering more profound insights into the resilience challenges faced by specific Indian states.

Table 8 presents the Innovation Diffusion Index that helps in identifying regions with greater capacity for adopting and scaling emerging technologies, which can be crucial for targeted policy interventions and strategic investments in sustainability and innovation. States like Karnataka and Maharashtra show high potential for innovation diffusion due to their strong R&D ecosystems and industrial activity. In contrast, states like Jharkhand and Chhattisgarh show lower diffusion potential, mainly because of challenges in R&D investment and infrastructure.

The Innovation Diffusion Performance Index (IDPI) helps assess each state's innovation diffusion capacity. R&D intensity, Innovation Index Score, and CO₂ Emissions Intensity are needed to assess technology diffusion.

Table 8. Innovation diffusion index (IDPI); Indian states.

State	R&D Intensity ¹	Innovation Index Score ²	CO ₂ Emissions Intensity ³	IDPI (Avg. Score)	Notes
Karnataka	1.44	18.01	Low	High	Leading in innovation; strong R&D ecosystem.
Maharashtra	1.19	16.06	Medium	High	High industrial activity; significant innovation output.
Tamil Nadu	1.07	15.69	Medium	High	Robust manufacturing sector; growing innovation initiatives.
Jharkhand	0.51	13.10	High	Low	Emerging innovation ecosystem: challenges in R&D investment.
Odisha	0.80	11.42	High	Low	Developing infrastructure needs an enhanced R&D focus.
Chhattisgarh	0.22	10.97	High	Low	Limited innovation activities; scope for growth.
Bihar	1.00	11.58	High	Low	High efficiency ratio; requires increased R&D spending.
Assam	0.65	11.29	High	Low	Potential in sectors like agriculture needs policy support.

Sources: R&D Intensity¹: Based on state-level R&D expenditure as a percentage of GSDP.

Innovation Index Score²: Derived from the India Innovation Index 2022 by NITI Aayog.

CO₂ Emissions Intensity³: Calculated from state-wise CO₂ emissions per unit of GDP.

IDPI: Developed for this study as the average of the three normalised scores to assess diffusion potential at the state level.

5.2.3. Step 3: Resilience-innovation coupling matrix

This step assesses how well different technologies and innovations are coupled with resilience objectives. Table 10 links technology readiness with resilience capabilities.

The Resilience-Innovation Coupling Matrix (Table 9) was created to align innovation maturity and climate resilience across technology types. The combined assessment of innovation maturity and climate resilience impact provides RICM strength. Innovation maturity reflects the level of technological development, and climate resilience explains the technology's contribution to strengthening climate risk.

These insights reflect the varying state adoption rates and highlight areas where targeted interventions could accelerate innovation and technology diffusion.

Table 9. Resilience-innovation coupling matrix (RICM) strengths; Indian states.

Technology Type	Innovation Maturity	Climate Resilience Impact	RICM Strength	Key Insights & Sources
Renewable (Solar, Wind)	Energy High	High	Strong	High maturity (Karnataka, Tamil Nadu); major contributor to emission reduction. [MNRE 2024; NITI Aayog 2020]
Electric Vehicles (EVs)	Medium	Medium	Moderate	Growing in Maharashtra and Tamil Nadu, with limited penetration in rural areas. [NITI Aayog 2020; MoRTH 2023]
Climate-Resilient Agriculture	Medium	High	Moderate	Active schemes are in place in Assam and Odisha; however, innovation diffusion is slow. [DST 2021; ICAR reports]
Energy Technologies	Efficiency High	High	Strong	Industrial energy efficiency is improving (PAT Scheme). Karnataka and Maharashtra are leading. [BEE 2023; NITI Aayog 2020]
Waste-to-Energy Solutions	Low	Medium	Weak	Innovation lagging, especially in high-risk states (Bihar, Assam). [MNRE 2023]
Water Management (Smart Irrigation)	Resource Medium	High	Moderate	Smart water management tech diffusion is improving but uneven. [MoWR 2022; DST 2021]

Sources: NITI Aayog (2020), *India Innovation Index 2020*; Department of Science and Technology (DST, 2021), *Climate Vulnerability Assessment for Adaptation Planning in India Using a Common Framework*; Ministry of New and Renewable Energy (MNRE, 2023–24), Annual Reports and renewable energy publications; Bureau of Energy Efficiency (BEE, 2023), energy efficiency reports; Ministry of Jal Shakti (formerly Ministry of Water Resources) (2022), smart irrigation and water management initiatives; and NITI Aayog (2023), e-mobility publications.

5.2.4. Step 4: Transition likelihood assessment

This step calculates the probability of different transitions between technology states or pathways.

Transition likelihood indicates how likely the technology is to significantly improve to maturity by 2030, based on secondary data trends.

Transition probability (Table 10) represents the estimated likelihood of a technology progressing from its current status to the expected status, considering factors such as policy support, investment, infrastructure, and market readiness in each state. These probabilities were assigned based on the qualitative assessment rather than exact probabilities.

Table 10. Dynamic transition probability (2023–2030); Indian states.

State	Technology Type	Current Adoption Status (2023)	Expected (2030)	Status Transition Probability (%)	Key Drivers
Karnataka	Solar Energy	High	Very High	90%	Firm policy (PMSKY scheme), private investments
Tamil Nadu	Wind Energy	High	Very High	85%	High wind potential, state incentives
Maharashtra	Electric Vehicles (EVs)	Moderate	High	75%	Urban EV adoption push, FAME-II scheme
Odisha	Climate-Resilient Agriculture	Low	Moderate	60%	Adaptation missions, agriculture modernisation programs
Jharkhand	Solar Mini-Grids	Low	Moderate	50%	Rural electrification efforts, yet infrastructural gaps
Bihar	Waste-to-Energy	Very Low	Low	40%	Limited urban infrastructure, new policies emerging
Assam	Smart Water Management	Low	Moderate	55%	Climate-smart villages programs, yet slow implementation
Chhattisgarh	Energy Efficiency (Industries)	Moderate	High	70%	PAT scheme expansion, energy conservation efforts

Sources: MNRE Annual Report (2023), NITI Aayog India Innovation Index (2021), Bureau of Energy Efficiency (BEE, 2023), FAME II Scheme Details, State Renewable Energy Policies.

5.2.5. Step 5: Adaptive pathway mapping

This step involves generating adaptive pathways that describe potential future trajectories of technological adoption and adaptation under various scenarios of uncertainty.

Table 11 outlines the technology transition pathway for selected states in India. These milestones and triggers are crucial for tracking technology diffusion and planning interventions that align with states' needs and capacities.

Table 11. Adaptive pathway mapping; Indian states.

State	Technology Focus	Initial Readiness (2023)	Milestone (2025-26)	1 Milestone (2030)	2 Final (2035)	Target	Trigger Shift	for	Path
Karnataka	Solar Energy	High	Statewide grid integration	Decentralised storage enabled	100% rooftop & floating solar	& Grid congestion or storage cost surge			
Tamil Nadu	Wind Energy	High	Hybrid zones	RE Offshore deployment	wind 60% energy mix	wind-based Coastal regulation or policy delay			
Maharashtra	Electric Vehicles	Moderate	State-level policy updates	EV 50% transport EV	public 80% urban vehicle electrification	Battery supply chain constraints			
Odisha	Climate-Resilient Agriculture	Low	Smart irrigation pilots	Climate-resilient seed zones	Scaled resilient farming models	Drought/flood frequency spikes			
Bihar	Waste-to-Energy	Very Low	Municipal-level pilots	Statewide policy framework	30% solid waste reused	Public-private partnership delays			
Jharkhand	Solar Mini-Grids	Low	20 rural microgrid installations	District-wide rollout	24/7 solar in rural blocks	Community opposition or tech failure			
Assam	Smart Water Management	Low	Pilot in districts	2 State-level integration	Resilient infra coverage	water Monsoon unpredictability			
Chhattisgarh	Energy Efficiency (Industries)	Moderate	Smart metering programs	AI-based industrial audits	35% reduction 2023	GHG Regulatory push or energy price spikes			

Note: The proposed milestones, targets, and pathway triggers were synthesised from NITI Aayog (2020), MNRE (2024), BEE (2023), ICAR (2021), DST (2021), and relevant sector-specific literature as part of DAPM-CR.

Sources: NITI Aayog, 2020. MNRE, 2024 (Ministry of New and Renewable Energy), BEE, 2023 (Bureau of Energy Efficiency), ICAR, 2021 (Indian Council of Agricultural Research), DST, 2021, and sector-specific studies on renewable energy, electric vehicles, and climate-resilient agriculture.

5.2.6. Step 6: Composite resilience index

A composite resilience index is constructed as the arithmetic mean of normalized indicators representing innovation capacity, human development, R&D intensity, and climate vulnerability (reverse-coded).

$$RI_i = \frac{1}{n} \sum_{j=1}^n X_{ij}^* \quad (1)$$

Where:

RI_i -Resilience Index of the i th state.

X_{ij}^* -normalized value of the j th indicator for the i th state.

4 indicators-innovation index score, human development index, climate vulnerability and R&D intensity.

Climate vulnerability is reverse-coded before normalization because higher vulnerability indicates lower resilience.

$j = 1, 2, 3, 4$ -four indicators,

n = total number of indicators ($n = 4$)

The analysis aims to assess relative resilience across the eight selected states using composite indicators. This approach provides a basis for comparing these states to identify deficiencies and required interventions.

The Resilience index* is calculated as Eq 1.

$$X_{ij}^* = \frac{X_{ij} - X_{min,j}}{X_{max,j} - X_{min,j}} \quad (2)$$

All variables are normalized using min-max scaling, and then the arithmetic mean is calculated. The minimum and maximum values for each variable are derived from the provided dataset and used for min-max normalization. Table 12 demonstrates the composite resilience index of all the eight states and the key insights.

Table 13 shows the calculation of the Resilience Index for the eight states, normalization of four indicators and the resulting composite resilience score.

Figure 4 presents the optimized resilience scores for selected states in India from 2023 to 2035, reflecting each state's capacity to adapt and thrive in the face of environmental and technological challenges.

Table 12. Composite resilience index calculated—Indian states.

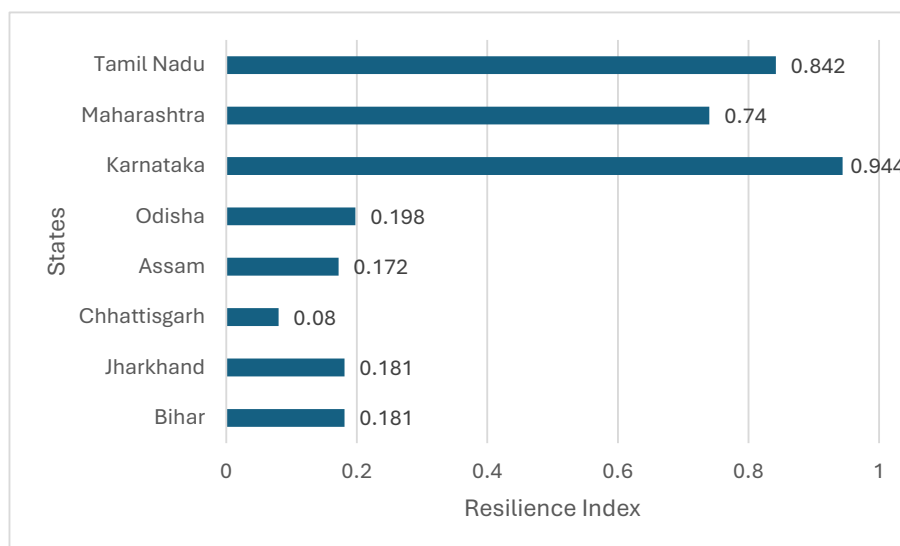
State	Technology Focus	Resilience Index*	Key Insights
Karnataka	Solar Energy	0.944	Strong solar base with grid stability improvements
Tamil Nadu	Wind Energy	0.842	High offshore wind potential, minor policy gaps
Maharashtra	Electric Vehicles	0.739	Growing EV ecosystem, battery infrastructure bottlenecks
Odisha	Climate-Resilient Agriculture	0.198	Agro-climatic vulnerabilities remain
Bihar	Waste-to-Energy	0.181	Low baseline infrastructure; high potential gains
Jharkhand	Solar Mini-Grids	0.181	Rural electrification boosts possibilities.
Assam	Smart Water Management	0.172	Flood resilience is a major challenge.
Chhattisgarh	Energy Efficiency (Industries)	0.079	Industrial reforms underway

Source: NITI Aayog Innovation Index (2020), India's Climate Vulnerability Report (DST, 2021), Climate Watch data (2024 updates), State-wise GSDP and CO₂ emissions estimates.

Table 13. Resilience index* calculation.

States	R&D Intensity	Innovation Index Score	HDI	CV	CV (reversed)	N-R&D Intensity	N-II Score	N-HDI	N-CV	Resilience Index
Bihar	1	11.58	0.574	3	1	0.639	0.087	0.000	0.000	0.181
Jharkhand	0.51	13.1	0.599	3	1	0.238	0.303	0.185	0.000	0.181
Chhattisgarh	0.22	10.97	0.617	3	1	0.000	0.000	0.319	0.000	0.080
Assam	0.65	11.29	0.613	3	1	0.352	0.045	0.289	0.000	0.172
Odisha	0.8	11.42	0.608	3	1	0.475	0.064	0.252	0.000	0.198
Karnataka	1.44	18.01	0.679	1	3	1.000	1.000	0.778	1.000	0.944
Maharashtra	1.19	16.06	0.701	2	2	0.795	0.723	0.941	0.500	0.740
Tamil Nadu	1.07	15.69	0.709	1	3	0.697	0.670	1.000	1.000	0.842

N-R&D Intensity-Normalized R&D Intensity, N-II Score-Normalised Innovation Index Score, N-HDI-Normalized HDI, N-CV-Normalised CV

**Figure 4.** Optimized resilience scores of selected states (2023–2035); Indian states.

These six stages of the DAPM-CR framework enable a comprehensive assessment of climate resilience across selected Indian states.

Discussion

From a risk perspective, these states represent high-exposure, low-mitigation environments, where climate shocks are more likely to translate into persistent socio-economic losses due to limited adaptive capacity.

The findings indicate that climate risk in India is not solely a function of hazard exposure but is significantly amplified by uneven innovation capacity across states. Regions with weak technology-innovation ecosystems face compounded systemic risk, where climate shocks interact with institutional and technological constraints, limiting recovery and adaptation. Callahan (2025) explained that countries with less adaptive capacity face greater exposure to climate change impacts.

The mismatch between innovation capacity and climate vulnerability among selected Indian states reveals that the states most exposed to climate risks are often poorly prepared in terms of technological and innovation capacity. Indian states like Assam, Bihar, Jharkhand, and Madhya Pradesh face high climate vulnerability but have low innovation capacity, hindering their ability to develop and implement adaptive strategies. The results do not reveal that higher innovation capacity corresponds to lower climate vulnerability. It extends the literature by demonstrating that innovation and climate vulnerability should not be assessed independently when evaluating regional climate resilience.

The study reveals a spatial mismatch between climate susceptibility and innovation capacity among selected Indian states, highlighting a significant barrier to achieving equitable climate resilience. Based on the selected Indian states, Maharashtra, Tamil Nadu, and Karnataka demonstrated high Innovation Index Scores and low climate vulnerability. Although Maharashtra, Tamil Nadu, and Karnataka demonstrate comparatively high Innovation Index scores alongside low to moderate climate vulnerability, the correlation analysis does not establish a statistically significant relationship between innovation capacity and climate vulnerability across the eight selected states ($r = 0.490$, $p = 0.218$). These state-level patterns should therefore be interpreted as descriptive evidence of spatial differences rather than as evidence of a statistically significant association. Tran et al. (2025) reported a significant increase in patents, examining the association between climate vulnerability and innovation. Furthermore, states like Assam, Bihar, Chhattisgarh, and Jharkhand show a mismatch. Climate vulnerability is high, while innovation capacity is low, making these states particularly vulnerable to climate risks. This highlights their structural disadvantages in resilience building and innovation capacity. These findings are consistent with studies on disparities across Indian states related to climate resilience (DST, 2020; Brenkert & Malone, 2005). The emphasis on financial discrepancies shows that Indian states such as Maharashtra and Karnataka have higher R&D expenditures and are well-positioned to mitigate climate risks. Jat et al. (2025) explained that these states have adopted approaches such as laser land levelling technology to improve soil conditions and crop modeling tools like DSSAT for agronomic adaptation (Debnath et al., 2021). Understanding the enabling and barrier factors to climate change adaptation is significant (Brullo et al., 2024). In contrast, Indian states like Chhattisgarh and Bihar invest less in R&D. These states are caught in a vicious cycle of high climate vulnerability and low innovation capacity, revealing a deep mismatch. The human development indicator (HDI) dimension affirms that Indian states with robust innovation ecosystems exhibit high HDI scores and low climate vulnerability. States with weak innovation capabilities and low HDI rankings experience a more pronounced mismatch. This difference makes them more vulnerable to the cascading consequences of climate change. At the micro-level, the study (Kumar & Mohanasundari, 2025) shows that socio-economic disparities and limited adaptive capacity determine climate vulnerability. Thus, all the findings consistently point toward an ingrained resilience-innovation mismatch in several Indian states, especially in the central and eastern parts of the country. This disparity must be addressed through technology-driven intervention, foresight planning, and state-specific adaptive pathways.

The results provide insights into the relationships among development indicators, innovation capacity, and climate vulnerability. The correlation analysis reveals a strong and statistically significant association between R&D intensity and the Innovation Index ($r = 0.804$, $p = 0.016$), suggesting that greater R&D intensity is associated with stronger innovation capacity. The Innovation Index is also strongly and significantly associated with HDI ($r = 0.839$, $p = 0.009$), highlighting the close relationship between socio-economic development and innovation capacity. However, the relationship between the Innovation Index and climate vulnerability is positive but not statistically significant ($r = 0.490$, $p = 0.218$). In contrast, HDI and climate vulnerability show a statistically significant relationship ($r = 0.776$, $p = 0.024$). Given the small sample of eight states, these relationships should be interpreted cautiously. These results support the use of the proposed DAPM-CR framework as an integrated approach for assessing multiple dimensions of regional climate resilience.

The DAPM-CR framework provides important insights into climate resilience and regional (Indian state) technology readiness. No studies have linked the DAPM-CR framework; however, the findings are broadly consistent with literature on climate vulnerability, innovation systems, and resilience assessment. The six-step approach reveals a significant mismatch in the implementation of innovative technologies among states. Southern states such as Tamil Nadu and Karnataka show strong readiness for wind and solar energy, while states like Jharkhand and Bihar face challenges due to low innovation capacity. The Innovation Diffusion Index emphasized Karnataka's strong innovation capability and its role in reducing climate risk. Argyroudis et al. (2021) found that novel technologies reduce uncertainties and can enhance climate resilience.

The Resilience-Innovation Coupling Matrix (RICM) reveals that states like Maharashtra require technologies such as climate-resilient agriculture and energy efficiency to build climate resilience. The Transition Likelihood Assessment highlights that states like Karnataka, with robust technological maturity, are more likely to attain the climate resilience goal by 2035. Moreover, Adaptive Pathway Mapping develops tailored pathways for each selected state. Considering their unique challenges and opportunities, Maharashtra focuses on scaling electric vehicles, and Odisha on climate-resilient agriculture. The Composite Resilience Index shows that states like Tamil Nadu and Karnataka benefit from large-scale renewable energy projects to enhance resilience. In their study, Monie et al. (2015) indicated that large-scale renewable energy projects strengthen climate resilience for long-term adaptation. Ikram & Sadki (2024), in their study conducted in Morocco, highlight the need for strategies that enhance climate resilience and technological capability to achieve sustainable development. Thus, the DAPM-CR framework provides an inclusive approach for creating area-specific strategies that balance climate resilience and technological capability to accelerate the country's sustainable development.

Practical & theoretical implications

The convergence of the innovation index and HDI reflects the linkage of technological progress and socio-economic advancement for climate resilience. Identifying a spatial mismatch between innovation capacity and climate vulnerability explains the need for area-specific technology strategies. Public authorities and development agencies should prioritize resource allocation, incentive structures, and capacity-building initiatives. States with high vulnerability and low innovation, such as Bihar,

Assam, and Jharkhand, need to bridge the resilience gap. Innovation hubs in states like Karnataka and Maharashtra can act as mentors or innovation-transfer platforms. Business leaders should consider climate resilience as a strategic innovation opportunity. They should align their investments with regulatory priorities in green technologies, sustainable infrastructure, and adaptation solutions. The funding agencies and banks can use these insights to design impact-driven financing models. They can target innovation-resilience mismatch zones to maximize social and environmental returns. The findings urge a foresight-informed, equity-oriented approach across all states for climate resilience.

The findings contribute to the climate resilience literature by proposing the DAPM-CR framework. It integrates climate vulnerability, innovation capacity, HDI, and R&D intensity into a unified assessment framework. This framework provides a comprehensive approach for evaluating regional climate resilience and identifying adaptive pathways. It also combines dimensions into a systematic decision-support approach.

Limitations and future study

The primary limitations were data availability, the level of aggregation, and methodological constraints. National-level sources can provide valuable insights, but state-level data on technological readiness, innovation capability, and sector-specific climate adaptation measures remain limited. The study relied heavily on secondary data sources and a cross-sectional design. This can lead to inconsistencies in reporting standards and limit the ability to capture changes over time. Another limitation is the sample size, which reduces statistical power and the generalizability of findings. Researchers could build on this research by incorporating longitudinal data and using district-level or sector-specific data that are directly affected by climate risks. Collecting primary data can validate secondary data findings.

Conclusions

In this study, we focus on the need to align technology and innovation with the demands of climate change to build climate resilience. We examine the spatial mismatch between climate vulnerability and innovation capacity across eight representative Indian states. The study shows that states exposed to climate change lack technological preparedness. The DAPM-CR approach identifies these gaps and provided a structured, foresight-informed basis for policy design. This resilience-assessment approach contributes a practical decision-support tool to the literature, helping identify regional priorities for formulating adaptation strategies. The analysis highlights the importance of tailored adaptive technological strategies among states to build climate resilience. Ultimately, accepting the resilience-innovation mismatch is vital for ensuring an impartial, sustainable, and inclusive transition in the country's path to climate resilience. By reframing innovation capacity as a mechanism for climate risk mitigation, this study contributes to the growing literature on subnational climate risk assessment and adaptive risk governance in emerging economies. Data availability and methodological constraints are limitations; however, the study lays the foundation for future research. This secondary data study can also be extended to other states in India using longitudinal data in future research.

Author contributions

Sheeja Krishnakumar, Simon Grima, Kiran Sood, and Rekha R Nair contributed equally to the conception and development of the study, methodology, analysis and interpretation of the findings, preparation of the manuscript, critical review, and revision of the final version. All authors read and approved the final manuscript and agree to be accountable for the work.

Use of generative AI tools

The authors used Grammarly solely for language-editing purposes, specifically to identify and correct grammatical errors and to improve sentence structure, clarity, and readability. The tool was not used to generate ideas, arguments, analyses, interpretations, research findings, or substantive academic content. All intellectual contributions, including the development of the research ideas, methodology, analysis, interpretation of results, and conclusions, are entirely the work of the authors. The authors take full responsibility for the accuracy, integrity, and originality of the content presented in this manuscript.

Data availability

Data are available as an attachment to the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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