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Future technologies for climate adaptation: AI-based modeling, ICT systems, and engineering solutions within India's governance framework

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ABSTRACT

Climate change is accelerating the frequency and intensity of climate hazards in India, heightening the urgency for robust, technology-enabled adaptation strategies. While emerging tools such as AI-based climate modeling, ICT-enabled monitoring systems, satellite analytics, digital-twin simulations, and climate-resilient engineering solutions offer transformative potential for anticipatory governance, their effective deployment depends on a responsive legal and institutional framework. This study critically examines how India's environmental governance architecture engages with these technologies and identifies the regulatory, institutional, financial, and intellectual-property constraints that shape their adoption. Using a qualitative doctrinal and policy-analysis methodology, the study assesses statutory instruments, judicial doctrines, and policy frameworks, complemented by comparative insights from the European Union, the United States, and Australia. The findings reveal that although India's environmental laws provide strong normative foundations, they remain mitigation-centric and lack explicit mandates for technology-driven adaptation. Institutional fragmentation, weak data governance systems, limited adaptation finance, and barriers to technology transfer further constrain technological integration. The study argues for a comprehensive climate-adaptation law that incorporates technology facilitation, harmonized data and IP frameworks, multi-level coordination, and equity-focused provisions. Such reforms are essential to build an innovation-enabling, accountable, and resilient adaptation regime suited to India's escalating climate challenges.

1. Introduction

Climate change has evolved into a complex international crisis, placing immense stress on the natural world, the economy, and society. Scientific analyses by the

Intergovernmental Panel on Climate Change (IPCC) suggest that the rate of climate change is remarkable, as evidenced by rising temperatures, increasing monsoonal variability, sea-level rise, glacier melt, and more extreme climatic events [1].

Despite the best-case scenario of 1.5°C warming, there are still risks to agriculture, water availability, infrastructure, and health. Given that mitigation strategies cannot completely eliminate the hazards posed by climate change, adaptation measures have become necessary in both developed and developing nations. Adaptation strategies involve not only biological and psychological changes but also technologically sophisticated systems that can predict, model, and mitigate climate threats with greater accuracy and speed [2].

The past decade has seen a revolutionary change in the domain of climate adaptation technologies. Some of these include climate prediction through Artificial Intelligence (AI), geospatial technologies, environmental intelligence using satellite imagery, the Internet of Things (IoT), remote sensing technology, digital twin cities, and engineering solutions that make systems resilient to the effects of climate change [3-5]. These technologies can help develop an understanding of risks in both time and space, enable anticipatory governance, increase efficiency in disaster response, allocate resources efficiently, and develop datasets to build infrastructure that will withstand risks and stresses. For example, using artificial intelligence in hydrological predictions can enable much earlier flood warnings than conventional methods; remote sensing technologies will help monitor deforestation, erosion, and agricultural stress in real time [6-8]. For India, being one of the countries highly vulnerable to climate change, these technologies become all the more necessary. The diverse geography, ecology, and socio-economics of India lead to an unequal distribution of vulnerability to climate hazards in different regions. Assessments have revealed the vulnerability of East India, Northeast India, coastal areas, and the Himalayas, with many people dependent on climate-vulnerable industries such as agriculture, fishing, and forestry [9]. With rapid urbanization and industrialization in the country, climate vulnerabilities are increasing in many low-lying, flood-prone urban areas [10].

Though technology-based adaptation is an important consideration, Indian laws and institutions have not kept pace with technological change. Basic environmental laws such as the Environment Protection Act, Water Act, Air Act, and Biological Diversity Act address pollution control, resource management, and ecosystem preservation; however, they were enacted before the advent of technological environmental intelligence systems. Consequently, none of them contain provisions for validating AI models, managing data in IoT systems, making algorithms transparent, applying digital twins, or developing climate-resilient infrastructure through engineering solutions. The judicial interpretation of environmental law, shaped by landmark judgments such as M.C. Mehta and Vellore Citizens' Welfare Forum, has strengthened environmental rights, the precautionary principle, the public trust doctrine, and sustainable development norms, but all these precedents were laid down at a time when the information age had not yet arrived [11].

The laws of India urgently need updating to keep pace with rapid technological advancements. There are numerous concerns about the mismatch between technological advancements and the existing legal framework in India. Adoption of new climate technologies is neither regular nor consistent, and it is not mandated without directives and regulations. Some of the reasons for the lack of uptake include

institutional fragmentation, lack of coordination among central, state, and local governments, insufficient adaptation finance, and limitations on IP rights that impede access to new technologies [12,13]. International experience shows that having a legally binding framework is crucial: the European Union, the United States, and Australia have begun incorporating technology-based adaptation methods into their legal frameworks, thereby making the implementation of technologies such as digital monitoring and artificial intelligence much easier [14].

Worldwide, the literature emphasizes the need for “transformative governance”, which combines innovation systems, cross-sector collaboration, and adaptable regulatory systems to govern emerging technologies effectively [15]. In the Indian context, however, academic research has largely considered technology and law as two discrete subjects. Adaptation research has been confined either to sector-based approaches or to vulnerability assessment maps, whereas studies related to law have been preoccupied mostly with environmental issues, human rights, and compliance mechanisms, but not with adaptation technologies [16]. This gap is especially significant for new domains like AI-driven climate modeling, precision agriculture, ICT-based water management, satellite-enabled disaster forecasting, blockchain-based environmental governance, and engineered climate-resilient infrastructure [17-19]. This research aims to bridge this gap by critically examining how India's environmental governance system can adapt to the demands of climate-technology integration. It investigates the extent to which current laws, policies, and institutional frameworks facilitate or constrain the uptake of AI, ICT systems, and engineering innovations; identifies governance, financial, and IP-related barriers; compares India's position with international best practices; and proposes legal-policy reforms to strengthen the law-technology-adaptation nexus. By situating India's adaptation needs within a rapidly evolving technological landscape, this study contributes to emerging interdisciplinary scholarship seeking to align environmental governance with future-oriented climate resilience.

1.1 Objectives

This study seeks to critically examine how India's environmental governance architecture can support the next generation of technology-driven climate adaptation and pursues several interconnected objectives. It seeks to analyze how existing environmental laws, policies, and judicial doctrines interact with emerging technologies such as AI-based climate modeling, ICT-enabled monitoring systems, digital-twin applications, and engineered resilience solutions. It further aims to evaluate the extent to which institutional structures, regulatory mechanisms, and administrative capacities facilitate or constrain technological innovation, diffusion, and risk governance. Additionally, the study seeks to identify gaps and equity concerns in data governance, financing, intellectual property, technology transfer, and multi-level coordination. It also aims to compare India's legal-technological readiness with international models in order to extract relevant governance insights. Ultimately, the study seeks to propose legal and policy reforms that foster an

innovation-enabling, equitable, and technologically robust climate-adaptation regime.

2. Methodology

2.1 Research design

The study adopts a qualitative, doctrinal, and policy-oriented research design to examine the interface between emerging climate-adaptation technologies and India's environmental governance framework. The doctrinal approach to analyzing law entails interpreting constitutional provisions, statutory rules, case law, and regulations applicable to environmental protection, as well as the use of technology. In addition, a technology-policy analysis will be used to determine whether India's institutions can adopt a policy to integrate artificial intelligence, ICT, and engineering adaptation techniques. The dual methodological approach will aid in assessing the technological climate adaptation processes from multiple perspectives.

2.2 Data sources

The study draws upon a structured body of primary and secondary materials. Primary legal sources include the Environment (Protection) Act 1986; Water (Prevention and Control of Pollution) Act 1974; Air (Prevention and Control of Pollution) Act 1981; Biological Diversity Act 2002; and Forest Rights Act 2006. Constitutional provisions, particularly Articles 21, 48A, and 51A(g), and landmark judicial decisions such as *M.C. Mehta v. Union of India*, *Vellore Citizens' Welfare Forum v. Union of India*, and *T.N. Godavarman v. Union of India* are examined for their relevance to environmental rights, governance principles, and regulatory obligations. Policy instruments, including the National Action Plan on Climate Change (NAPCC), State Action Plans on Climate Change (SAPCCs), National Water Policy, renewable-energy missions, and recent digital governance frameworks (such as the National Data Governance Framework Policy and the Digital Personal Data Protection Act), are analyzed to identify institutional arrangements relevant to technology-enabled adaptation. The technological aspects are covered in documents on AI-powered climate modeling, digital twin technology, IoT-enabled environmental surveillance, satellite-based remote sensing, smart infrastructure design and construction, and blockchain technology in environmental governance. Further empirical and comparative data have been drawn from reports issued by the IPCC, UNEP, World Bank, OECD, NASA, ISRO, and other highly credible organizations. Secondary data sources used include scholarly journals, policy papers, and topical reports on contemporary issues in climate governance and technological innovations.

2.3 Comparative component

A limited comparative study is conducted to situate India's regulatory approach within the international context. Legal and policy instruments in Europe, the US, and Australia are studied with a specific focus on climate adaptation policies, AI regulation, data governance laws, and regulations for adaptation using digital and engineering technologies. It is expected to identify common elements across the policies, pinpoint key differences between national systems, and formulate lessons learned regarding Indian climate

technology regulation. The comparative study conducted here is limited to only certain elements relevant to India.

2.4 Analytical framework

The analysis methodology includes the following four steps. In the first step, the doctrinal analysis method identifies the principles of law, institutions, and legal instruments relevant to climate change adaptation and technology regulation. The second step is policy and institutional mapping, which assesses whether India's current regulatory framework is equipped to facilitate advanced technological solutions. The third step includes the technology-regulation analysis, which analyses whether the existing legal framework supports or impedes the application of AI-enabled predictive modeling technologies, ICT technologies, engineering breakthroughs, remote-sensing systems, and digital governance systems. In this stage, topics such as intellectual property rights, liability, data management, interoperability, and interagency collaboration are considered. Equity, accessibility, and governance legitimacy are treated as cross-cutting analytical considerations.

2.5 Ethical and reliability considerations

The study complies with accepted academic standards for accuracy, objectivity, and honesty. All legal and policy materials are analyzed within their original contexts to prevent any distortion. The citation style used is APA, and the claims are verified through the triangulation of data from various sources. To ensure reliability, results are checked against authoritative evaluations by the IPCC, UNEP, OECD, and the World Bank. Because the study uses publicly available legal, policy, and technical documentation, there are no ethical issues involving human subjects. The study complies with accepted academic standards for accuracy, objectivity, and honesty. All legal and policy materials are analyzed within their original contexts to prevent any distortion. The citation style used is APA, and the claims are verified through the triangulation of data from various sources. To ensure reliability, results are checked against authoritative evaluations by the IPCC, UNEP, OECD, and the World Bank. Because the study uses publicly available legal, policy, and technical documentation, there are no ethical issues involving human subjects.

3. Results

3.1 Governance framework for technology-enabled climate adaptation in India

The analysis shows a gradual evolution in India's environmental governance framework, including recognition of the importance of technological advancement in climate adaptation. However, this is not comprehensive. In this regard, traditional environmental legislation, such as the Environment Protection Act, 1986; Water Act, 1974; Air Act, 1981; and Biological Diversity Act, 2002, remains the basic regulatory framework. They did not consider digital technology or AI-based modeling at the time of inception, but these are now driving technological advancements in remote sensing, environmental sensors, and digital modeling. The constitutional rights of citizens under Articles 21, 48A, and 51A(g) strengthen science-based environmental governance.

Judicial rulings such as those in *M.C. Mehta v. Union of India* and *Vellore Citizens' Welfare Forum v. Union of India* have improved environmental rights jurisprudence by allowing for the acceptance of scientific evidence and digital data within environmental cases. Despite the expansion of normativity, India does not currently have any legislation that specifically addresses the regulation of the use of AI-based predictive models, Internet of Things-enabled monitoring tools, or digital twins as climate technology interventions. While policy mechanisms such as the NAPCC and SAPCCs acknowledge the use of technologies for intervention, they lack binding authority. Policies such as the National Data Governance Framework Policy and the Digital Personal Data Protection Act provide guidance for data governance but not for climate technologies. [Table 1](#) illustrates the main governance frameworks relevant to technologies.

3.2 Sectoral integration of AI, ICT, and engineering technologies

The findings suggest that technology uptake in climate-dependent industries in India is highly inconsistent and largely relies on policy initiatives rather than legislation. In the water industry, artificial intelligence models for hydrological forecasting, Internet of Things-based sensors in river basins, and satellite data for rainfall analysis have been adopted to support early warning and risk assessment. However, the lack of regulatory standards for model and sensor calibration, as well as interagency data sharing, impedes consistent technology adoption. In agriculture, digital advisory services, imaging drones, precision irrigation systems, and climate-smart seeds have been recommended within the National Mission on Sustainable Agriculture framework. The technology improves adaptive capacities, but it is constrained by intellectual property restrictions, affordability issues, and poor digital literacy among small-scale farming communities.

Urban environments exhibit a growing trend toward digital twin models for infrastructure design, heat-resistant building materials, and stormwater management systems; nevertheless, local government regulations do not include enforceable adaptation norms. Coastal environments have adopted advanced early-warning mechanisms, tidal modeling programs, and protective barriers, facilitated in part by ISRO's satellite information systems, although there are no coastal technology policies. Biodiversity management is increasingly incorporating geographic information system-based habitat mapping and ecological modeling systems, while legislation does not recognize digital biodiversity governance strategies. [Table 2](#) highlights the link between technological sectors and relevant governance deficiencies.

3.3 Role of the judiciary in supporting technology-driven adaptation

Evaluations of judicial interventions indicate that the judiciary has been supporting the role of scientific and technological information in environmental management decision-making. The use of satellite imagery, hydrological modeling, and GIS-supported ecosystem assessments has been considered by environmental courts, thereby enhancing the importance of digital technology in providing evidence in environmental cases. The Supreme Court's affirmation of the precautionary principle, sustainable development, and the public trust doctrine has indirectly contributed to the promotion of digital tools for assessing environmental risks. The results, however, show that judicial involvement in climate-adaptation technologies remains largely reactive. There are no standards in place in court that stipulate what is required for algorithmic transparency, liability for algorithmic forecasts, requirements for digital-twin-based decision support, or data authenticity. Therefore, judicial principles offer a solid normative framework for technology-enabled adaptation, but there is no 'jurisprudence' for the emerging technologies.

Table 1. Governance instruments relevant to technology-driven climate adaptation in India

| Instrument | Year | Relevance to Emerging Technologies | Key Strengths | Limitations |
|--|---------------|--|--|--|
| Environment (Protection) Act | 1986 | Enables deployment of digital monitoring tools and remote-sensing systems for compliance | Broad regulatory mandate supporting environmental technology use | No explicit provisions for AI, IoT, or climate-adaptation technologies |
| Biological Diversity Act | 2002 | Supports GIS-based habitat mapping and digital biodiversity assessment | Strong ecosystem governance foundation | Limited digital-integration requirements |
| National Action Plan on Climate Change (NAPCC) | 2008 | Promotes renewable technologies, climate-data systems, and adaptive digital tools | Multi-sectoral coordination platform | Non-binding and lacks digital standards |
| State Action Plans on Climate Change (SAPCCs) | 2009+ | Encourage state-level deployment of ICT, GIS, and early-warning systems | Localized adaptation initiatives | Weak institutional capacity and variable digital readiness |
| National Data Governance Framework Policy | 2022 | Enhances accessibility and standardization of environmental datasets for AI/ML models | Supports interoperability for climate-tech applications | Implementation still evolving |
| Digital Personal Data Protection Act | 2023 | Provides legal alignment for responsible climate-data processing | Strengthens privacy norms | Unclear applicability to environmental datasets |
| Supreme Court Environmental Jurisprudence | 1980s–present | Accepts scientific evidence, satellite data, hydrological models | Recognizes environmental rights; enables evidence-based adaptation | Does not address AI or algorithmic standards |

Table 2. Sectoral integration of advanced technologies and governing instruments in India

| Sector | Technologies in Use | Governing Instruments | Integration Level | Regulatory Gaps |
|------------------------|--|--|-------------------|---|
| Water Resources | AI-driven hydrological forecasting, IoT sensors, satellite data analytics | National Water Policy, EPA 1986, NDGFP 2022 | Moderate | No validation standards for AI models; weak data interoperability |
| Agriculture | Precision farming, drone imaging, climate-smart advisories, digital soil mapping | NMSA, DPDP Act, Agricultural Data Frameworks | Moderate to High | Limited farmer digital capacity; IP barriers for climate-smart technologies |
| Urban Infrastructure | Digital twins, heat-resilient materials, smart stormwater systems | Smart Cities Mission, municipal laws, building codes | Low to Moderate | Lack of mandatory adaptation codes; weak enforcement |
| Coastal Zones | Early-warning systems, tidal-modelling software, satellite-based monitoring | CRZ Notification, ISRO satellite governance | Moderate | No unified coastal-technology integration policy |
| Biodiversity & Forests | GIS-based habitat models, ecological simulation tools | Biological Diversity Act, Forest Conservation Act | Low | Absence of digital ecosystem-governance provisions |

Table 3. Barriers to legal–technological integration for climate adaptation in India

| Barrier Category | Description of Constraints |
|--|---|
| Governance Fragmentation | Overlapping mandates across ministries and states result in inconsistent technology deployment and disjointed data systems. |
| Regulatory Weakness | Lack of statutory standards for AI-based forecasts, sensor calibration, digital-twin modelling, and remote-sensing validation. |
| Financial Limitations | Insufficient adaptation-focused funding; limited investment in R&D for climate technologies; mitigation favoured over adaptation. |
| Institutional Capacity | Inadequate technical expertise to manage AI/ICT systems; limited staffing for digital-environmental governance. |
| Data Governance Issues | Weak interoperability; absence of climate-data standards; limited environmental-data sharing under DPDP Act constraints. |
| Technology Transfer and IP Constraints | Restricted access to advanced global technologies due to IP barriers, costly licensing, and limited public-private innovation mechanisms. |

The lack of statutory guidance regarding the governance of AI, ICT and engineering systems in the context of climate adaptation is highlighted.

3.4 Institutional and regulatory barriers to technology adoption

The analysis points to a set of institutional challenges that hinder the effective deployment of advanced technologies in India’s climate adaptation institutional landscape. Data incompleteness, lack of (or uneven) digitalization, and the lack of uniformity in the application of regulation across central, state, and local agencies cause data fragmentation. Moreover, public institutions often lack the technical expertise to assess AI-based climate predictions, manage IoT sensor networks, and set up digital twin infrastructure. Lack of funds also restricts the deployment of adaptation technologies because funding sources remain directed toward mitigation rather than climate resilience. Poor data governance frameworks make it difficult to integrate environmental data for use in AI modeling and IP protection and to transfer it for international use, limiting access to new solutions. These findings collectively show that systemic barriers limit the widespread uptake of new technologies for adaptation. The main categories of regulatory and institutional problems that emerged during the analysis are summarised in [Table 3](#).

4. Discussion

The results of this study suggest that the environmental governance system in India provides a general, normative framework for climate regulation but is insufficiently specific, institutionalized, or technology-oriented to meet today’s climate adaptation requirements. Existing laws like the Environment (Protection) Act 1986 and the Biological Diversity Act 2002 provide vital protections for environmental quality and ecosystems but lack specific provisions for integrating new adaptation technologies, such as AI-powered climate models, IoT-based monitoring systems, or digital-twin simulation systems. In line with this global trend, technological change is outpacing governance and regulatory innovation, as witnessed in recent reviews of climate governance and new innovation systems [\[16,20\]](#). The judicial pronouncements in India have played a significant role, notably through the use of the precautionary principle, the polluter pays principle, and the public trust doctrine. They have emerged from decisions such as M.C. Mehta and Vellore Citizens’ Welfare Forum, which bolster the environmental-rights doctrine and indirectly aid data-driven, science-backed environmental decision-making. The results, however, show that the judiciary has been reactive rather than proactive with regard to influence; it has embraced satellite data, hydrological models, and geospatial information, but hasn’t considered the governance issues of AI algorithms, model transparency, liability for automated forecasts, or validation of the digital-twin infrastructure modeling. This stands in stark contrast to the current global scholarship, which calls

for explicit approaches towards digital climate-intelligence systems [13,21]. By comparing the study with the literature, it can be seen that several perspectives are reinforced. Previous studies have suggested that the ability of states and communities to adapt is influenced by the legal environment [22]. The current study supports this, demonstrating the enabling role of the Indian legal system in protecting the environment, but it does not explicitly define how technology-based adaptation is operationalized. This judicial expansion of the right to a healthy environment, a central topic in Indian climate-law scholarship, is affirmed here, particularly in its justification for the use of digital and scientific tools in environmental governance. Simultaneously, it highlights a gap not adequately addressed in previous research – the need for statutory requirements mandating or regulating the use of new technologies to facilitate adaptation. This institutional divide is echoed by the international comparison. The EU has prepared a series of legally binding adaptation plans, such as the EU Adaptation Strategy, that combine financing, monitoring, and technology-deployment requirements. Likewise, the USA and Australia have included technology-related aspects of adaptation in documents like the National Climate Assessment and the National Climate Resilience and Adaptation Strategy [14]. In this context, it seems that India's approach of relying on non-binding plans such as the NAPCC and SAPCCs is proving inadequate. This study builds on the existing research by LawBlend [11] and Kubernein Initiative [9], which have shown that India's adaptation finance has not been tapped to its full potential and is largely mitigation-focused, and that institutional fragmentation is limiting the effectiveness of implementing technology solutions.

The results also show that innovation ecosystems comprising research institutions, tech developers, PAs, and international partners are key enablers for deploying digital and engineering adaptation solutions. However, a supportive legal basis is required for these ecosystems to function. The findings are consistent with the idea of Könnölä et al. [15] that incentives for experimentation, streamlined administrative procedures, and intentional embedding of technology solutions in long-term adaptation plans are necessary for transformative governance. But constraints on IP rights are still significant in India. The research findings support Burrell et al.'s [12] thesis that the IP regimes in the global arena create institutional barriers to access to climate-relevant technologies for developing countries. This is especially true for tools in precision agriculture, such as specific environmental sensors, AI-modelling software, and geospatial analytics platforms, which have been expensive and hard to access through traditional licensing channels. Equity implications also come to the fore. Smallholder farmers, coastal communities, and the urban poor are particularly vulnerable to climate change and are less likely to have access to digital tools that could enable an anticipatory approach to decision-making or a locally based approach to climate resilience planning. This is consistent with Hjelmskog et al. [23], who found that climate adaptation technologies can increase or even re-create inequalities if they are not guided by justice-oriented approaches. The results of this study indicate that legal transformation in adaptation governance should incorporate distributive and procedural justice

concepts, as this does not mitigate socio-economic inequalities.

4.1 Limitations

There are some limitations to this study that need to be recognized when interpreting its results. First, doctrinal and qualitative analyses are limiting the evaluation of the implementation of climate adaptation technologies such as artificial intelligence models, Internet of Things (IoT) systems, and digital twin tools across various ecological and administrative regions of India. Second, attention is focused on national-level legislation and policy, while little attention is given to the governance processes at the state and local levels that often influence the feasibility of implementing the technology. Third, the dynamic and fast-changing character of digital- and AI-governance structures suggests that regulatory developments could occur outside the time frame analyzed in this study. However, the study provides a precursor to further empirical and policy work, based on a legal-technological mapping.

4.2 Future directions

Future research should include empirical methods to complement doctrinal insights to better understand how CAT technologies work on the ground. Case studies, field reviews, and interviews with stakeholders in each sector would illuminate the practical difficulties of implementing AI-based forecasting, remote-sensing, or climate-resilient engineering solutions. Analyses of other developing countries could help determine regulatory models suitable for India's institutional setup. Further research into intellectual property reform, cross-border technology transfer processes, and interoperable data governance structures is crucial to overcoming existing structural barriers. Lastly, interdisciplinary studies integrating legal analysis with engineering, data science, and socio-economic analysis would help design equitable, scalable, and technologically sound strategies for climate resilience in India.

5. Conclusion

India's climate adaptation program is at a turning point: the basic laws of the environment remain important but are no longer sufficient to address the scale, speed, and technological dimensions of current climate risks. This study shows that current laws, including the Environment (Protection) Act, Water Act, and the Biological Diversity Act, offer valuable principles for regulation but were created before the advent of the digital age and do not include specific requirements for the implementation, management, or investment of new adaptation technologies. While judicial developments and jurisprudence in *M.C. Mehta and Vellore Citizens' Welfare Forum* have created a robust framework for environmental rights and strengthened the need for science-based decision-making, they have been reactive and insufficiently instructive for algorithmic transparency, AI-model validation, digital-twin simulations, and technologically informed risk assessments. The analysis identifies structural barriers such as weak institutional mandates, lack of adaptation financing, intellectual property rights, and a lack of technology transfer mechanisms, among others, which have persisted. The experience of the EU, the USA and Australia confirms that legally binding adaptation

strategies, in tandem with innovation incentives, data governance standards and long-term funding mechanisms, have a major positive impact on climate resilience and technological readiness. With these lessons learned, India needs a paradigm shift towards a comprehensive adaptation law that includes technology facilitation, harmonization of IP and data governance approaches, and institutional coordination at multiple levels. Vulnerable populations, including smallholder farmers, coastal communities, and the urban informal, should be prioritized, with technology working for them. In this context, Indian environmental law can move beyond a protective framework toward a forward-looking environmental governance system that promotes innovation, enhances resilience, and fosters sustainable development.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically regarding authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with research ethics policies. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, additional data will be provided by the corresponding author upon reasonable request.

Conflict of interest

The authors declare no potential conflict of interest.

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