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Integrating indigenous knowledge into climate change adaptation to strengthen community resilience: case studies from India, Nepal, and Sri Lanka

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Abstract

Indigenous and local communities (ILCs) are the most impacted by climate change, as they face a combination of environmental and socio-economic challenges. However, ILCs hold extensive, complex, and rich knowledge and deep-rooted understandings of climate and environmental change that can inform climate change adaptation (CCA) strategies. Through a literature review, the study investigates the effectiveness of Indigenous knowledge and CCA. This helped to critically and systematically interrogate the adaptive measures. Using case studies of India, Nepal, and Sri Lanka, this study specifically examines the ILCs can partner with authorities, lead and co-learn in resilience building at local and regional levels. Firstly, through literature review, we understand the dominant adaptation strategies employed across the region and how they vary in effectiveness. Secondly, through the knowledge co-production approach, we mapped (1) Indigenous and traditional practices and (2) the major actions and roles to be taken up by various levels of institutions for the case study areas with high vulnerability. The adaptation strategies range from tangible to intangible practices/knowledge systems, which are grouped as social, physical, environmental, institutional, and cultural. Research findings from the preliminary surveys of the case study areas from the Southeast Asia region indicate that indigenous applied community knowledge, such as microclimate adaptation strategies, seasonal livelihood resource mapping, and environmental stress management, are highly effective at the local level. This approach will not only support adaptive transformation in response to climate change events but also strengthen community cohesion by promoting the integration of indigenous, local, and long-practiced strategies by communities into current and future climate action frameworks. The study advocates an innovative three step process ensuring participatory, locally grounded knowledge co-production approach to climate resilience that supports livelihoods in vulnerable regions.

1. Introduction

Climate extreme events like flooding and heat waves have become some of the most frequent and destructive natural hazards worldwide, intensified by climate variability and changing rainfall patterns. These events are not only seasonal but are also increasingly unpredictable, causing widespread damage to

agriculture, infrastructure, and human lives [1]. Among the most vulnerable to these recurring disasters are Indigenous and local communities (ILCs), whose livelihoods remain closely tied to natural resources and who often have limited access to formal disaster management systems [2]. Flood risk management has been widely studied at national and global levels, with an emphasis on large-scale engineering solutions, early warning systems, and institutional disaster response mechanisms [3]. Similarly, heat impacts have been studied with respect to institutional response mechanisms. While these approaches are important, they often overlook the realities of small, resource-dependent communities, especially ILCs, whose vulnerabilities and coping strategies differ significantly from mainstream settings [4].

The ILCs face unique challenges due to their fragile ecosystems and socio-economic conditions. Existing studies have highlighted the ecological sensitivity of these regions and the increasing frequency of floods [5]. Despite these vulnerabilities, ILCs have long relied on traditional knowledge and collective practices to cope with floods. However, such strategies are gradually weakening under the pressures of environmental change, economic stress, and policy neglect. Current research remains limited to general vulnerability assessments, with little focus on how ILCs' knowledge can be integrated into formal risk management. Indigenous communities are often treated as passive beneficiaries of aid rather than active partners in resilience-building. There is also a gap in local-level assessments and the adaptation of indigenous and local strategies to the emerging risks. Addressing this gap requires research that not only documents local strategies but also situates them within structured frameworks capable of guiding policy and practice [6]. This research, therefore seeks to understand the Indigenous practices for addressing extreme events that cause flood risk in five case study areas, across three countries India, Nepal and Sri Lanka, drawing upon both geospatial risk analysis and community-based knowledge systems. By combining both analytical tools and participatory models, the study aims to highlight pathways that strengthen Indigenous resilience while bridging the gap between local practices and institutional planning.

2. Review of existing work

Climate change adaptation (CCA) has become a central theme in global environmental research, as communities worldwide face mounting risks from rising temperatures, extreme weather events, and erratic rainfall [7]. While scientific and technological innovations have dominated adaptation discourse, scholars increasingly acknowledge that solutions grounded in local realities are equally vital. Indigenous knowledge, often referred to as traditional ecological knowledge, has emerged as a key resource for shaping locally appropriate and culturally rooted adaptation strategies [8]. Indigenous knowledge systems (IKSs) are deeply tied to the environment, shaped over centuries through observation, experimentation, and cultural practice. Studies across Asia, Africa, and Latin America highlight how such practices—ranging from crop diversification and soil fertility management to water harvesting and forest stewardship—contribute significantly to resilience under climatic stress [9]. These also include informal risk-sharing mechanisms like community water-sharing arrangements, crop diversification, and raised homesteads, which are often not regarded as solutions. Unlike external interventions, these practices are embedded within social norms and collective institutions, making them more sustainable and adaptive to local conditions.

However, challenges such as globalisation, policy neglect, and generational shifts have affected the continuity and transmission of this knowledge in many regions [10]. The role of Indigenous knowledge and traditional practices in adapting to climate change remains to be further explored through cross learning.

Despite a growing body of work on Indigenous knowledge and adaptation, three gaps are evident. First, most studies generalize Indigenous practices at the regional level without focusing on specific landscape, where ecological and socio-economic conditions are unique. Second, limited attempts have been made to integrate traditional knowledge with structured analytical tools that can communicate effectively with policymakers [11]. Third, while global literature emphasizes the value of local knowledge, adaptation policies in numerous Southeast Asian countries continue to prioritize technical interventions over community-driven strategies [11]. These gaps underscore the need for district-level, participatory research that both documents Indigenous practices and demonstrates their potential within established frameworks.

The paper is structured as follows:

Section-I- provides the thematic Literature review

Section-II covers knowledge co-production processes and outcomes based on risk mapping of five case study areas from India, Nepal and Sri Lanka and adaptation strategies at the local and regional levels.

Section-III- develops 'Responsibility Assignment Matrix' to assign accountability for adaption to climate extreme events.

3. Thematic literature review

In this section, we cover literature review themes, methodology, and theme wise literature appraisal for the purpose of knowledge co-production and development of Responsibility Assignment Matrix. In order to systematically understand concepts, recent discourses, best practices, regional state of knowledge co-production, examples of adaptive strategies, knowledge co-production processes, techniques and implementations, the following theme-based literature is covered (1) Classification of resilience and operational definitions in the region, (2) Inclusion of IKSs in CCA: Trends, Debates, and Warnings, (3) Distinctiveness of the community-driven climate resilience studies, (4) Best practices in community-driven approaches, (5) Observation notes on best practices in India, Nepal, and Sri Lanka, (6) Adaptive strategies in different geographies and contexts, and (7) Knowledge co-production: processes, techniques, and implementation implications.

3.1. Review methodology

Thematic literature review was conducted to synthesize recent (2019–2025) research on IKSs, CCA, and community resilience. First, different combinations of possible keywords were identified that were further used in the document screening process. The search was conducted using Scopus database to ensure coverage of peer-reviewed and high-impact publications. Advanced search queries were developed using combinations of keywords such as 'Indigenous knowledge,' 'traditional ecological knowledge,' 'climate adaptation,' 'community resilience,' 'knowledge co-production,' and 'community-based adaptation,' along with Boolean operators (AND/OR). Searches were restricted to publications from 2019 to 2025 to capture emerging trends and recent advancements.

The initial search yielded 186 records. Initially, the papers were manually screened by the authors team on the basis of title and abstract, followed by full-text screening of 134 shortlisted articles. Irrelevant results were excluded. A subset of highly cited and recent review papers was also included to identify theoretical frameworks and emerging research directions.

To enhance thematic synthesis, AI-assisted tools were used to analyse full-text articles independently to extract predefined themes. After extraction, all themes from each article, if present, were critically reviewed manually and organized using AI-assisted tools.

3.2. Classification of resilience and operational definitions in the region

Across the three countries, India has the richest and most diversified resilience classifications as per recent regional publications in the domain. Appendix Annexure 1 presents a comparative classification of resilience: India, Nepal, and Sri Lanka. It includes climate, community, economic, adaptive, absorptive, transformative, and disaster risk reduction (DRR)-oriented resilience. There are various examples of building resilience through telecentres, Ladakh irrigation, Nagaland's Ruza system, Sikkim's Dzumsa governance, mangrove protection, and Himalayan water management.

Nepal's literature is more focused on vulnerability, voice, and knowledge politics. Its strongest contribution is not only technical adaptation but the methodological shift that allows farmers and marginalized communities to define their own vulnerability through participatory video, radio dialogues, and Indigenous warning knowledge.

Sri Lanka is the least elaborated in the available bibliography. The cascading tank system is a strong example of climate, water, agricultural, community, and absorptive resilience, but recent literature gaps remain around governance, gender, class/caste access, maintenance, policy integration, and whether tank systems are still community-controlled or increasingly state/project-managed.

3.3. Inclusion of IKSs in CCA

Trends, Debates, and Warnings—Literature indicates that authors increasingly argue that IKS, traditional ecological knowledge, and local knowledge should move from the margins into climate adaptation planning, governance, education, and climate services. IKS is presented as practical and evidence-based knowledge [12]: describe agricultural heritage as cultural memory and a 'living laboratory' for adaptation, while [13] show how Indigenous weather knowledge can be co-produced with scientific climate

records [14]. Further show that farmers in Zimbabwe actively use Indigenous and local forecasts for seasonal decisions.

A key trend is hybridisation, where authors suggest combining IKS with science, AI, remote sensing, local governance, and participatory planning rather than replacing one knowledge system with another. This trend appears across agriculture, water governance, forestry, food systems, DRR, coastal planning, education, and urban resilience, with studies from South Asia, Africa, Southeast Asia, Latin America, Australia, Alaska, Canada, and Europe. However, authors also warn against tokenistic inclusion. Researchers caution that IKS must not be extracted without respecting Indigenous sovereignty, intellectual property, oral traditions, language, self-determination, and epistemic justice [15–18]. The key debate, therefore, is not only whether IKS is useful, but who controls it and whether its inclusion changes power relations.

3.4. Distinctiveness of the community-driven climate resilience studies

Academic discourses suggest that community-driven climate resilience is becoming more than the documentation of local coping practices; it is increasingly framed as co-production, governance reform, power negotiation, and justice-oriented transformation. C Xie and C Chen [12] treat agricultural heritage systems as ‘living laboratories for climate adaptation’ (p. 2), making community knowledge part of a wider system involving IKS, climate science, AI, IoT, and policy. Hill *et al* [13], are more critical: they ask ‘under what conditions can co-production between scientific and Indigenous knowledge generate adaptation pathways’, warning that colonial institutions can ‘enable and constrain adaptation options’.

The novelty of many studies lies in moving beyond descriptive case studies. Butler *et al* [19], make resilience political by mapping ‘decision-making and power,’ using participatory pathways planning, and creating ‘political spaces’ for negotiation. Nipa, Farjana [20], show that third-sector organisations can create ‘a relational space for co-production’ through local knowledge, shared goals, and inclusive engagement. Manda [21] provides an important warning: even community-driven projects may render invisible Indigenous and local knowledge by promoting ‘policy-centric knowledges and interventions’. Dewi [22] similarly find that community involvement in urban co-production often remains consultative rather than fully co-initiated. Thus, the key debate is whether community-driven resilience genuinely shifts authority to communities or simply repackages top-down adaptation in participatory language.

3.5. Best practices in community-driven climate resilience

The reviewed literature shows that community-driven climate resilience is moving beyond technical adaptation toward more relational, justice-oriented, and knowledge-sensitive approaches. A major trend is the growing recognition that Indigenous and local knowledge can complement scientific climate information, especially in forecasting, agriculture, and disaster preparedness. Xie and Chen [12] show how Indigenous indicators such as bird behaviour can support planting decisions, while Zvobgo *et al* [14], demonstrate the value of combining Indigenous/local forecasts with scientific seasonal forecasts. However, the literature also warns that such integration must not become extractive. Knowledge must be recognized, attributed, protected, and governed by communities themselves.

A second strong theme concerns communication, trust, and reciprocity. Local-language communication is repeatedly emphasized as a way to improve access and usability of climate information, but the deeper issue is cultural translation, not only linguistic translation. Hill *et al* [13], foreground trust, respect, and cultural protocols as conditions for co-production, while Iwama [23] show that long-term reciprocity is necessary to avoid extractive relationships. This suggests that community-driven resilience cannot be built through short project cycles alone; it requires time, continuity, and relational accountability.

A third theme is the political nature of participation. Several studies argue that co-design must retain decision-making power with communities rather than treating them as validators of externally framed solutions [12, 24]. Butler *et al* (2022) make this point more explicitly by showing that resilience planning must map ‘power, knowledge and networks’ so that it does not reproduce inequality (p. 230). Similarly, workshops and scenario-planning exercises are useful only when they move beyond outputs toward concrete action and negotiated pathways (Butler *et al* [19], p 231; Rimlinger *et al* [24], p 4). Nipa and Farjana [20] further show that community groups require legitimacy, continuity, and resources if they are to function as meaningful co-production spaces. The literature also broadens who counts as a resilience actor. Women, elders, youth, farmers, and informal neighbourhood groups are increasingly treated as knowledge holders and implementers and agents of CCA [25] rather than vulnerable beneficiaries. Women’s leadership in adaptation is emphasized by Rida [26], p 3 and Adusei and Agyemang-Duah ([27], p. 1), while Patrick *et al* [28] and Figus, Ki, and Trainor [29] show the importance of older adults, elders, youth, and students as active knowledge partners (Patrick *et al* [28], p 1; Figus *et al*

[30], p 12). Indigenous data sovereignty is another critical best practice, especially where knowledge is sacred, sensitive, or place-based (Ciocco *et al* [17]; Figus *et al* [30], p 12). Indigenous-led governance gives resilience moral and political legitimacy because it affirms jurisdiction, responsibility, and self-determination (Wienrich *et al* [31], p 3). Annexure 2 tabulates the best practices from India, Nepal, and Sri Lanka.

In practical terms, the literature identifies a range of locally grounded adaptation strategies: agroecology, farmer field schools, home-gardens, seed banks, food storage, rainwater harvesting, nature-based solutions, disaster plans, mutual aid, early warning, participatory risk mapping, storytelling, and climate education. These practices work best when communities are treated as experimenters and decision-makers, not passive recipients (Mnukwa *et al* [32], pp 1, 5; [27], p 9). Agroecology and home gardens strengthen autonomy, biodiversity, nutrition, and gendered resilience, but they still require supportive policy and markets (Chisadza [33], p 1; Mallick *et al* [34], pp 5–8). Water harvesting must be linked with equitable water governance (Haque *et al* [35]; Teweldebrhan and Dinka [36]), while nature-based solutions must avoid displacing local rights (Hunter *et al* [37], pp 7, 11; Rida [26], p 10). Finally, the reviewed studies suggest that resilience is not only infrastructural but also social, cultural, and institutional. Social safety nets, mutual-aid groups, rituals, customary norms, cultural landscapes, schools, libraries, and storytelling practices all operate as resilience infrastructure [38–40]. A detailed literature review of type of resilience from each country was found to be different and tabulated as Annexure 1. The terms—CCA, resilience building, DRR have been widely discussed by researchers in various contexts. Dorji *et al* [41] define CCA as ‘adjusting to the physical environment or human systems in response to potential or anticipated climatic shocks and their impacts’. Hunter *et al* [37] similarly define adaptation as ‘the process of adjustment to actual or expected climate and its effects’. Further, climate resilience is defined as ‘the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner’ Dorji *et al* [41]. DRR is aimed at preventing new and reducing existing, disaster risk (exposure, hazard or vulnerability), and managing residual risk, all of which contributes to strengthening resilience and achieving sustainable development [42].

Technology, AI, and digital tools can support resilience, but they should not replace face-to-face participation or local institutions [43, 44]. The literature argues that community-driven resilience must be locally defined, politically aware, culturally grounded, and adaptively governed. Adaptation should not be dictated from outside; communities must define their own needs, pathways, and futures [45].

3.6. Key observation on best practices in India, Nepal, and Sri Lanka

The literature on India, Nepal, and Sri Lanka (Refer Annexure 2) shows that community-driven climate resilience in South Asia is rooted in local institutions, Indigenous and local knowledge, ecological infrastructure, and participatory methods. In India, the literature is relatively richer and more diverse. It identifies best practices such as Kerala’s post-flood farmer collectives, Odisha’s mangrove protection, Himalayan community drinking-water management, disaster-related rural telecentres, Ladakh’s traditional irrigation and artificial glacier initiatives, and Nagaland’s Ruza system [35, 46, 47]. These examples show that Indian cases combine ecological practices, community labour, digital information systems, water governance, and traditional resource-management systems [48, 49].

In Nepal, the literature highlights community voice and Indigenous environmental observation. Participatory video, radio dialogues, household surveys, and deliberative debates help vulnerable farmers become knowledge producers rather than passive research subjects [16], pp 70–71. Indigenous flood-warning indicators, such as cloud patterns, animal behaviour, and river sounds, also show the value of local observation in disaster preparedness [50], pp 16–17.

Sri Lanka is less elaborated in the recent publications. The cascading tank system appears as an important traditional water-management practice linking hydrology, agriculture, community institutions, and climate resilience [35]. However, a visible literature gap remains: recent studies provide limited detail on how these systems are governed today, who participates, how gender and caste/class relations shape access, and how traditional systems are being integrated with contemporary climate policy.

3.7. Adaptive strategies in different geographies and context

Adaptive strategies are strongest where they are place-based, low-cost, locally governed, and culturally meaningful. South Asian examples emphasize grassroots resilience, water systems, mangroves, telecentres, and community institutions. African cases show strong livelihood-linked adaptation through coastal protection, pastoral mobility, agroforestry, crop diversification, and Indigenous forecasting. Indigenous cases from Aotearoa New Zealand and Alaska show that adaptation is not only technical; it also includes land return, relocation justice, kinship continuity, food sovereignty, and community-led monitoring. A visible literature gap remains in the need for deeper recent country-specific documentation from Sri Lanka

and India, especially beyond general best-practice examples and toward detailed community-level adaptive processes. Refer table 1 that lists the various adaptation strategies to climate change events across nations.

4. Knowledge co-production processes

This section focuses on the knowledge co-production processes and outcomes based on risk mapping of five case study areas from India, Nepal, and Sri Lanka, as well as adaptation strategies at the local and regional levels. The development of workable, community-led adaptation solutions is the main focus of this theme.

Across the literature, knowledge co-production is not presented as simple consultation. It is repeatedly described as a multi-stage process involving documentation, trust-building, co-design, dialogue, validation, feedback, and adaptive revision. The strongest studies also treat co-production as political: it must address power, ownership, data sovereignty, Indigenous authority, gender, caste/class hierarchies, institutional inertia, and long-term capacity. Techniques range from participatory video, storytelling, Talking Circles, community mapping, focus groups, and World Café methods to AI-enabled visualisation, climate services, sensor networks, scenario planning, and GIS. The common implementation lesson is that scientific knowledge and technology are useful only when they are locally interpreted, culturally grounded, and governed with communities rather than imposed on them.

4.1. Methodology

Using a variety of co-production processes and techniques such as case studies, expert input, classroom discussions, community participation, and stakeholder meetings, the strategy entails establishing a comprehensive set of tactics across many metrics aimed at improving CCA in rural environments. The study initially lists the community's current and traditional tactics, from each case study through primary and secondary data collection.

Data gathering for narrative construction is made possible by the development of discussion guides and questions that identify specific impacts and vulnerabilities. This stage also included community mapping and the creation of mapping legends using a participatory approach. Major spatial elements and community structures that represent local vulnerability, hazards, and adaptability were incorporated in the study.

Themes related to the development of strategies for CCA tap into indigenous local practices and knowledge of adaptation, thereby making the strategies local and context-specific. The process emphasizes co-learning, co-designing, and co-researching in the local setting through different tools such as focus group discussions (FGD), participatory mapping, workshops, interviews, and community engagement activities. This cyclic process of learning, practice, and reflection is intended to enhance community capacity and support informed decision-making for climate resilience.

To examine and analyse the indigenous knowledge, five case studies from developing countries were studied to rapidly capture the problem of community in the context of climate change events. Community-based case studies (failure & success stories) provide evidence-based knowledge material for self-reliance, better understanding, improved communication, and creating awareness. They also support the dissemination of knowledge for better responses at different levels (community, stakeholders, policy-makers & the student community). The knowledge co-production across the case studies is tabulated in Annexure 3.

4.2. Case studies

The study is part of the project 'GoAL: Gender oriented adaptive transformation cross-learning for climate change and Disaster Risk Resilience among India, Nepal, and Sri Lanka,' funded by the Asia-Pacific Network for Global Change Research (refer figure 1). Under the project, the case study areas were identified and finalised based on multi-dimensional criteria, namely, exposure to disaster and climate risks; presence of vulnerable/marginalised groups including tribal and Indigenous population, women; high dependence of livelihood opportunities on natural resources; depletion/degradation of natural resources and ecosystems; low development indices (health, education, employment opportunities), among others. This required a thorough review of prevailing disaster management and climate action plans, demographic and census reports, reports on developmental programmes and welfare schemes along with temporal analysis of land use and land cover maps.

The study employed a qualitative, participatory approach through FGDs, aimed at eliciting diverse stakeholder perspectives in a structured yet interactive setting. The method was selected for its ability to

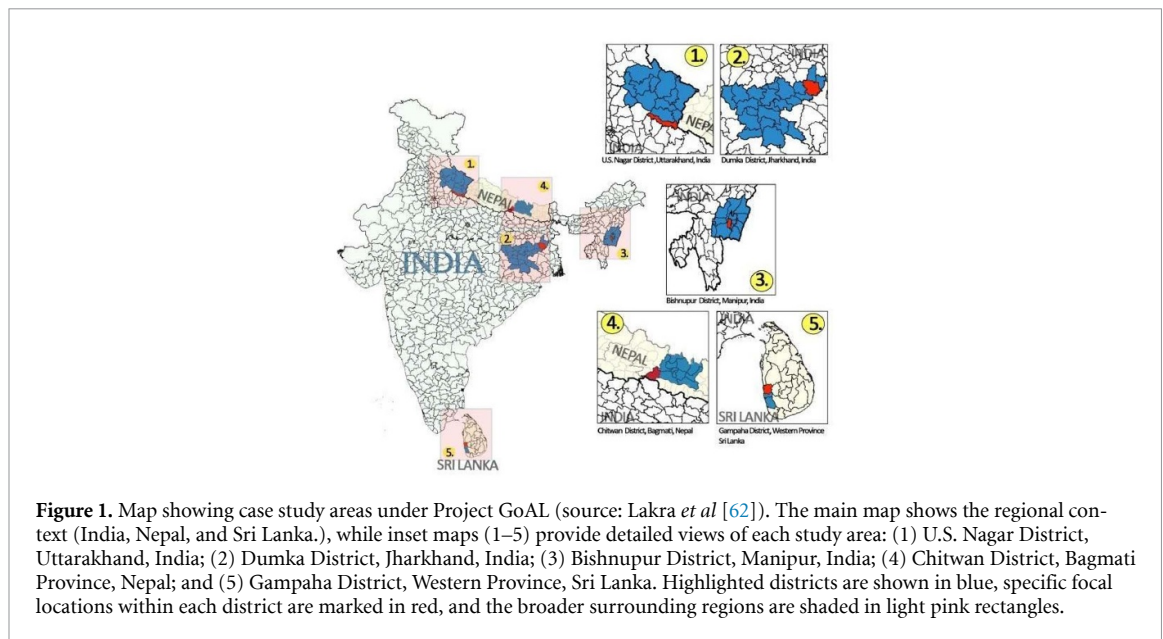
Table 1. Adaptive strategies across regions.

Geography/context	Climate risk/development context	Adaptive strategies identified	Citation
South Asia: Bangladesh, India, Pakistan, Nepal, Bhutan, Maldives, Sri Lanka	Community resilience across floodplains, islands, mountains, and coastal regions	Grassroots initiatives, local institutional empowerment, traditional knowledge use, nature-based solutions, technology adoption, alternative livelihoods, rainwater harvesting, Sri Lanka's cascading tank system, mangrove protection in Odisha, community-based drinking-water management in Himalayan towns	[51]
India: disaster-prone regions including Odisha, Bhuj, Pondicherry, tsunami-affected and drought-prone areas	Multi-hazard disaster risk, cyclone, earthquake, tsunami, drought, and coastal fishing risks	Community-owned rural telecentres, early warning systems, local-language dissemination, community IT volunteers, women-led information centres, telemedicine, tele-education, weather information, agriculture advisories, and e-governance	[49]
Bangladesh: Mongla coastal region	Salinity, unsafe drinking water, and climate-vulnerable coastal livelihoods	Rainwater harvesting at household, community, and public-building levels; use of traditional rainwater harvesting with affordable filtration; maintenance training; courtyard meetings on water safety, rationing, hygiene, climate effects, and rainwater preservation; street theatre and school campaigns	[20]
Nepal: Tarai-Madhes	Agrarian stress, climate stress, irrigation insecurity, migration, caste/class/gender inequality	Male out-migration as a household adaptation strategy; demand for irrigation technologies, tube wells, dams, roads, electricity, agricultural inputs, and scientific advice; older collective labour, common-pool resource management, and mud-dam construction remembered as earlier adaptive systems	[16]
Sri Lanka/South Asia regional case evidence	Water scarcity, dry-zone water management, and community resilience	Cascading tank systems are identified as a community-relevant water-management and resilience practice within South Asian community-driven climate resilience examples	[51]
Ghana: coastal communities	Coastal erosion, sea-level and livelihood risk	Cocoa leaf-wall and fibre units, seawalls and gabions, stone breakwaters, bamboo revetments, tree planting along coastlines, sandbags, palm-wood barricades, landfilling, concrete sea walls, wooden walls, and coconut leaf walls	[52]
Northern Ghana: smallholder farming	Drought, rainfall variability, crop and livelihood stress	Use of neem, manure, agroforestry, mixed farming, and crop diversification. Strategies vary by locality: Nandom prioritizes neem and manure, Savelugu agroforestry and mixed farming, and Bongo crop diversification	[39]
North-Western Ghana: Fulani herders	Pastoral climate stress, grazing scarcity, water scarcity, livestock stress	Mobility patterns, diversifying feed sources, division of labour, and stress management. Specific practices include circular and migratory movement, pruning tree branches, using crop residues, dewfall grass sprouts, shaded kraals, larger kraals, and sub-herd formation	[53]
Zimbabwe/South Africa policy and community contexts	Climate variability, seasonal uncertainty, harvest risks, and policy gaps in IKS integration	Indigenous early-warning systems; prediction of seasons through animal behaviour, sounds, moon haze circles, star movements, wild-fruit abundance, and plant flowering; organic farming, bamboo planting, tree planting, mulching, soil conservation, land conservation, and natural-resource protection	[54]
Aotearoa New Zealand: Māori communities	Managed retreat, flooding, coastal risk, land justice, and cultural continuity	Māori-led adaptation planning, ecosystem restoration, co-governance, culturally grounded relocation, use of surplus Crown land, rebuilding marae and homes to higher standards, restoring wetlands, flood protection, keeping hapū together, and protecting whenua, wai, moana, forests, fisheries, and mahinga kai	[55]

(Continued.)

Table 1. (Continued.)

Geography/context	Climate risk/development context	Adaptive strategies identified	Citation
Alaska Native communities	Permafrost thaw, erosion, flooding, storms, usteq, and severe environmental change	Protection-in-place, managed retreat, community relocation, erosion control, infrastructure protection, rebuilding housing and public infrastructure at safer sites, maintaining kinship networks, and community-based monitoring of erosion, storms, thawing permafrost, flooding, and usteq	[56]
Southeast Alaska: Kake Climate Partnership	Food sovereignty, salmon streams, shellfish safety, and local climate services	Ocean monitoring by residents; tracking pH, salinity, temperature, fecal coliform, metals, mercury, and shellfish tissue indicators; planned stream monitoring combining Traditional Knowledge and Western science for salmon streams	[29]
Somalia/Horn of Africa water governance	Water scarcity, pastoral vulnerability, regional water insecurity	Stronger regional partnerships, inclusive governance, integrated water-resource management, transboundary water cooperation, reliable weather and water information for pastoralists, safe drinking-water access, community health protection, and locally tailored climate-data communication	[57]
Global/Indigenous and local knowledge review	Disaster preparedness, livelihood risks, agriculture, water, fisheries, food storage, and cultural conservation	Indigenous weather prediction, early warning, disaster preparedness, religious/cultural conservation practices, agriculture-based adaptation, food storage, migration, transhumance, fishing knowledge, water-resource management, medicinal plants, income diversification, and combining IK with scientific forecasting	[41]
Indo-Pacific region	intensifying climate risks, including accelerating sea-level rise, extreme weather events	Co-production of knowledge, community-led climate planning, use of traditional ecological indicators	[22]
Central & South Asia (rice-growing regions)	rainfall variability and temperature stress	Indigenous farming calendars, crop diversification, traditional water management	[12]
Central Sulawesi, Indonesia	Post-disaster reconstruction	Community decision-making, traditional housing designs, collective labour systems	[58]
Nepal	Climate adaptation	Indigenous coping strategies differentiated by gender, caste, and livelihood.	[35]
Pangandaran, Indonesia	Disaster communication	Oral traditions, local warning signals, community media	[58]
Sundarbans (India–Bangladesh)	Mangroves	Traditional mangrove stewardship, customary harvesting rules	[59]
Multiple case studies (Global South)	—	Participatory mapping, mental maps, local spatial knowledge	[49]
Central Nepal		Intergenerational knowledge transfer, blending scientific & indigenous knowledge	[35]
Himalayan region	Glacial Lake outburst, ice avalanches, landslides, or intense precipitation	Traditional flood markers, communal infrastructure maintenance	[60]
South Sulawesi, Indonesia	Tsunami	Community monitoring, Indigenous forecasting indicators	[58]
Canadian Arctic (Inuit Settlement Region)	The Arctic is projected to warm at more than twice the global average.	Community-based adaptation built on Indigenous knowledge, participatory governance, and transparent partnerships,	[61]



uncover both consensus and divergence in viewpoints, allowing participants to co-create insights through dialogue. Sessions were facilitated by community knowledge partners and case study lead while documentation and synthesis were coordinated by the RAs of respective case studies. Discussions were conducted about the local language of the community (Eg; Santhali language is used in Jharkhand, Meitei language in Manipur, Hindi and Kumaoni in Uttarakhand, Nepali in Nepal and Sinhala in Sri-Lanka), and summarized anonymously.

For each case study, separate men and women groups were formed (10–11 participants in each group) to ensure diversity and capture gendered narratives and experiences for capacity building and adaptation strategies. Each FGD lasted approximately two hours per session according to the availability of the local people. For each session, a brief presentation was used to introduce the project and share examples from similar case studies, followed by six thematic discussion rounds, plus opening and closing reflections. Observational notes, where permitted and audio/video recordings were used to ensure accuracy of reporting.

State-District-Block-Village level workshops were then conducted in which participants jointly reviewed each strategy and agreed which actor should be primarily Responsible for on-ground execution, which institution is Accountable for coordination and resource allocation, and which stakeholders need to be Consulted or Informed during planning and implementation. Facilitators guided the discussions using a standard RACI template, while research associates documented the agreed role assignments and any justifications raised by participants. The completed matrices were synthesized into RACI tables which present a context-specific community-based adaptation strategies in the study areas.

5. CCA techniques in case study areas

The study of Indigenous techniques in case study areas aimed to create co-learning of global research from different APN countries (India, Nepal, Sri Lanka & Japan) on adaptive transformation in Climate Change (CC). The case study regions of the project are as follows;

1. India—Udham Singh Nagar District, Uttarakhand
2. India—Dumka District, Jharkhand;
3. India—Bishnupur District, Manipur;
4. Nepal—Chitwan District, Bagmati Province
5. Sri Lanka—Gampaha District, Western Province

In all the 5 case study areas, the project was implemented in collaboration with local stakeholders keeping the local communities at the core. Various relevant community-based participatory tools were

leveraged for doing so. For example, in Udham Singh Nagar (Uttarakhand, India), to gather and process baseline data, field surveys were conducted. The development of case studies and field-based participatory methods was used by community trainers. Visual documentation, focus groups, and participatory mapping were all carried out. In Dumka (Jharkhand, India), participatory research methodologies were used to undertake baseline assessments. Focused group discussions for data collection were facilitated by community trainers. The impacts of climate change and disasters were determined by gender. The results influenced techniques for DRR and adaptation that were applicable locally. In Bishnupur (Manipur, India), community-driven risk-ranking exercises and participatory risk mapping were carried out. Participatory storytelling and content creation were encouraged by community trainers. Vulnerabilities and adaptation abilities specific to gender were recorded. The case study backed egalitarian and context-specific resilience planning. In Chitwan, Nepal, community trainers fostered community participation and collected baseline data. Impacts of climate change and disasters that differed by gender were examined. Adaptive transformation plans based on evidence were produced by the case study [63]. In Gampaha, Sri Lanka, tools for gender-sensitive risk communication and participatory mapping were created. Focus groups and participatory research were led by community trainers. Disaster risk was determined by gender. Strategies for DRR that are applicable locally were informed by the case study. Cross-learning between APN nations was facilitated by the reference case. Extreme weather events like floods have caused millions of fatalities and continue to cause tens of billions of dollars of direct economic loss each year [64]. Identifying the areas at risk of river flooding, urban flooding, and coastal flooding is a complicated process, which depends on their causes.

It is well known that flood risk increases with climate change, and that risk is dynamic, constantly changing with changing conditions [65, 66]. This study specifically focuses on extreme events like floods, drought, heat wave, wildlife conflicts which are common and cause disaster risks to local communities in all the case study areas of India, Nepal, and Sri Lanka.

The literature-based case study and expert inputs through hybrid mode were also sought in India, Nepal, and Sri Lanka, which share similar cultural contexts in addition to their economic and climate change and disaster risks and were therefore adopted as case study areas for this study.

FGDs were conducted in multiple rounds across the study sites to capture variation in local experiences over time. The specific months were selected based on the availability of community members and the local context, including livelihood patterns, agricultural calendars, and cultural practices, so that the discussions could be held when participation was most feasible. In each location, the FGDs were conducted in the local language with the support of community knowledge partners and were organized in small groups of 5–6 participants to ensure that everyone had an opportunity to express their views. FGDs were carried out from the beginning of the research. In the initial stages, discussions were held at the ward/village level with corresponding chairpersons, representatives of the study areas, and community members. Later, further information was obtained from workshops organized in block/district/state, which included scholars, government representatives, researchers, representatives from NGOs and INGOs, and local communities. In which participants were divided into three equal groups and requested to make conclusions based on the theme. Furthermore, a short transect walk was also conducted in the villages before the FGDs. The discussions were organized as follows: in Bishnupur, Manipur, they were held in two rounds, first online in June 2025 and later in the field in August 2025, coinciding with the kharif monsoon cropping season; in Chitwan, Nepal, they were held in January and February 2024, during the winter-to-pre-spring agricultural transition; in Dumka, three rounds were held in July 2024, September 2024, and January 2025, covering key phases of the monsoon-dependent cropping cycle; in Udham Singh Nagar, two rounds were held in December 2023 and March 2024, around the rabi and spring transition period; and in Gampaha, Sri Lanka, discussions were held in August 2024 and November 2024, corresponding to the seasonal shift toward the Maha monsoon.

The following techniques were derived from FGDs conducted under the GoAL project in 2023–2025 [62] with ILCs in Bishnupur (Manipur), Chitwan (Nepal), Dumka (Jharkhand), Udham Singh Nagar (Uttarakhand) and Gampaha (Sri Lanka), capturing locally grounded adaptation practices and knowledge systems.

5.1. Udham Singh Nagar District, Uttarakhand

The Tharu community's reliance on agriculture heightens their vulnerability to unpredictable rainfall and temperature changes. To cope with these shifts, farmers reported adjusting their agricultural calendars, often delaying sowing by approximately 15–20 d, as revealed in FGDs with Tharu households. Tharu people worship mainly their Tribal Goddess (The Earth), called '*Bhumsen*' in their folk language [67], and practice keeping and maintaining sacred groves as a cultural and spiritual practice. It acts as a

volunteer-based conservation method for the environment, which in turn helps to ensure ecological stability and resilience. Communities prepare their own organic manure and fertilizers using dry leaves, animal waste, kitchen scraps, and other biodegradable materials, consistent with broader evidence of organic, low-external-input farming among Tharu communities in the Terai region of Udham Singh Nagar District. The community also shared that their elders predict impending rain through the changing behaviour of ants. Elders say that if you see ants building their mounds higher or building them from different materials, this might signal the coming of rain, though scientific experimental evidence on ants' ability to forecast rain remains limited.

Adjustment of agricultural calendars: Delaying planting by about 15–20 d to align crop seasons with the unpredictable rainfall patterns.

As one farmer explained, *'Earlier we used to sow on fixed dates, but now the rains are confused, so we delay planting by about two to three weeks and watch the sky first'*

Sacred grove protection: These were places where the sacred groves were protected and conserved as part of the worship of Bhumsen, serving as a means by which the community conserved nature.

A participant noted, *'This grove belongs to Bhumsen, our mother earth goddess; no one is allowed to cut trees or hunt here.'* Thus highlighting how sacred groves function as a volunteer-based conservation system that supports ecological stability and local resilience.

Organic soil fertility management: Preparation and application of organic manure or fertilizer from dry leaves, animal droppings, kitchen wastes, and other biodegradable substances to cut reliance on external resources.

As one-woman farmer described, *'We make our own manure from dry leaves, cow dung and kitchen waste; we do not depend only on market fertiliser'*

Low-External-input farming system: Continuing with traditional methods of agriculture that are resource-efficient and adapted to agro-ecological conditions.

Indigenous weather forecasting: Interpretation of ecological indicators, specifically ant activity, for predicting rainfall to inform agricultural practices, based possibly on intergenerational learnings recognized in these practices.

One elder stated, *'When we see ants making their mounds higher than usual, we understand that heavy rain may come soon, so we prepare our fields accordingly'*

Collective environmental stewardship: Volunteer-based participation for protection of the environment is based on cultural & religious norms.

5.2. Dumka District, Jharkhand

According to the FGDs held in Jharkhand, the community participants said that they plant water-intensive crops like rice in low-lying regions (*khets*) and crops like maize, which need minimal standing water, in uphill areas (*Bari*). They added *'In the upper fields, we grow crops like Bhaddhai or Karhani that need less water, while in the lower fields we grow Swarna and Baihard because those areas naturally hold more moisture... Earlier, Baihard dhan grew very well with only gobar khad (cow dung), and the plants used to become tall and strong... Now Baihard is not as strong as before, and it needs more fertilizer and care than it used to... When the higher fields are planted with Swarna and fertilizer flows down, the lower fields also get affected, and the Baihard crop grows too fast but becomes weak,'* indicating that there are disruptions to the traditional cropping practices due to changes in climatic conditions and inputs.

Respondents discussed using a variety of animal wastes, including adding cow dung to soil to raise its organic content. Quoting the community members *'When the soil becomes hard and dry, we run the cattle... Nowadays tractors, so that the land becomes porous again. We spread wood ash, dried leaves, cow dung ash, or even gointha ash on the field to soften the soil and protect the crop. Sometimes we also use Palash leaves in the field, because they help when the soil needs moisture and care.'* Another member added *'We sprinkle the ash when the seeds are sown, and again when the saplings are a few inches tall, because it helps the soil breathe and also works like an insecticide'* suggesting the use ash as a low-cost, locally available indigenous multi-purpose input during sowing and the early growth phases to improve soil quality - and help prevent pest attacks. To further enhance soil fertility after harvest, cattle are grazed in the fields.

Community members also pointed out experimenting with intercropping, combining drought-resistant cereal crops like maize with cowpea or bajra in one field. Respondents report that this strategy

enables several harvests from a single field, despite restricted land availability. Due to the delayed advent of the monsoons, community members are coordinating their planting activities with the monsoons, out of need rather than choice.

Farmers have begun using the Swarna rice variety in recognition of the changing environment, quoting *'Changing from Baihard to Swarna has become a local adaptation method for us because the old crop no longer performs as it used to.'* Swarna needs less water to grow than regular rice. Swarna Purvi Dhan 2 (released and notified for cultivation in the state of Jharkhand) is semi-dwarf, high-yielding (5.0–5.5 t ha⁻¹), early-duration (115–120 d), multiple stress tolerant, fertilizer responsive, lodging resistant, with desirable cooking quality traits, and having a long slender grain type. In the face of more erratic rainfall patterns, this change in planting techniques enables them to keep producing rice while maximizing water use. While this helps them to overcome the crop failure, some responses raised the issue of some traditional rice types (called *hudu* in Santali) going extinct, such *Karhani hudu*, which is medicinal rice, particularly for pain alleviation. *Satti hudu*: Rice with a brown hue. White and red rice is known as *saan hudu*; water shortages have made *bhadai hudu* scarce; and *lugu hudu* is a relic from the past.

Use of forest resources: During crop failure, community participants turn to the forest for sustenance. They gather edible leaves to use as vegetables and collect wild mushrooms to supplement their diet and provide essential nutrients. This dependence on forest resources ensures they have a backup plan when faced with food insecurity.

Collective decisions: In a collaborative effort, three villages near to Chigal Pahari Village have collectively decided not to cut down trees in the nearby hills. The women who gather firewood diligently adhere to this rule, quoting *'In our village (Chigal pahari Village), we (women) decided that no one would cut down any trees on Chotta Pahad (small hill). We all know the importance of protecting these trees for future generations. While collecting firewood, we follow this practice because it was decided it collectively.'*

Infrastructure development: Living in a region prone to high temperatures, the community participants have also taken steps to mitigate the risks associated with these extreme weather events. Many households have installed fans in their homes. The increased air circulation provides some comfort during the intense heat.

Assistance from government: The community participants have secured their food supply by leveraging government assistance programs. The subsidized rice distributed at one rupee per kilo acts as a safety net during difficult times, ensuring they have enough to eat even when harvests are poor.

Diversification into non-farm livelihood activities: Other adaptation strategies against changing climate in Dumka include engaging in casual labour to meet food and other household needs; selling of live-stock; timely planting; and undertaking small livelihood activities such as selling handicraft products made of leaves, running shops, local restaurants, and kiosks, and selling crops, among others.

5.3. Bishnupur District, Manipur

The agricultural and fishing communities of Bishnupur, Manipur, offer a good example for climate adaptation rooted traditionally and supporting sustainable practices [68]. Local innovations such as the reuse of dried crop stubble for organic mulching, rotational and multi-cropping systems, and eco-friendly pest control using wood ash reveal a deep ecological consciousness that foregoes formal adaptation frameworks. Similarly, practices like identifying 'soft fungi' zones for sustainable fishing in Loktak Lake and the use of sodium bicarbonate to maintain inland fishery health show local knowledge that supports livelihoods. These approaches align with the IPCC's ecosystem-based and behavioural adaptation, offering low-cost, scalable solutions that reduce climate vulnerability while enhancing agricultural productivity [69]. When strategically integrated into programs like the Manipur state action plan on climate change (SAPCC) under Directorate of Environment and Climate Change, Govt of Manipur, India (<https://imphaleast.nic.in/directorate-of-environment/>), and the National Mission on Sustainable Agriculture (NMSA), these practices can help in the shift toward climate-resilient rural livelihoods across India's northeast. The action plan aims to integrate climate adaptation and mitigation into the state's development planning while protecting its fragile mountain ecosystems, biodiversity, agriculture, and vulnerable communities. Under SAPCC (Version 2.0) 2025, adaptation and mitigation measures are planned at local levels, like climate-resilient infrastructure development to protect vulnerable populations, and natural ecosystems at Loktak Lake (a prominent wetland which has high livelihood dependency). The department uses high-resolution historic weather data for climate projections and informed

decision making. Project collaborators used qualitative tools such as storytelling and FGDs, that indicate similar temporal trend of changes in climatic parameters and associated impacts at the local level. The various practices in Bishnupur as given below, show how local agricultural and fishing communities in Bishnupur have historically adapted to climate shocks and environmental shifts:

Weather prediction and traditional knowledge: Communities in Manipur can predict weather through wind direction and also by looking at the hilly region with the formation/movement of the cloud; they predict the rainfall. Another traditional way of predicting the climate for the whole year is through the bird behaviour of making a nest. If birds build their nests high in the trees, it is believed to be a lighter rainfall year. But if they build their nests in the lower part, they predict heavy rainfall.

Use of agricultural residue for soil enrichment: After harvest, farmers collect the remaining crop stubble (grass), dry it, and then apply it as organic manure to enrich soil fertility for the next cropping cycle. A middle-aged farmer shared, *“After harvesting, we never waste the crop stubble. We dry the grass and spread it back on the field as manure for the next season. My father told us, ‘If you return the residue to the soil, the land will not get tired and will be healthy for the next crop.’*

Transition to multi-cropping systems: Many farmers have shifted to double or triple cropping and rotational cropping throughout the year to optimize land use, increase profit, and diversify risk amid climate variability.

A farmer who has a big family shared, *“Earlier we took only one crop, mainly rice, but now we plant two or three crops in a year so that even if one fails due to erratic rain, the others can support my big family from starving.”*

Farmers practice paddy-cum-fish culture: Farmers increasingly shifted to aquaculture as an adaptation strategy and adopted paddy-cum-fish culture and also integrated makhana plantations for livelihood diversification. Ducks are also reared alongside fisheries, as their droppings serve as natural fish feed, providing parallel income through fish and poultry.

Use of cow dung as organic fertilizer: Cow dung was traditionally used as a natural fertilizer, enriching soil nutrient content. However, declining livestock numbers have made it difficult to use.

A female farmer shared, *“Earlier every household had cattle and we used cow dung regularly to the fields to keep the soil fertile. Now there are fewer animals, so it is difficult to get enough cow dung like before.”*

Use of wood ash for pest control: To protect crops from pests, farmers used to burn wood and spread the ash across fields, a low-cost, eco-friendly pest deterrent with soil-enriching benefits.

A male farmer shared how they do not rely on market-based fertilisers and instead convert their kitchen wet waste, cow dung and dry leaves into manure, ‘

Sustainable fishing knowledge: Fishermen in Loktak Lake have developed ecological knowledge passed down by their elders, identifying ‘soft fungi’ zones as indicators of fish-rich areas while avoiding ‘hard fungi’ zones with fewer fish. This shows traditional wisdom’s deep understanding of aquatic microecology.

A fisherman shared, *“Our elders taught us to look for the “soft fungi” places; those areas have more fish and we avoid the “hard fungi” zones where there are very few. By reading the water and fungi patches, we know where to catch fishes without disturbing the lake too much.”*

Use of sodium bicarbonate in inland fisheries: Farmers use sodium bicarbonate (‘white powder’) in small inland water ponds to help reduce water pollution and maintain aquatic health for better fish yield.

5.4. Chitwan District, Nepal

FGDs from the study area Chitwan, Nepal reported elevated granaries and improved corn storage structures as important measures to address food insecurity and post-harvest losses, ensuring better food preservation during extended dry periods [70].

The transition toward climate-smart farming continues to be fostered through peer learning and farmer-to-farmer knowledge exchange, which strongly influence the choice of crop varieties and agricultural practices. Community forestry is another effective participatory strategy for forest protection and management. The indigenous system of forest management not only conserves forest biodiversity but also generates money for the community.

For irrigation purposes, some of the community people use *Sancho*, a device made from a tree trunk that is inserted in an irrigation canal to distribute water to smaller canals that provide water to the farming area, which is shared by the farmers. The promotion of local and indigenous water management knowledge, technologies, and practices open up possibilities for incorporating them into CCA strategies, particularly in terms of making irrigation systems more resilient to support local livelihoods and food security in the face of increased climate change stress [71].

Some indigenous and ancestral knowledge that is still prevalent in Nepal's communities includes using cattle urine as pesticides, manufacturing rope from tree bark, pottery making, drying foods to save for the future to prevent food insecurity, and so on. The community shared that these practices are passed down from their ancestors, which help in conservation and livelihood sustenance.

Enhanced post-harvest storage technologies: Construction of elevated granaries and improved corn storage structures in order to limit losses due to spoilage, pests, and drying. Elevated granaries help us to protect our food, mainly paddy and corn, against water damage during floods,' said the farmers.

Sharing knowledge: Peer learning approaches help shape crop choice, agricultural practices, and climate-smart practices adoption independent of the conventional extension services. 'We learned more advanced agricultural practices, the use and selection of seeds, as well as pesticides, during visits to various agricultural farms organized by our local Krishi Samuha and through discussions with farmers from nearby villages,' said the farmers during the FDGs.

Management of forest communities: Community-centred forest protection systems and management approaches that ensure biodiversity and collectively produce income for social well-being. After the formulation of the community forest concept, each community regularly checks and protects the forest. The construction of fences around community forests reduces human-wildlife conflict (Poudel S and Vergalli S [72]). 'We can regularly get fodder for our livestock from community forests, and earn money from tourists through Homestays and by working as nature guides for them.'

Indigenous irrigation systems (Sancho): Locally manufactured wooden water diversion systems for the efficient distribution of water from the canals to small watercourses, enhancing irrigation systems' resiliency.

Traditional pest management: The use of cattle urine and other natural materials as cheap and eco-friendly alternatives to pesticides. One of the farmers said, 'Our parents previously used a mixture of cow urine, ash, chili powder, Titepati, Neem leaves, etc, to control pests in our crops.'

Natural material utilisations: Rope manufacturing through tree bark and ceramics, which is crucial in creating jobs and using renewable materials.

Food preservation methods: Drying foods for preservation, as well as storing them for future use as an adaptation mechanism to cope with seasonal deficiencies in food security during times of climate change-induced variability in climate conditions. Dried foods like Gundruk, Maseura, dried mushrooms, radishes, and cauliflower are often stored and used as vegetables during food shortages. We love the taste of gundruk and mushroom pickle during the rainy season, and they are easy to cook,' said the farmer.

Intergenerational knowledge transfer: Oral and practical transfer of indigenous knowledge that enhances long-term adaptability and cultural continuity. Wearing white clothes while going to the forest, using traditional techniques to catch fish, and using medicinal plants such as bhojo, pudina, and turmeric have been passed down from generation to generation.

5.5. Gampaha District, Sri Lanka

In Sri Lanka, inferences drawn from FGDs with local communities highlights the indigenous adaptation practices play an important role in responding to climate variability and environmental change. Farmers shared that the use of mulching, crop rotation, agroforestry, and organic manure are some of the agricultural practices that help them in sustaining the climate change impacts. Such practices help in enhancing soil organic matter and improved water retention, and boosting biodiversity, as well as carbon sequestration, which also helps in adapting to and mitigating climate change. The community further noted the significance of traditional knowledge regarding crop rotation and natural pest control approaches to remedy decreased soil nutrient quality and decreased crop yields. This approach to low

external inputs makes farming systems less reliant on chemical fertilizer and pesticide inputs, improving climate stress resilience [73].

-Water scarcity is commonly mentioned as one of the important challenges quoting, 'Rainfall has become unpredictable and during dry months wells dry faster than before'. The communities were found to be using traditional water-saving systems like the tank cascade system as an important method to adapt to the conditions. As explained by the respondents, these systems help to control the surface runoff, increase the groundwater recharge, and provide water in need. The fisherman showed that traditional fishing practices, in relation to seasonal fishing knowledge, still inform fishing activities in a manner that contributes to the conservation of marine biodiversity.

Sustainable farming practices: Community discussions showed that practices like mulching, diversified cropping, agroforestry, and organic soil amendments are still central to managing climate-related risks in farming.

Locally embedded knowledge related to soil and pest management: under declining soil productivity, traditional soil quality and pest management have been maintained through the inherited knowledge systems that rely on methods other than chemicals.

Traditional water governance and storage systems: Communities often cited water stress, which has been managed using traditional water management structures for a long time in taming runoff, recharging groundwater, and allowing supplies to last throughout the dry months.

Traditional fishing practices: Fishing communities reported that timing fishing activities according to seasonal ecological patterns continues to support marine biodiversity conservation and the long-term sustainability of fish stocks. During the FGD, it is noted 'Beach seine fishing, locally called as *Madal* support to long term sustenance of fish stocks as it is seasonal and size selective.'

5.6. Adaptation strategies and dimension of resilience

Various risk management and adaptation strategies observed in the study areas can be linked with different dimensions of resilience, namely, physical resilience, social (community) resilience, economic resilience, ecological resilience, and institutional (governance) resilience. While most of these can be classified as absorptive strategies which enable anticipation, absorption, prompt response and rapid recovery from shocks, others are transformative in nature. The latter are aimed at addressing systemic drivers of risk. They are often long-term strategies which are governance/institutional-oriented. Table 2 below categories some of the key strategies from the study areas using this lens.

6. Implementation mechanism and accountability

Output of Section-II yielded a list of local indigenous techniques adapted in the Five case study areas that were then applied in the RACI (Responsible–Accountable–Consulted–Informed) matrix as a role-clarification tool to translate community identified adaptation strategies into an implementable governance framework. This analysis provided a specific and policy-relevant assessment, and to further implement institutional climate adaptation initiatives, ranging from local to regional.

6.1. Methodology

The RACI approach is widely used in sustainability and climate-risk governance to define clear responsibilities, minimize overlaps and gaps between institutions, and strengthen accountability for sustainability and adaptation actions [48]. In each case-study, the list of adaptation strategies derived from FGDs and participatory exercises served as the starting point.

The RACI (Responsible, Accountable, Consulted, Informed) Matrix clarifies who is responsible for carrying out tasks (R), who is accountable for ensuring their completion (A), who needs to be consulted for input (C), and who must be kept informed (I) [74]. In gender-responsive climate adaptation, this structured approach enhances coordination among ministries, NGOs, and local communities, ensuring equitable participation and efficient resource allocation [75]. To ensure effective implementation of gender-wise adaptation strategies, a RACI matrix is a valuable tool for defining roles and responsibilities in decision-making and execution (PMI 2021 [76]).

Table 2. CCA strategies and Resilience type.

Strategy	Study area	Resilience dimension	Type of resilience
Preservation of sacred groves	Uttarakhand, India Jharkhand, India	Social Ecological	Transformative
Seasonal adjustment of agricultural calendars	Uttarakhand, India	Economic	Absorptive
Collective environmental stewardship	Uttarakhand, India Jharkhand, India	Social Ecological	Transformative
Using folk arts- folk songs, painting, etc for risk communication	Uttarakhand, India; Jharkhand, India	Social	Absorptive
Use of agricultural residue and animal waste for soil enrichment and pest management	Uttarakhand, India; Jharkhand, India;	Ecological	Absorptive
Weather prediction through bio-indicators	Manipur, India	Ecological	Absorptive
Multi-cropping pattern and crop rotation	Uttarakhand, India; Manipur, India; Gampaha, Sri Lanka	Economic	Absorptive
Dependence on forest produce during crop failure	Jharkhand, India	Social	Absorptive
Diversification into non-farm livelihood activities	Jharkhand, India	Economic	Absorptive
Livelihood diversification through paddy-cum-fish farms	Manipur, India	Economic	Absorptive
Community-forestry for forest conservation	Chitwan, Nepal	Ecological Institutional	Transformative
Indigenous irrigation systems- <i>Sancho</i>	Chitwan, Nepal	Physical	Transformative
Elevated granaries and storage structures	Chitwan, Nepal	Physical	Absorptive
Traditional water-saving systems like the tank cascade system	Gampaha, Sri Lanka	Ecological	Transformative

A case study-wise detailed tabular format is presented to suggest key responsibilities and accountability for the adaptation measures.

The nomenclature adopted here in the matrix is as follows:

NG: National Government/Line Ministries

DM: Disaster Management Centre

(DMC)/Disaster Management Authority

LA: District & Local Authorities (Gampaha)

Uni: University/Lead Institution

Cy.: Community Trainers/Knowledge Partners

N/S: NGOs/Civil Society/Self Help groups

R/I: Regional/International Partners

DA: District level Authorities

CG: Central Government

SG: State Government

To effectively implement the strategies for addressing flood risk impacts, various actors are identified at different levels: national, state, local, NGO, SHG, institutional, and community. Each actor's role is defined using a RACI matrix, a framework that clarifies responsibilities in terms of being Responsible (R), Accountable (A), Consulted (C), or Informed (I).

- Responsible (R): Those directly tasked with carrying out specific actions or strategies.
- Accountable (A): The authority that ensures the task is completed and is answerable for its success.
- Consulted (C): Individuals or group of people whose input is sought to inform decisions or strategies.
- Informed (I): Stakeholders who are not directly participating but are informed of developments.

Table 3. RACI matrix of flood risk management strategies for Udham Singh Nagar District, Uttarakhand.

Strategy type	NA	DA	LA	U/R	Cy	N/S	R/I
<i>Social</i>							
Peer-support groups through SHGs for safe spaces	I	C	A	C	R	C	I
Community mental health promoters for first-line support	I	C	A	C	R	C	I
Public messaging via radio, fairs, cinema halls	C	C	A	C	R	C	I
Wellness activities (yoga, storytelling circles)	I	C	A	C	R	C	I
Training community champions (female volunteers)	I	C	A	C	R	C	I
School & community-based mental health education	C	C	A	C	R	C	I
Telecounseling via frontline workers	C	C	A	C	R	C	I
Catch-up classes & flexible school hours	I	I	A	C	R	C	I
Training teachers & health volunteers in trauma counseling	C	C	A	C	R	C	I
Awareness & prevention campaigns for vector-borne diseases	I	C	A	C	R	C	I
Integrate mosquito control with mobile health camps	I	C	A	C	R	C	I
<i>Physical</i>							
Improve drainage systems to reduce stagnant water	C	C	A	I	C	C	I
Temporary learning spaces with WASH facilities	C	C	A	I	C	C	I

For each strategy, roles are allocated to ensure clarity and effective collaboration. National and state governments create policies and allocate resources, while local governments focus on implementation and coordination with institutional actors. NGOs and SHGs engage directly with the community to ensure the strategies address local needs, facilitate participation, and promote inclusive solutions. Research institutions provide research, technical expertise, and monitoring frameworks, while community members play an active role in identifying issues and implementing solutions. Using the RACI matrix ensures that all stakeholders understand their responsibilities, fostering better coordination and efficiency in addressing climate change impacts through gender-focused strategies.

6.2. Case study: Udham Singh Nagar, Uttarakhand, India

Indian Institute of Technology Roorkee (IITR), in collaboration with Resilience Innovation Knowledge Academy (RIKA) India, serve as nodal institutions for thematic research, strategy development, and learning processes for the Udham Singh Nagar case study. However, in future other local research institutes can take up the role. Community trainers identified as locally appointed community knowledge partners and trained through the training of community trainers (ToCT) process are Responsible (R) for field-level data collection, participatory risk mapping, community consultations, and co-design of gender-sensitive CCA and DRR strategies. Local governments, including Gram Panchayats, block-level institutions, and the district administration in Udham Singh Nagar, are Accountable (A) for community-level implementation, coordination, and stakeholder engagement. District, state, and national authorities retain policy formulation and coordination roles rather than direct operational control. Flood risk actions remain embedded within an integrated CCA-DRR framework, guided at the state level by the Uttarakhand State Disaster Management Authority (SDMA). The following matrix in table 3 details the RACI matrix for the Udham Singh Nagar case study.

6.3. Case study: Dumka, Jharkhand, India

For the project, the Indian Institute of Technology Roorkee (IITR), in collaboration with Jawaharlal Nehru University (JNU) serves as the nodal institution for Jharkhand case study. These institutions

Table 4. RACI matrix of strategy type and role of institutions for Dumka District, Jharkhand.

Strategy type	NA	DA	LA	U/R	Cy	N/S	R/I
<i>Social</i>							
Village level CCA visioning, mapping, resource mobilisation plan and communication through Traditional Santhali Wall Painting	I	C	A	C	R	I	I
Peer-support groups through SHGs for safe spaces	I	C	A	C	R	C	I
Community mental health promoters for first-line support	I	C	A	C	R	C	I
Public messaging and learning via Wall painting, Community radio, Podcast, Folk Songs, fairs, cinema halls, flash cards	C	C	A	C	R	C	I
Wellness activities (yoga, storytelling circles)	I	C	A	C	R	C	I
Training community champions (female volunteers)	I	C	A	C	R	C	I
School & community-based mental health education	C	C	A	C	R	C	I
Telecounseling via frontline workers	C	C	A	C	R	C	I
Catch-up classes & flexible school hours	I	I	A	C	R	C	I
Training teachers & health volunteers in trauma counseling	C	C	A	C	R	C	I
Awareness & prevention campaigns for vector-borne diseases	I	C	A	C	R	C	I
Integrating mosquito control with mobile health camps	I	C	A	C	R	C	I
Drainage improvement to reduce stagnant water	C	C	A	I	C	C	I
<i>Physical</i>							
Temporary learning spaces with WASH facilities specially for women	C	C	A	I	C	C	I
Boat/bridge schools during floods	C	C	A	I	C	C	I

partnered with Sido Kanhu Murmu University (SKMU, Dumka) Jharkhand and *Lahanti, Dumka* (meaning “development” in Santhal language), a non-government organisation; and the gram panchayat building long term relationships. Community trainers, later renamed community knowledge partners—Kisan Mitra (Farmer’s Friends), Jal Mitra (Water Friends), Sahiya (frontline health workers), school teachers, and youth volunteers and trained through the ToCT process and involved in research as partners, are Responsible (R) for field-level data collection, participatory risk mapping, community consultations, and co-design of gender-sensitive adaptation and DRR strategies. Local governance institutions, including Gram Panchayats, Block-level offices, and the District Administration in Dumka, are Accountable (A) for community-level implementation, coordination, and stakeholder engagement. State- and national-level authorities retain policy formulation and coordination roles rather than direct operational control. Flood risk actions remain embedded within an integrated framework of CCA and DRR, guided at the state level by the SDMA, Jharkhand.

The following matrix details the RACI matrix for the Dumka case study (table 4).

6.4. Case study: Bishnupur, Manipur, India

For the project, the Maulana Azad National Institute of Technology (MANIT) Bhopal in collaboration with IIT Roorkee (IITR) as a nodal institute for research in Manipur. However, in future other local research institutes can take up the role as the lead for thematic research. Community trainers, identified as locally appointed Community Knowledge Partners are Responsible (R) for field-level data collection, participatory risk mapping, community consultations, and co-design of gender-sensitive adaptation and DRR strategies. Local governance institutions, including Gram Panchayats, block-level offices, and the District Administration in Dumka, are Accountable (A) for community-level implementation, coordination, and stakeholder engagement. State- and national-level authorities like the MoEFCC State of Manipur retain policy formulation and coordination roles rather than direct operational control.

The table 5 list out the RACI matrix for Manipur.

6.5. Case study: Chitwan, Nepal

For the project, Science Hub Nepal and collaborating institutions were the lead for thematic research, strategy development, and learning processes, as described in the Nepal case study. However, in future other local research institutes can take up the role as the lead for thematic research. Community trainers are Responsible (R) for field-level data collection, participatory mapping, and co-design, Local governments are Accountable (A) for community-level implementation and engagement, National and district-level authorities retain policy and coordination roles, not operational control, Flood risk actions remain

Table 5. RACI matrix of strategy type and role of institutions for Bishnupur, Manipur.

Strategy	CG	SG	DA	LA	N/S	U/R	Cy
<i>Social</i>							
Peer-support groups through SHGs for safe spaces	I	C	C	A	R	C	I
Public messaging via radio, fairs, cinema halls	C	C	A	R	I	C	I
Wellness activities (yoga, storytelling circles)	I	C	C	A	R	I	I
Train Atmiyata (female volunteers)	I	C	A	R	C	I	I
School & community-based mental health education	C	A	R	C	I	C	I
Telecounseling via ASHA phones (CBT-lite)	C	A	R	C	C	I	I
<i>Physical</i>							
Temporary learning spaces with WASH facilities	C	A	R	C	C	I	I
Boat & bridge schools during floods	C	A	R	C	C	I	I
Improve drainage systems to reduce stagnant water	C	A	R	R	C	I	I
Ensure menstrual hygiene kits in relief camps	C	A	R	C	C	I	I
Mobile health vans for maternal/reproductive services & anemia screening	C	A	R	C	C	I	I
Subsidized/free flood-resistant boots, gloves, trousers	C	A	R	C	C	I	I
Seasonal mobile health camps post-flood	C	A	R	C	C	I	I
Awareness of ecological impacts of electric fishing	C	A	R	C	C	C	I
Diversify into climate-resilient livelihoods	I	C	C	A	R	C	I
Women-led water monitoring committees	I	C	C	A	R	I	I
Promote bamboo-reinforced resilient housing via SHGs	I	C	C	A	R	I	I
Restore wetlands as natural flood basins	C	A	R	C	C	C	I
Legalize tenant farmer registries for subsidy/insurance access	R	A	C	C	C	C	I
Inventory landless households & facilitate joint land titles	C	A	R	C	C	I	I
Document tribal farmers' horticultural land rights	C	A	R	C	C	C	I

Table 6. RACI matrix of flood risk management strategies for Chitwan District, Nepal.

Climate risk	NA	DM	LA	U/R	Cy	N/S	R/I
<i>Physical</i>							
Mobile health vans for maternal/reproductive services and anemia screening	C	A	R	C	C	I	I
Seasonal mobile health camps	C	A	R	C	C	I	I
<i>Social</i>							
Gender-sensitive flood risk awareness & dialogue	I	A	C	R	R	C	R
Distribution of subsidized or free protective gear	C	A	R	C	C	I	I
Promote diversification into climate-resilient livelihood	I	C	C	A	R	C	I
Train health volunteers and community health volunteers to detect and respond early to climate- risks	C	A	R	C	C	I	I
Conduct awareness programs on nutrition, and heat-related illnesses	I	A	C	R	C	I	I
Community-level awareness on ecological impacts of illegal and electric fishing	C	A	R	C	C	C	I
Formation and strengthening of women-led self-help groups for livelihood and adaptation activities	I	A	C	C	R	I	I
Maintenance of river embankments and flood protection infrastructure	C	A	R	C	I	C	I
Early warning dissemination through FM radio, SMS alerts, and community networks	C	A	R	C	I	C	I

embedded within CCA, DRR, like disaster management committees at local, district, and state levels that coordinate for implementation, awareness, and monitoring. The table below details the RACI matrix for the Nepal as table 6.

6.6. Case study: Gampaha, Sri Lanka

University of Colombo (UC) and partner institutions remain the lead Accountable (A) actors for thematic research, strategy development, academic validation, and cross-learning processes, as outlined in the Sri Lanka case study. However, in future other local research institutes can take up the role as the lead for thematic research. Table 7 presents RACI matrix for Gampaha, Sri Lanka.

Table 7. RACI matrix strategies for Gampaha, Sri Lanka.

Strategy type	NA	DM	LA	U/R	Cy	N/S	R/I
<i>Social</i>							
Climate & flood risk review	A	C	I	R	C	I	C
Gender wise flood risk and vulnerability assessment	C	C	I	A	R	C	C
Participatory risk mapping & local data collection	I	I	C	C	R	C	I
Documentation of lived flood impacts	I	I	I	A	R	C	I
Knowledge dissemination	C	I	I	A	R	C	C
Policy dialogue & feedback loop to governance systems	A	C	I	R	C	I	C
Validation workshops with stakeholders & communities	I	I	C	A	R	C	I
Risk communication & community-friendly tools	I	C	C	A	R	C	I
<i>Human Resource</i>							
Capacity building (ToCT) for flood preparedness & response	I	C	C	A	R	C	I
Monitoring, reflection & learning (adaptive transformation)	C	I	I	A	R	C	C
<i>Institutional</i>							
Development of flood adaptation strategies	C	C	I	A	R	C	C
Development of flood-related DRR strategies	C	C	I	A	R	C	C

7. Discussions

The study proposes a three-step process to institutionalize indigenous techniques employed by local communities as climate adaptation processes. A comprehensive review of the literature revealed that, although limited in number, several approaches have been adopted across Southeast Asia and the Pacific region. These practices highlight the concepts of co-production of knowledge, community-led climate planning, and the use of traditional ecological and indigenous forecasting indicators to enhance adaptive capacity in the face of climate-related adversities. Such approaches promote resilience by co-learning and co-production knowledge bases among community members and facilitate intergenerational knowledge transfer, enabling the integration of scientific and IKSs. The adaptation strategies are both adopted by referring to robust literature review and adopted from local context integrating IKS and cross learning from five case study areas.

Furthermore, evidence from FGDs and household interviews indicates that flood and heat events have multiple impacts on communities. They disrupt agricultural cycles, reduce productivity, and increase the prevalence of waterborne diseases, disproportionately affecting low-income households and women in particular. The analysis reveals cascading impacts across multiple sectors, including crop damage leading to food insecurity, loss of income, and increased psychosocial stress. Field evidence also demonstrates the continued use of adaptive practices such as short-duration rice varieties, elevated homesteads, and community-based labour sharing during flood recovery. These strategies are consistent with Indigenous adaptation patterns identified across other flood-prone landscapes in South and Southeast Asia [8, 9].

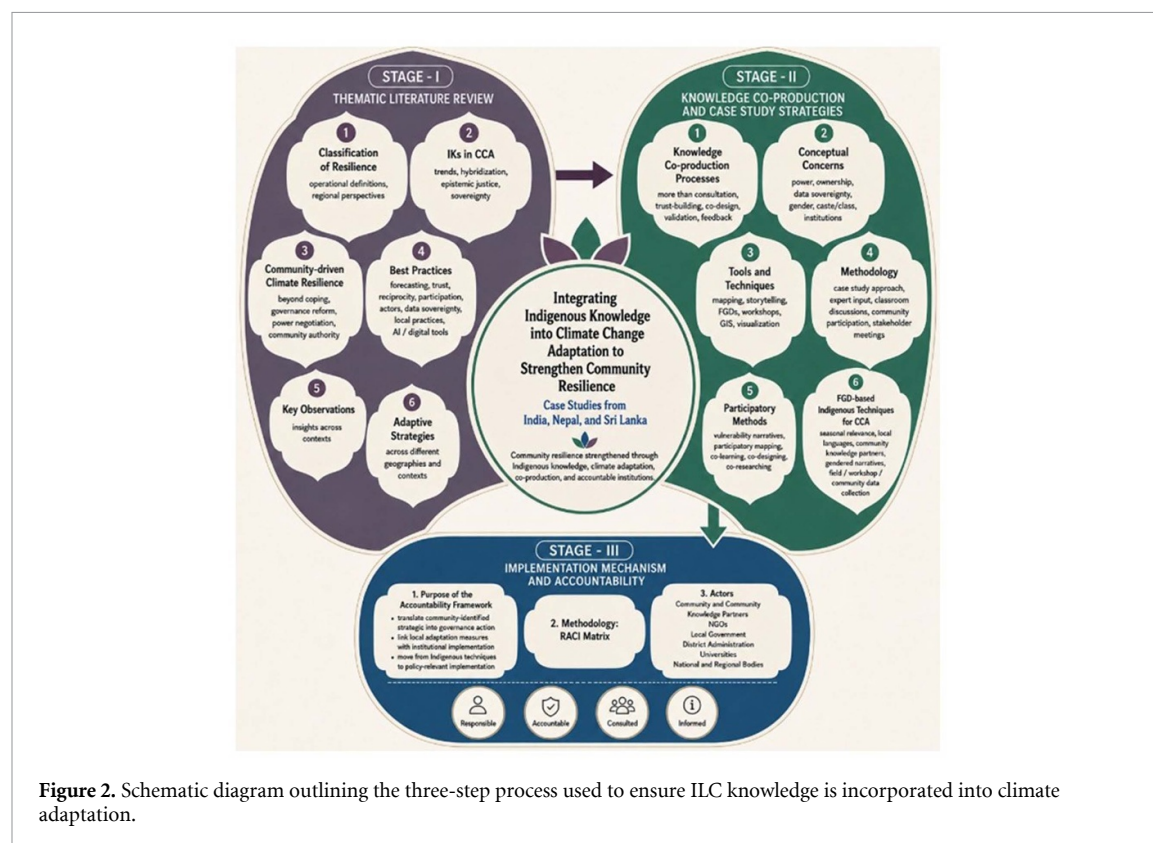
However, these practices are under pressure from environmental degradation and youth outmigration, underscoring the need for policy mechanisms that institutionalize and fund community-led adaptation. At the institutional level, the stakeholder and community perception mapping revealed fragmented coordination between district authorities, local councils, and community-based organisations. Responsibilities for adaptation often overlap or remain unclear, resulting in delayed response and weak accountability. By explicitly assigning roles through the RACI framework, this study provides a practical structure for better coordination where communities act as Responsible agents in local adaptation, state-district departments are Accountable for coordination, and NGOs and research institutions serve as consulted facilitators, ensuring that Indigenous knowledge informs action. Table 8 summaries the case study wise characteristics, key stresses and role of institutions in implementation.

Lessons from case study areas highlight that community-driven adaptation, when supported by spatial evidence and institutional clarity, can significantly enhance resilience across other flood-prone regions.

Overall, the research shows that reducing climate change risk in ecologically vulnerable areas requires more than engineering or relief-based responses, it demands integrated Indigenous systems and coordinated governance. The community-based risk analysis through local decision frameworks, strengthening institutional accountability through tools like the RACI model, and mainstreaming Indigenous knowledge into district planning can together create a more adaptive and equitable management system.

Table 8. Summary of climate stress and implementation strategy.

District	Eco-zone	Dominant agriculture	Main non-farm /industrial activity	Key climate stress	Community-driven adaptation	RACI
Udham Singh Nagar, Uttarakhand	Terai ecological zone	Paddy, wheat, sugarcane	Agro-industrial and manufacturing sector	Heat, water stress, drainage issues	Water-efficient farming, drainage, diversification	Farmers, agro-industry, block departments, NGOs
Dumka, Jharkhand	Rain-fed tribal plateau	Paddy, maize, pigeon pea, vegetables	Sericulture (tassar silk), forest-based activities, mining/construction materials	Drought, rainfall variability	Intercropping, ash use, crop switching, forest coping	Community trainers, SHGs, panchayat, district agencies
Bishnupur, Manipur	Central valley/wet-land	Paddy/rice, fisheries, horticulture	Handloom, handicrafts, fishery-based industries, tourism	Flooding, monsoon variability	Water management, livelihood diversification, cropping adjustment	Community groups, local bodies, fisheries dept., NGOs
Chitwan, Nepal	Terai/lowland plain	Farming, livestock-linked agriculture	Tourism-centred activities, poultry industry, wage labour	Flood risk, rainfall variability	Flood preparedness, farm diversification, occupational shifts	Community, tourism actors, poultry sector, local government
Gampaha, Sri Lanka	Lowland/agro-industrial mixed zone	Paddy, coconut plantations	Apparel/textiles, electronics, machinery	Rainfall variability, flooding	Water management, livelihood diversification, household adaptation	Community groups, local authorities, industrial stakeholders

**Figure 2.** Schematic diagram outlining the three-step process used to ensure ILC knowledge is incorporated into climate adaptation.

8. Conclusions

The study concludes with identifying three-step institutional mechanisms for CCA processes that recognizes and supports the local communities' Indigenous ways of sustaining livelihood and enhancing security against extreme events like floods, drought, heat waves, wild life conflict. It draws on case study areas from diverse geographies that facing similar issues. The figure 2 below depicts the three-step process of CCA.

It is crucial that Indigenous techniques and coping strategies are well supported by robust institutional mechanisms with defined roles. The study proposes a novel methodology that can be adopted by decision-makers in ecologically fragile geographies. The role-based implementing framework enables climate security from the local to global level. The study serves as a proof of concept for adopting a bottom-up approach in facilitating local climate resilience by integrating Indigenous knowledge with participatory mapping tools and governance in local decision-making.

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Data availability statement

Data is shared publicly via a URL/DOI: <https://www.iitr-apn-goal.com/> [76]. The data is part of reports of the project funded by APN.

Ethical statement

The study involved minimal-risk human participation through focus group discussions. Participants' perceptions were documented with Free, Prior and Informed Consent, without collecting or disclosing personally identifiable information. An application for exemption/waiver from full ethical review was submitted to the Institute Ethics Committee of IIT Roorkee, India, and a provisional certificate was received.

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Annexure 1. Comparative classification of resilience: India, Nepal, and Sri Lanka

Resilience type	Working definition/ quote from literature	India	Nepal	Sri Lanka
Climate resilience	[41] define climate resilience as ‘the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner’ (p 1102).	Seen in community-based adaptation, telecentres, early warning, mangrove protection, Himalayan water systems, Ladakh artificial glaciers, Nagaland Ruza system, and Dzumsa governance in Sikkim. Giri <i>et al</i> ([77]) state that Dzumsa plays a ‘pivotal role in resources management, environmental conservation, climate resilience and conflict resolution’ (p 1).	Seen in farmers’ responses to drought, floods, rainfall variability, irrigation failure, and agrarian stress in Tarai-Madhesh. [16] frame vulnerability as exposure to environmental and social stress plus ‘absence of capacity to adapt’ (p 68).	Seen mainly through water-based resilience. The cascading tank system is cited as a traditional water-management practice supporting community resilience in South Asia ([51], p 2).
Climate change adaptation	[41] define climate change adaptation as ‘adjusting to the physical environment or human systems in response to potential or anticipated climatic shocks and their impacts’ (p 1102). Hunter <i>et al</i> [37] similarly define adaptation as ‘the process of adjustment to actual or expected climate and its effects’ (p 1).	India’s cases show both autonomous and planned adaptation: rural telecentres, community IT volunteers, Ladakh artificial glaciers, and traditional ecological systems. Kumar and Saizen [47] state that ‘community-based adaptation is an effective way to address the challenges posed by climate change’ because bottom-up approaches ‘empower people and enhance communities’ adaptive capacity’ (p 2).	Nepal’s adaptation is strongly methodological and political: participatory video, radio dialogues, deliberative debates, irrigation, migration, and demands for infrastructure.	Kekulandala <i>et al</i> ([78]) shows that Sri Lanka’s adaptation is represented through inherited water infrastructure, especially cascading tanks, but detailed recent classification is limited in the bibliography.
Community resilience	Haque <i>et al</i> [51] frame resilience as linking ‘community-based climate adaptation (CBA) with the UN Sustainable Development Goals (SDGs) and principles of resilience and efforts at disaster risk reduction’ (p 4).	Strongly visible in post-flood farmer collectives in Kerala, Odisha mangrove protection, community-based drinking water management, and multi-purpose telecentres. Srivastava [49] shows that telecentres combine agriculture, disaster reduction, networkingII, entitlements, IT services, and e-governance (p 55).	Seen in community voice and knowledge production. Clement and Sugden [16] show how participatory video gives ‘a political voice to marginalised or underrepresented citizens’ (p 70).	Seen through traditional tank-based water governance, Vidanage <i>et al</i> ([79]) shows that historically, these systems were farmer-managed via customary laws, fostering community stewardship. Although modern institutional changes have weakened this.
Social resilience	Social resilience is visible where networks, trust, cooperation, and cultural institutions help people respond collectively. Opoku-boateng <i>et al</i> [38] define social capital as ‘networks, norms, and relationship that enable people to work collectively’ (p 3).	In India, social resilience appears through local institutions, women-led information centres, village-level water governance, communal labour, and Dzumsa conflict-resolution systems.	In Nepal, social resilience appears through farmer cooperation, labour exchange, community discussions, radio dialogues, and social relations, but [16] also show that isolation and structural inequality weaken this resilience (pp 74–75).	In Sri Lanka, social resilience can be inferred where tank systems depend on collective maintenance and water-sharing norms, but the bibliography does not give enough recent detail on social relations around these systems.

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Resilience type	Working definition/ quote from literature	India	Nepal	Sri Lanka
Economic/livelihood resilience	Economic resilience refers to protection and diversification of livelihoods under climate stress.	In India, economic resilience appears through agriculture advisories, tele-education, livelihood recovery after disasters, rice-fish systems in Nagaland, Ladakh water security, mangroves, and farmer collectives. Srivastava [49] notes that telecentres provide services including weather information, agriculture advisories, and e-governance (p 47).	In Nepal, economic resilience is linked to migration, remittances, debt, irrigation, farming insecurity, and livelihood stress. Clement and Sugden [16] show that vulnerability is tied not only to climate but also to agrarian and economic structures (pp 72–73).	Sri Lanka's cascading tanks support agricultural resilience and therefore livelihood resilience, Vidanage <i>et al</i> ([79]) emphasize that tanks provide non-market benefits such as maintaining groundwater, and supporting micro-environments.
Adaptive resilience/adaptive capacity	Adaptive capacity refers to the ability of people, institutions, and systems to adjust to climate stress. Kumar and Saizen [47] connect community-based adaptation with enhanced 'adaptive capacity' (p 2).	India shows adaptive resilience through Ladakh's artificial glaciers, Nagaland's Ruza system, Himalayan water management, telecentres, local-language climate information, and community-based disaster preparedness.	Nepal shows adaptive resilience through local flood-warning knowledge, irrigation practices, migration decisions, farmer testimonies, and participatory video that makes lived vulnerability visible.	Sri Lanka's adaptive resilience is visible through tank systems that historically manage rainfall variability and water scarcity, though more recent empirical work is needed.
Absorptive capacity	Absorptive capacity is the ability to absorb shocks and continue functioning. Dorji <i>et al</i> [41] definition includes the ability to 'anticipate, absorb, accommodate, or recover' from hazards (p 1102).	India's absorptive capacity is seen in warning systems, telecentres, water storage, mangrove buffers, community drinking water systems, and Ruza's closed-loop resource cycling.	Nepal's absorptive capacity appears in local early-warning indicators, coping with drought/flood stress, and social coping systems; however, [16] suggest this capacity is limited by debt, poverty, irrigation failure, and structural inequality (pp 68, 72–73).	Dayananda <i>et al</i> ([80]) shows that Sri Lanka's cascading tank system can be interpreted as absorptive infrastructure because it stores and regulates water during rainfall variability and drought stress.
Transformative resilience/adaptive transformation	Haque <i>et al</i> [51] emphasize the need for both 'incremental and transformational adaptation strategies' to address future climate impacts (p 12).	India's transformative resilience appears where Indigenous/local knowledge is fused with scientific systems, digital platforms, women-led governance, and institutional innovation. Srivastava [49] presents disaster-risk knowledge as a fusion of tacit, implicit, Indigenous, and scientific knowledge (p 46).	Nepal's transformative resilience appears where participatory video challenges top-down vulnerability narratives and allows farmers to become knowledge producers. Clement and Sugden [16] warn that apolitical policy discourses can block 'transitional and transformative forms of adaptation' (p 73).	Sri Lanka has transformative potential if cascading tanks are not only preserved as heritage but revitalized through equitable governance, climate policy, and contemporary water-management planning. However, this remains a visible literature gap.
Disaster risk reduction/resilience building	Haque <i>et al</i> [51] explicitly connect community-based adaptation with 'efforts at disaster risk reduction' (p 4).	India has strong DRR evidence through telecentres, early warning, Pondicherry fisher information systems, Bhuj setus, mangrove protection, and community-based water systems. In Pondicherry, fishermen considered wave-condition information 'life-saving' [49], p 50).	Nepal's DRR is seen in Indigenous flood-warning indicators and participatory knowledge practices. Kenney and Phibbs [50] identify cloud colour, cloud shape, animal behaviour, river sounds, and river scent as Indigenous flood-warning indicators (pp 16–17).	Sri Lanka's DRR is mainly water-risk related through cascading tanks, but the bibliography gives limited detail on early warning, disaster institutions, or contemporary DRR governance.

Annexure 2. Best practices from India, Nepal, and Sri Lanka

Country	Source/case	Best practice identified	Why it is a strong best practice	Citation with page number
India	South Asia community resilience cases, including Kerala, Odisha, Himalayan towns	Post-flood farmer collectives in Kerala; mangrove protection in Odisha; community-based drinking water management in Himalayan towns	These practices are community-based, low-cost, locally grounded, and adaptable. They show how resilience can be built through collective action, ecosystem protection, and local institutional engagement rather than only through external technical interventions.	([51], p 2)
India	Disaster-prone regions: Pondicherry and Bhuj	Community-owned rural telecentres, early warning systems, local-language dissemination, community IT volunteers, women-led information centres, telemedicine, and tele-education networks	This is a strong example of linking Indigenous/local knowledge with scientific and digital information systems. In Pondicherry, fishermen considered wave-condition information ‘life-saving’; in Bhuj, <i>setus</i> acted as ‘a bridge between the community and the government.’	([49], pp 47, 49–50, 55)
India	Ladakh	Traditional irrigation systems combined with community labour and artificial glaciers	Ladakh’s case is important because it combines traditional water rights, local irrigation institutions, NGO-community collaboration, and social innovation. Community engagement from project inception to operation is especially important.	([47], pp 10, 14)
India	Nagaland: Ruza system	Vertical integration, gravity-fed resource flow, closed-loop resource cycling, and participatory governance	This is one of the strongest ecological-cultural models. It integrates forest conservation, water-livestock management, rice-fish farming, natural terrain-based water movement, nutrient recycling, and communal labour.	[48] pp 1, 10–11, 13–14, 16–17)
India	Integrated natural resource management review	CBNRM, PRA, ecosystem-based management, TEK, economic diversification, agroforestry, wetland management, mangrove restoration, participatory watershed management, organic farming, and integrated rice-fish farming	These practices are comprehensive because they combine livelihoods, ecology, traditional knowledge, and participatory planning. They also show that resilience must be social, ecological, and economic at the same time.	([59], pp 4, 8, 12)
India	Gender and climate governance	Women’s representation, gender-sensitive funding, Indigenous knowledge, care ethics, and grassroots women’s movements	This is a critical governance best practice because it warns against tokenistic inclusion and calls for women’s substantive empowerment, agency, and leadership in community-driven climate solutions.	([81], pp 268, 280–281)

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Country	Source/case	Best practice identified	Why it is a strong best practice	Citation with page number
Nepal	Tarai-Madhesh	Participatory video, focus groups, semi-structured interviews, household surveys, film screenings, radio dialogues, and deliberative debates	This is a strong methodological best practice. It allows vulnerable farmers to become 'primary knowledge producers' and gives political voice to marginalized communities rather than fitting them into externally defined vulnerability categories.	[16], pp 70–71)
Nepal	Indigenous flood-warning knowledge	Use of Indigenous flood-warning indicators such as cloud colour, cloud shape and patterns, animal behaviour, river sounds, and river scent	This is a locally grounded disaster-risk practice. It shows that Indigenous environmental observation can support early warning and preparedness, especially where formal warning systems may not reach communities in time.	([50], pp 16–17)

Annexure 3. Knowledge co-production: processes, techniques, and implementation implications

Author/geography context	Knowledge Co-production process	Techniques/methods used	Implementation implications	Citation
Xie & Chen agricultural heritage systems	Co-production is framed as respectful bridging of traditional and scientific knowledge. Successful cases involve documenting traditional hydrologic knowledge, co-designing with knowledge holders, and creating feedback channels for continuous adaptation.	Documentation of hydrologic knowledge, co-design with water priests/elders/knowledge holders, sensor data, AI tools, feedback channels, adaptive revision.	Technology should support, not replace, cultural systems. Implementation must be community-led, culturally mediated, ethically designed, and attentive to data sovereignty and algorithmic bias.	[12]
Malik, Borde, & Ford—political ecology/Indigenous governance	Co-production is understood as a decolonial method where Indigenous peoples help shape research, policy, and governance frameworks.	Participatory mapping, citizen science, collaborative modelling, community-led approaches, agenda-setting by communities.	Communities should not only be consulted; they should set research agendas, define success, and hold decision-making power.	[82]
Hill <i>et al</i> Indigenous adaptation pathways, Australia	Co-production works through respectful partnership, cultural governance, and the five tasks of 'prepare, communicate, discuss, bring together and apply.'	Local weather recollections, scientific climate data, workshops, Arrernte-language presentations, ranking cards, field demonstrations, erosion-control trials, monitoring, reflection.	Implementation requires consent, trust, accountability, reciprocity, Indigenous cultural resurgence, and local decision-making power.	[13]

(Continued.)

(Continued.)

Author/geography context	Knowledge Co-production process	Techniques/methods used	Implementation implications	Citation
Wellmann <i>et al</i> nature-based solutions/urban systems	Co-production is organized through interfaces connecting social, ecological, and technological knowledge systems.	Online learning platforms, decision-support tools, sensor networks, citizen science, human-biodiversity interactions, web apps, GIS, remote sensing, visual tools.	Digital tools must remain inclusive and should be combined with offline and democratic engagement to avoid excluding less-connected groups.	[43]
Patrick <i>et al</i> healthy ageing, Indigenous elders, climate resilience	Co-production is linked to co-design with older adults, Indigenous elders, community organisations, and local governments.	On-country knowledge exchange, oral histories, storytelling, community mapping, mediated modelling, dialogue, consultation, participatory research.	Climate-resilient ageing frameworks should include food, water, income, energy security, shelter, and community agency.	[28]
Butler <i>et al</i> —climate-resilient development, Papua New Guinea	Co-production is a structured, participatory, and political process to feed climate-resilient development knowledge into decision-making.	Power mapping, actor analysis, stakeholder workshops, downscaled climate projections, population projections, market forecasts, scenario planning, values mapping, ecosystem-service valuation, trade-off analysis, Theory of Change evaluation.	Co-production must address politics, networks, power asymmetries, and local capacity. Local knowledge brokers need capacity-building beyond the project period.	[19]
Neset <i>et al</i> —AI, weather warnings, climate adaptation	Co-production occurs through collaboration between practitioners and AI-supported climate information systems.	Stakeholder interviews, workshops, collaborative assessment, assessment-support documents, AI image analysis, text mining, machine learning, NLP, interactive visualisation, social-media analysis, practitioner validation	AI should support, not replace, local expertise. Implementation must address data bias, representativeness, algorithmic reliability, and human validation.	[83]
Rimlinger <i>et al</i> —public-private-civil partnership, Greece and Portugal	Co-production is created through dialogue, co-creation, and collaboration between public authorities, private actors, and civil society.	Participatory mapping, risk-chain analysis, solution prototyping, governance scenario testing, site visits, simulation games, visual mapping, storytelling, role play, feedback surveys, iterative capitalisation.	Co-production becomes meaningful when it leads to roadmaps, shared responsibilities, policy uptake, cross-sector trust, and practical action.	[24] pp 3, 5–8)
Nipa, Lino, & Arun—BRAC/Bangladesh climate action	Co-production is created through participatory arenas where vulnerable citizens interact with public and third-sector actors.	Community Action Groups, interviews, observation of meetings, solicited diaries, document analysis, baseline surveys, training modules, community meetings, local-government engagement.	Relational spaces must be supported by trust, local dialects, pictures, real-life examples, women's participation, rights-based awareness, and community action plans.	([20], pp 5–6, 9, 11)

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Author/geography context	Knowledge Co-production process	Techniques/methods used	Implementation implications	Citation
Afyare—Somalia/water and climate resilience	Co-production combines scientific data, local knowledge, community participation, and regional governance.	Stakeholder interviews, focus groups, policy analysis, environmental assessments, quantitative water-resource analysis.	Water and climate policy should include local narratives, pastoralists, displaced communities, NGOs, and Indigenous knowledge within formal policy frameworks.	([57], pp. 1, 3, 5, 8)
Zvobgo <i>et al</i> —Zimbabwe/seasonal forecasts and smallholder farmers	Co-production blends Indigenous/local knowledge with scientific climate forecasts for local decision-making.	Face-to-face semi-structured interviews in Shona, farmer indicators, reliance levels, decision data, adaptation actions, blended forecast sources.	Forecasts should be translated into plain language and shared through SMS, mobile phones, and extension officers. Scientific forecasts should complement, not replace, IK/LK.	([14], pp 13, 15, 21)
Lama <i>et al</i> —TEK and climate adaptation	Co-production is described as hybridisation of Traditional Ecological Knowledge and science.	Local participation in research, technology development, implementation, dissemination, evaluation, capacity-building, training, practical experience, intergenerational exchange.	TEK should not be treated as inferior or merely validated by science. Implementation must address power dynamics and equitable knowledge-sharing.	[84], pp 156, 162,
Rinawati <i>et al</i> —coastal community resilience	Co-production is located within collaborative governance through joint decision-making, trust-building, and diverse stakeholder participation.	Thematic synthesis, bibliometric analysis, governance framework coding, stakeholder engagement analysis, community dialogue, institutional coordination.	Co-production must avoid token participation. It requires fair power-sharing, Indigenous/local epistemologies, and long-term institutional learning.	([85], pp. 2, 4, 6–8)
Clement & Sugden—Tarai-Madhesh, Nepal	Knowledge is understood as co-produced with social identities, institutions, discourses, and representations.	Participatory video, farmer-made films, farmer interviews, documentation of lived experience, screening to experts and policymakers, radio and policy dialogues.	Local knowledge documentation is not enough. Implementation must address power, scale, caste, class, gender, and whose knowledge becomes authoritative.	([16], pp 69–71, 75)
Figus, Ki'ye Jackson, & Trainor—Kake Climate Partnership, Southeast Alaska	Ellam Yua co-production brings Indigenous knowledge systems and science together to create knowledge that neither system could produce alone.	Consensus-based project selection, monthly updates, written logs, reflective conversations, Talking Circle, local field teams, NDAs, Tribal archives, locally determined monitoring priorities.	Climate services should be institutionalised over decadal, not annual, timeframes. Relationship-based Indigenous-centred science needs trust, continuity, sovereignty, and sustained capacity.	([29], pp 1, 3–4, 8–12)

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Author/geography context	Knowledge Co-production process	Techniques/methods used	Implementation implications	Citation
Ciocco <i>et al</i> —Indigenous knowledge in climate adaptation planning	The authors prefer ‘incorporation’ over ‘integration’ because climate adaptation planning often remains shaped by Western science.	Site visits, regular meetings, scenario planning, semi-structured interviews with Ute elders, coordination with the Tribal Historic Preservation Office.	Implementation requires long-term relationships, rapport, social-science expertise, tribal data governance, culturally appropriate settings, and respect for tribal priorities.	([17], pp 2–4)
Adusei <i>et al</i> —Ghana/gendered adaptation	Knowledge is co-constructed through interaction, reflection, and shared understanding between researchers and participants.	Semi-structured interviews, focus group discussions, field observations, verbatim quotations, participatory collective reflection.	Adaptation must be gender-transformative, recognise women’s Indigenous and ecological innovations, improve extension access, support credit and land rights, and bridge formal climate services with community forecasting.	([27], pp 1, 6–7)
Curry & Lopez—Wainwright/environmental governance	Co-production is supported through partnership, visual communication, and Multiple Evidence Base reporting.	Iterative participatory process, Traditional Council guidance, semi-structured interviews, Native artwork, photographs, photomontage, sample reports, questionnaires, follow-up interviews.	Reports combining Western science, local quotes, and context-rich images can improve credibility and representation in environmental decision-making.	([86], pp. 5–10)
Rastogi <i>et al</i> —climate services/local knowledge	Climate services are produced through collaboration across data providers, integrators, service providers, purveyors, and users.	Deliberate and cyclical cooperation, data selection, model calibration, communication-channel design, validation of outputs, user decision-making.	Local knowledge should shape how climate services are produced, negotiated, and used. Co-production should avoid cherry-picking only local indicators.	([87] 6, pp. 1–2, 11)
Chisadza—agroecology in Zimbabwe	Agroecology is grounded in diversity, knowledge co-creation, system resilience, and farmer autonomy.	Transdisciplinary farmer-led research, thematic synthesis, NVivo coding, farmer field schools, participatory platforms, farmer diaries, citizen science, community-defined indicators, participatory monitoring.	Implementation needs a National Agroecology Strategy, public extension support, education integration, farmer-led platforms, participatory guarantee systems, procurement, financing, and regional collaboration.	([33], pp. 1, 2, 5, 11–14)

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