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Indigenous Ecological Knowledge and Communication for Climate-Risk Adaptation among the Toto: An Ethnographic Study

Roushan Akhtar Hossain[1], Dr. Samarjit Kachari[2]

[1]Research scholar, Department of Electronic Media and Mass Communication, Pondicherry University,
[2]Assistant Professor, Department of Electronic Media & Mass Communication, Pondicherry University

Abstract

Background: Research on climate-risk communication typically treats indigenous knowledge, formal early-warning systems, and everyday media use as separate categories, rarely examining how they operate together within a single person's daily life. This gap is especially significant for India's Particularly Vulnerable Tribal Groups (PVTGs) small, isolated communities rarely studied on either dimension, let alone both together.

Objective: This study examines climate-risk perception and response among the Toto of Totopara, West Bengal, using a knowledge–Communication–Adaptation (KCA) Pathway framework that treats indigenous knowledge, communication, and adaptive decision-making as one interacting system. It asks how the Toto perceive and articulate environmental change; how climate and hazard information moves through oral, textual, and digital channels; and how this knowledge and communication translate into household- and community-level adaptation, and its points of connection with formal early-warning systems.

Methods: An ethnographic design aligned each KCA stage with a corresponding method: participatory seasonal calendars and photo-elicitation for the knowledge stage; communicative-ecology mapping supported by diary entries written in Bengali for the communication stage; and the Most Significant Change technique for the adaptation stage. Participants were recruited through purposive and snowball sampling to capture variation in age, gender, and connectivity. In-depth interviews formed the core instrument across all three phases; data were analysed thematically and mapped onto the KCA stages, with attention to linkage and disjuncture between indigenous and formal systems.

Results: Risk perception among the Toto emerged from the interaction of inherited ecological knowledge shifting heat, rainfall, and seasonal boundaries, and indicators drawn from ants, birds, frogs, and prolonged fog with a layered, unevenly trusted mix of oral, mobile, and broadcast communication. A small, informally constituted set of "hub" individuals teachers, health workers, youth volunteers, and elders who translate outside information into locally trusted, Toto-language terms provided the clearest evidence of the knowledge-to-communication link the KCA framework anticipates. A Most Significant Change narrative showed that direct experience of a hazard event, more than the warning that preceded it, drove durable household adaptation, including routine forecast-checking, structural reinforcement, and emergency stockpiling. The clearest points of disjuncture were the district-scale resolution mismatch between mobile and broadcast forecasts and hyperlocal terrain, the continued absence of any Toto-script

or clan-structure channel for hazard information, and the unsystematised nature of the community's own intermediary "hub" role.

Conclusion: This study contributes new ethnographic evidence from a little-studied PVTG, using the KCA framework to treat indigenous knowledge, communication, and adaptive decision-making as a single system rather than separate topics. It identifies concrete, culturally grounded points language, trusted intermediaries, and hazard-specific alerting at which formal early-warning systems could integrate more closely with existing local practice, contributing toward more inclusive climate-risk policy.

Keywords: Indigenous ecological knowledge; climate-risk communication; Particularly Vulnerable Tribal Group; Toto tribe; communicative ecology; Knowledge–Communication–Adaptation framework

1. Introduction

Climate change is no longer a distant projection but a lived reality for the world's most marginalised populations, and Indigenous communities occupy a position of acute and disproportionate exposure (Ara Parvin & Reazul Ahsan, 2013; Leal Filho et al., 2022). Indigenous Knowledge (IK) systems the ecological, social, and cultural understandings communities develop through generations of direct engagement with their environments have repeatedly been shown to underpin local resilience and adaptive capacity under climatic stress (Berkes & Folke, 1998; Berkes, Colding, & Folke, 2000; Petzold, Andrews, Ford, Hedemann, & Postigo, 2020). Systematic reviews confirm that IK is dynamic, continuing to inform how communities interpret environmental signals, anticipate hazards, and organise collective responses (Petzold et al., 2020; Dorji, Rinchen, Morrison-Saunders, Blake, & Banham, 2024). Yet IK remains inconsistently integrated into formal climate assessments and adaptation planning, a gap the IPCC itself has acknowledged across successive assessment cycles (Petzold et al., 2020). Studies of cyclone and flood warning across South Asia show that early-warning system (EWS) effectiveness depends less on forecasting sophistication than on "last-mile connectivity" the social and institutional conditions determining whether a warning reaches and is acted upon by the people it protects, as illustrated by post-Cyclone Titli case studies in Andhra Pradesh (Dash & Jagirdhar, 2022). Reviews around the UN's Early Warnings for All initiative similarly stress that isolated, vulnerable communities are those most likely left behind by generalised, top-down alert architectures, even as the initiative's own four-pillar model risk knowledge, observation and forecasting, dissemination and communication, and preparedness implicitly separates the technical act of warning from the cultural work of interpretation. This literature rarely asks how formal information streams interact with the indigenous ecological knowledge community members already hold, or how the two are reconciled within a single person's daily understanding of risk.

The Toto, one of three communities historically designated a "primitive tribal group" in West Bengal and now recognised as a PVTG, exemplifies this neglected intersection. Settled almost exclusively in the enclave village of Totopara in Alipurduar district along the Indo-Bhutan border, the Toto number under 1,500 individuals (2011 Census) and possess their own script and oral tradition. This is true regarding their historical oppression in the context of Bhutanese rule, social and cultural change due to interaction with surrounding peoples, as well other accounts more recently (i.e. over the past 70 years) e.g., their educational and livelihood status (Ghosh & Saha, 2017; Upadhay & Jamal, 2021). What has not been explored in this literature is how the Toto perceive, talk about and mobilise (or do not) climate and environmental risk; nor what role oral tradition, village meetings, family networks, and alongside these increasingly mobile phones, WhatsApp and television play together. In a community defined by ecological

embeddedness and communicative isolation, this gap is precisely what dedicated ethnographic inquiry can fill.

It is this gap the present study addresses. Drawing on ethnographic fieldwork among the Toto of Totopara, this study introduces a Knowledge–Communication–Adaptation (KCA) Pathway framework to examine how indigenous ecological knowledge, everyday communication, and adaptive decision-making operate as a single, mutually constitutive system within a PVTG, contributing new empirical evidence from a community largely absent from this literature, and connecting local and formal early-warning systems to the realities of one of India's smallest, most isolated tribal communities.

2. Literature review

This gap is especially consequential for India's Particularly Vulnerable Tribal Groups (PVTGs), a state-designated sub-category of Scheduled Tribes identified by small population size, pre-agricultural technology, geographic isolation, and stagnant or declining demographic trends. India recognises seventy-five such groups across eighteen states, many in ecologically fragile, forest-dependent, climate-sensitive regions where livelihoods rest heavily on rain-fed agriculture and non-timber forest produce (Ministry of Tribal Affairs, Government of India, 2019). Emerging scholarship on PVTGs in states such as Jharkhand documents both the integration of indigenous knowledge into climate adaptation and the persistent absence of coordinated policy linking tribal development frameworks to climate planning (Soren, Rana, & Sharma, 2024; Kumar, Devi, & Mohanasundari, 2025). A recent Indian policy assessment similarly finds that national and state climate-vulnerability assessments rely on aggregated indicators that mask the location-specific risks facing different tribal groups (Ratha & Barik, 2026). PVTGs are, however, rarely the subject of dedicated empirical research on indigenous knowledge or formal risk communication, let alone both together a striking omission, since isolation, the defining PVTG trait, is precisely what should make this interface most consequential for their survival.

Two bodies of theory offer partial purchase on this problem without fully resolving it. The communicative ecology framework (Tacchi, Slater, & Hearn, 2003) treats the whole structure of communication and information in a community's way of life as one interacting system rather than a set of discrete channels well suited to a community where oral, textual, and digital sources coexist. Separately, risk-perception scholarship grounded in the Social Amplification of Risk Framework (Renn, 2011; Kasperson, Webler, Ram, & Sutton, 2022) and its recent applications to Indigenous populations shows that hazard perception and response are shaped as much by social trust, cultural worldview, and interpersonal communication as by objective hazard severity (Cervantes Benavides, Mc Dermott, Seddighi, & van den Berg, 2025). Neither framework, however, was designed to trace the full pathway from indigenous ecological knowledge, through communication to the household-level adaptive decisions that follow the very loop most climate-risk communication research treats as three unrelated stages.

3. Methodology

3.1 Research design

An ethnographic qualitative design examined how Indigenous ecological knowledge, climate-risk communication, and adaptive responses interact within the Toto community. The study was structured around the Knowledge–Communication–Adaptation (KCA) Pathway framework, which treats these processes as interconnected components of climate-risk understanding rather than as independent domains. Data collection and analysis were aligned with the three KCA stages to trace how environmental

observations were interpreted, communicated through traditional and contemporary channels, and translated into household- and community-level adaptive action. The KCA framework is introduced here for the first time: it was developed for this study by integrating two qualitative traditions already established for use with ethnographic data, communicative ecology (Tacchi, Slater, & Hearn, 2003) and the Social Amplification of Risk Framework (Renn, 2011; Kasperson, Webler, Ram, & Sutton, 2022), which provide methodological precedent for its application to qualitative data.

3.2 Study setting

The study was conducted in Totopara, in the Madarihat–Birpara block of Alipurduar district, West Bengal, near the Indo-Bhutan border. Totopara is the principal settlement of the Toto, a PVTG characterised by a small population, geographical isolation, and a distinct linguistic and cultural identity, including use of the Toto script. The setting was purposively selected because it offers a geographically bounded Indigenous community in which traditional ecological knowledge coexists with increasing access to mobile phones, television, social media, and formal weather-warning systems, allowing examination of how Indigenous environmental knowledge interacts with contemporary climate-risk communication and household-level adaptation.

Figure 1. Methodological flowchart of the ethnographic study, structured according to the Knowledge–Communication–Adaptation (KCA) pathway.

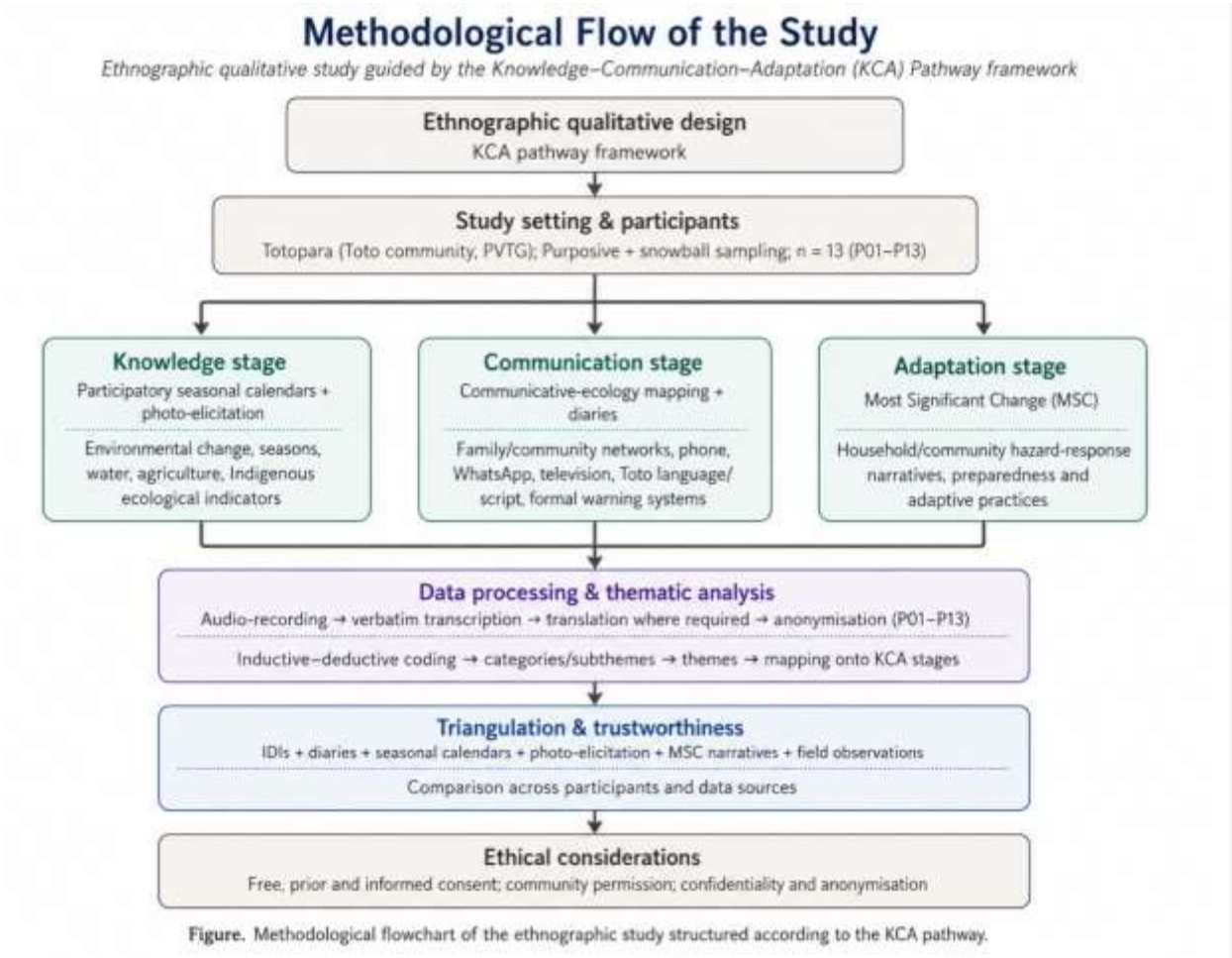


Figure. Methodological flowchart of the ethnographic study structured according to the KCA pathway.

3.3 Study participants and sampling

Thirteen participants took part in the study, representing variation in age, sex, occupation, livelihood dependence, and community role, and including farmers, teachers, a health volunteer, a homemaker, a shopkeeper, a driver, a cultivator, and a student/community participant (Table 1). Participants were recruited using purposive and snowball sampling: initial purposive recruitment focused on individuals with experience of environmental or hazard events and those involved in community information networks, and snowball sampling subsequently identified additional information-rich participants through community referrals. Recruitment sought variation in age, gender, occupation, livelihood context, and access to communication channels such as mobile phones, television, and WhatsApp, to capture differing experiences of environmental change and adaptation; sampling aimed for diversity of perspective appropriate to an ethnographic design rather than statistical representativeness of the Toto population. Participants were assigned alphanumeric identifiers (P01–P13), used throughout analysis and reporting.

3.4 Data collection

Data collection was organised around the three KCA stages and drew on multiple qualitative and participatory methods.

3.4.1 Knowledge stage

Participatory seasonal calendars were developed with participants to explore perceived changes in temperature, rainfall, seasonal boundaries, agricultural cycles, water availability, and hazard timing, and to compare contemporary conditions with patterns remembered from earlier periods. Photo-elicitation, using photographs of locally relevant environmental features, supported discussion of environmental change and indigenous ecological knowledge; field photographs documenting environmental and adaptation-related features were retained as contextual material for the Results.

3.4.2 Communication stage

Communicative-ecology mapping examined how climate and hazard information moved through the community through family networks, village interactions, mobile phones, WhatsApp, television, the Toto language and script, and formal administrative warning systems. Selected participants additionally kept communicative-ecology diaries documenting instances of receiving, interpreting, discussing, or passing on weather or hazard information, with particular attention to trusted sources, influential intermediaries, and the relationship between interpersonal and digital channels.

3.4.3 Adaptation stage

The Most Significant Change (MSC) technique elicited detailed narratives of household and community responses to climatic or hazard events, including actions taken before and after the event and the reasoning behind particular adaptive choices. This enabled exploration of how warnings, indigenous knowledge, and direct hazard experience each contributed to changes in preparedness.

3.4.4 In-depth interviews

In-depth interviews were the primary data source across all three KCA stages, covering perceptions of environmental change, indigenous ecological indicators, climate-risk communication, information sources and trust, livelihood transitions, household preparedness, and community adaptation. Interviews were conducted in Bengali and/or the Toto language according to participant preference, with interpreter assistance where required, and were audio-recorded after informed consent was obtained.

3.5 Data analysis

Audio-recorded interviews were transcribed verbatim and, where required, translated into English while preserving intended contextual meaning; identifying information was removed during transcription and each participant represented by their assigned code. Data were analysed using inductive–deductive thematic analysis (Fereday & Muir-Cochrane, 2006): repeated familiarisation with transcripts generated initial codes, which were grouped into categories and subthemes and then into broader themes. For example, codes such as hotter summers and unpredictable rainfall were grouped under seasonal disruption, and codes relating to teachers, health workers, and house-to-house communication contributed to informal communication hubs. Candidate themes were reviewed across participants and data sources for coherence and consistency before being mapped deductively onto the Knowledge, Communication, and Adaptation components of the KCA pathway.

Seasonal-calendar and photo-elicitation data were examined for recurring perceptions of environmental change and locally recognised ecological indicators; communicative-ecology data were analysed for dominant channels, trusted intermediaries, and barriers to warning dissemination; and MSC narratives were analysed for how hazard experience and risk information shaped household adaptive decisions. Areas of convergence and disjuncture between Indigenous and formal climate-information systems were examined across the three stages. Representative quotations, attributed only by participant code and age (e.g., P01, 56 years), were selected to illustrate the final themes, and the analytic structure was presented as KCA stage → major theme → subtheme/category → illustrative codes → representative quotation, summarised in Table 2.

3.6 Triangulation and trustworthiness

Trustworthiness (Lincoln & Guba, 1985) was strengthened through methodological and data-source triangulation: findings from interviews were examined alongside communicative-ecology diaries, seasonal calendars, photo-elicitation material, MSC narratives, and field observations, comparing themes across participants differing in age, occupation, and connectivity. Interpretations were retained only where supported by the underlying material rather than by isolated statements. Triangulation across methods was also used to relate the different KCA components to one another for example, examining environmental observations from interviews and seasonal calendars alongside reported communication practices and adaptive actions.

3.7 Ethical considerations

Given the Toto community's status as a PVTG and its small, geographically concentrated population, particular attention was given to culturally appropriate procedure and participant confidentiality. Free, prior, and informed consent was obtained from all participants in their preferred language; participation was voluntary, and participants were informed of their right to decline individual questions or withdraw at any stage without consequence. Community-level permission was sought alongside individual consent, reflecting the community's collective, kinship-based social organisation. Identifying information was removed from transcripts and records, and each participant was assigned an anonymous alphanumeric identifier (P01–P13), used throughout the Results; participant names were never used, and quotations were reported with code and age only where this contributed to interpretation.

4. Results

A total of 13 participants contributed through in-depth interviews, with two participants additionally contributing communicative-ecology diary data; participant characteristics are shown in Table 1. Findings

are organised according to the three KCA stages Knowledge, Communication, and Adaptation followed by an examination of convergence and disjuncture between Indigenous and formal climate-information systems.

The participatory seasonal calendar identified four broad seasons summer, monsoon, winter, and spring historically associated with established livelihood and ritual activity, which participants nonetheless described as increasingly disrupted or "topsy-turvy": monsoon onset shifting earlier, from around June towards may; summer heat remembered as "28–29" now felt as "always above 30"; and a shortening winter season. These changes formed the environmental backdrop against which participants interpreted climate risk.

Table 1. Characteristics of study participants (n = 13).

Participant code	Age/Sex	Occupation/role	Livelihood/context	Data source
P01	56/F	Farmer	Areca nut, ginger, turmeric, vegetables	In-depth interview
P02	43/M	Farmer/shopkeeper	Areca nut, black pepper, grocery shop	In-depth interview
P03	27/F	School teacher	Teaching; family areca nut plantation	In-depth interview
P04	38/F	Health volunteer	Health work, kitchen garden, areca nut	In-depth interview
P05	20/M	Student/community participant	Household farming	IDI + communicative-ecology diary
P06	53/M	Cultivator	Household farming	IDI + communicative-ecology diary
P07	45/F	Farmer	Farming	In-depth interview
P08	24/F	Homemaker	Household work	In-depth interview
P09	28/M	Shopkeeper	Small business/shop	In-depth interview
P10	48/M	Teacher	Teaching	In-depth interview
P11	36/M	Farmer	Farming	In-depth interview
P12	32/M	Driver	Driving/transport	In-depth interview
P13	52/M	Farmer	Farming	In-depth interview

4.1 Knowledge stage: perceiving and interpreting environmental change

Changing environmental patterns

Participants described conditions as increasingly different from remembered seasonal patterns, particularly regarding heat, rainfall, and seasonality. Heat was seen as disrupting outdoor livelihood activity:

"We often stop by eleven o'clock because the heat becomes unbearable." (P01, 56 years)

Rainfall was thus characterised as variable in terms of timing and intensity more than an absolute reduction in volume "it comes very abruptly one moment and not the next at all" (P06, 53 years), with a younger participant summarising the broader uncertainty:

"The greatest challenge is that nobody can confidently predict what the next season will look like." (P03, 27 years)

These accounts suggest that environmental change was experienced less as a directional shift in specific variables than as a loss of predictability in once-familiar seasonal patterns.

Indigenous ecological indicators

Respondents recounted biological and atmospheric signals historically associated with forecasting weather: ants moving their eggs uphill, elevated vocalisation of birds and frogs, nimbostratus cloud formation for multiple days sans rain, persistent multiday fog without precipitation. The following signs were read together rather than individually:

"Weather should never be understood by looking at only one sign." (P03, 27 years)

Prolonged fog in particular was associated with sustained rainfall and possible flooding:

"It is often observed that although there is no rain, the sky remains completely shrouded in fog for several days… that's when it feels like heavy rain will keep raining continuously for a few days and lead to flooding." (P06, 53 years)

Figure 2. Fog over the hills surrounding Totopara. Prolonged fog was identified by participants as a locally recognised environmental indicator associated with sustained rain and possible flooding.



Environmental change, forests, and water

Changes in forests and water were closely tied to participants' sense of environmental change and livelihood security. Streams once remembered as perennial were described as becoming seasonal or drying

up "Most households now depend on borewells" (P01, 56 years) and forest thinning was associated with rising local heat and wildlife movement towards settlements; birdsong and other cues also featured in narratives of changing conditions.

Intergenerational erosion of ecological knowledge

A recurring concern was declining transmission of ecological knowledge between generations. Detailed knowledge of indicators was seen as increasingly concentrated among older members, while younger people oriented more toward schooling, salaried work, and digital information, among other factors:

"Out of a hundred, maybe only one, two, or three people might know about it." (P05, 20 years)

This suggests that while indigenous ecological knowledge continues to inform contemporary climate-risk interpretation, its intergenerational continuity may be weakening.

4.2 Communication stage: the communicative ecology of Totopara

Layered traditional and contemporary communication

Climate and hazard information flowed through a layered communication ecology that included combinations of family and community networks with mobile phones, television, WhatsApp, and formal sources; digital communication has supplemented rather than displaced face-to-face contact. Even if the Toto script exists, participants reported that it is not yet commonly used to provide climate or hazard information due to limited levels of literacy in the Toto script (limited mostly by generations).

Spoken, voice-based communication accordingly had greater practical reach across differing levels of literacy and digital access.

Formal–local information mismatch

A prominent gap concerned the spatial mismatch between district-level forecasts and Totopara's hyperlocal terrain:

"Rain might not fall everywhere across the entire district it might occur in some places but not in others." (P06, 53 years)

A second participant stated that mobile forecasts "do not always take into account very localized weather in mountainous terrain" and concluded, "In my opinion the future is merging both systems," (P03, age 27). Block and subdivision authorities provided an administrative pathway, but the function was one way (predominantly upward reporting) and not a reliable downward warning mechanism; clan and festival structures were likewise unused for climate-risk communication.

Trusted informal communication hubs

Teachers, health workers, youth volunteers, and elders emerged as informal intermediaries who translated externally generated information into locally meaningful language and action:

"Teachers, health workers, youth volunteers, and village leaders can play an important role in translating these messages into simple language that everyone understands… it should clearly explain what actions families need to take." (P03, 27 years)

A health volunteer described communicating directly with households when digital channels were unavailable (P04, 38 years), and another participant proposed formalising such roles through a standing village disaster committee (P02, 43 years) evidence that trusted individuals already function as an informal bridge between formal information and household understanding.

Communication vulnerability during hazards

Digital communication was also seen as vulnerable during severe weather, precisely when it was most needed:

"Connectivity has been cut before for two to three days." (P05, 20 years)

Participants therefore considered exclusive reliance on digital systems insufficient for hazard communication in Totopara.

4.3 Adaptation stage: from knowledge and communication to action

Livelihood transition and climate sensitivity

Participants described a long-term shift from diversified subsistence agriculture maize, finger millet, orange cultivation toward growing dependence on areca nut, often intercropped with black pepper. While viewed as economically practical under increasingly unreliable rainfall, this transition also carries recognised vulnerability:

"One weather event can affect two crops at the same time." (P02, 43 years)

This refers to the practice of growing pepper vines on areca trees, so that storm damage to one crop damages the other.

Figure 3. Areca nut cultivation in Totopara. The plantation provides visual context for participants' accounts of increasing livelihood dependence on areca nut and associated intercropping practices.



Housing and environmental adaptation

Traditional elevated timber housing has increasingly been replaced by tin-roofed and concrete structures. Structural strengthening and improved drainage were seen as adaptations to heavier rainfall, though participants simultaneously associated concrete and metal roofing, together with declining forest cover, with rising local heat one participant directly linked "the prevalence of concrete houses and tin-roofed structures" to increasing ground heat (P06, 53 years).

Figure 4. Housing forms observed in Totopara. (A) Large elevated wooden structure in Totopara (B) newer masonry structure with a metal roof; (C) a further traditional elevated wooden house, with two community members present for scale .



Participants discussed changing housing forms in relation to protection from rainfall and environmental exposure, while also associating concrete and metal-roofed construction with increased heat.

Experience-driven household preparedness

The clearest Most Significant Change narrative concerned a severe monsoon storm that caused roof damage and loss of areca trees after an initial warning had received limited attention. Afterwards, household practice changed:

"After that event, we changed several things. We started checking weather forecasts more regularly. We trimmed weak branches near the house. We strengthened the roof and improved drainage around the garden. We also began storing dry food, candles, batteries, and basic medicines during monsoon." (P02, 43 years)

As the same participant reflected, "The event taught us that warnings are useful only if people know what action to take." This illustrates the Communication–Adaptation link the KCA pathway anticipates: receipt of a warning alone did not produce sustained preparedness, whereas direct hazard experience did.

Community-based and collective adaptation

At community level, afforestation and slope stabilisation emerged as locally supported responses to landslide risk:

"Trees need to be planted and not just planted, but also properly cared for and protected." (P06, 53 years) a claim corroborated by field observation of individually tagged saplings on previously open ground.

Figure 5. Field documentation of a tagged sapling in Totopara. The photograph provides contextual evidence of local tree-planting and vegetation-management activity discussed by participants in relation to afforestation and slope stabilisation.



Participants also described collective coping during disruptive events neighbours clearing blocked roads, sharing food and water, and checking on older or vulnerable residents indicating that adaptation depended on social networks and reciprocity as much as on individual household action.

4.4 Convergence and disjuncture between Indigenous and formal systems

Triangulation across interviews, diaries, seasonal-calendar exercises, and photo-elicitation showed both convergence and disjuncture between Indigenous and formal climate-information systems. At the Knowledge stage, the two broadly converged on increasing heat, less predictable rainfall, and changing seasonality, but differed in spatial resolution: Indigenous knowledge read the immediate local environment, while formal information typically operated at district or broader scale. At the Communication stage, the two systems largely ran in parallel mobile, television, and administrative channels ran alongside, rather than through, the Toto script, clan structures, and festivals, none of which were routinely used for hazard communication, leaving trusted intermediaries as the main informal bridge. By the Adaptation stage there was a higher degree of convergence: participants not only used formal forecasts but some also incorporated local signals when making household decisions even though there is no institutional mechanism that explicitly connects the two. Facilitators projected ideas for pragmatic improvements such as Toto-language warnings, broadcasting via voice, supplementary outreach in Nepali and Hindi when appropriate, hazard-specific siren signals and dissemination through safe community intermediaries implying that effective communication requires a process of translation into locally actionable information, not just technical precision.

Table 2. Thematic analysis showing major themes, subthemes, illustrative codes, and representative participant quotations across the KCA pathway.

KCA stage	Major theme	Subtheme/category	Illustrative codes	Representative quotation
Knowledge	Changing environmental patterns	Increasing heat and seasonal disruption	hotter summers; shorter winter; altered monsoon onset; unpredictable rainfall	"We often stop by eleven o'clock because the heat becomes unbearable." (P01, 56 years)
Knowledge	Indigenous ecological indicators	Biological and atmospheric signs	ants carrying eggs uphill; frog calls; bird behaviour; low clouds; prolonged fog	"Weather should never be understood by looking at only one sign." (P03, 27 years)
Knowledge	Erosion of ecological knowledge	Intergenerational knowledge loss	ageing knowledge holders; reduced transmission; schooling; salaried employment; digital orientation	"Out of a hundred, maybe… one, two, or three people might know." (P05, 20 years)
Communication	Layered communication ecology	Interpersonal and digital channels	family networks; village communication; mobile phones; WhatsApp; television; oral communication	"Climate information circulated through both interpersonal and mediated channels."
Communication	Formal–local information mismatch	Hyperlocal limitations of formal forecasts	district-level forecast; mountainous terrain; local rainfall variation; spatial mismatch	"Rain might not fall everywhere across the entire district." (P06, 53 years)
Communication	Informal communication hubs	Trusted local intermediaries	teacher; health worker; youth volunteer; elder; translation; actionable information	"Teachers, health workers… can play an important role in translating these messages…" (P03, 27 years)

Communication	Communication vulnerability	Connectivity disruption during hazards	network failure; electricity interruption; inaccessible households; reliance onface-to-face communication	"Connectivity has been cut… for two to three days." (P05, 20 years)
Adaptation	Livelihood transition	Increasing dependence on areca nut	decline of subsistence crops; areca nut; black pepper; livelihood concentration; storm sensitivity	"One weather event can affect two crops at the same time." (P02, 43 years)
Adaptation	Experience-driven preparedness	Post-hazard behavioural and structural change	forecast checking; roof strengthening; branch trimming; drainage; emergency supplies	"After that event, we changed several things…" (P02, 43 years)
Adaptation	Collective adaptation	Ecosystem-based and social responses	afforestation; slope stabilisation; tree protection; road clearing; food sharing; support to vulnerable households	"Trees need to be planted and not just planted, but also properly cared for and protected." (P06, 53 years)

5. Discussion

5.1 Indigenous knowledge and perception of environmental change

Ghosh-Jerath et al. (2021) found akin feelings from the Sauria Paharia of Jharkhand who experienced irregular precipitation and droughts longer than regular periods, cropping, and lack of forest productive capacity, which hindered food availability. Declining intergenerational transmission seen here mirrors the findings of Kumar et al. (2025), who identify links between cultural erosion and modernisation and call for retaining Indigenous knowledge in adaptation planning. This is in accordance with earlier research from Totopara documenting the movement away from traditional livelihoods as communities became more connected externally (Ghosh & Saha, 2017). Collectively, these observations imply that Indigenous ecological knowledge continues to be a potent resource for identifying local climatic change even as continuing socio-economic and livelihood transitions threaten its persistence.

5.2 Climate-risk communication and early-warning systems

Climate information in Totopara passes through a variety of channels interpersonal networks, mobile phones, broadcast media but no one uses Toto script for hazard communication; district-level forecasts appear inadequately locally contextualised, and connectivity may be compromised during hazard events, with teachers health workers volunteers elders acting as informal intermediaries. That said, these findings

echo trends in the wider literature on climate systems formal and informal, with Ratha & Barik (2026) arguing that aggregated national- and state-level measures of vulnerability mask location-specific risks to tribal populations while Dorji et al. (2024) similarly make the case for integrating Indigenous and scientific forecasting. This aligns with the role of gatekeeping local intermediaries identified by Kasperson et al.'s (2022) Social Amplification of Risk Framework which includes the role by opinion leaders, personal networks and public agencies as "amplification stations" that interpret and diffuse risk information. Collectively, these results suggest that increasing trusted local communication networks and culturally receptive warning formats may be just as important as enhancement of the technical availability of forecasts.

5.3 Livelihood change and adaptation

The long-term shift from diversified subsistence agriculture toward areca nut, often intercropped with black pepper, sits alongside household- and community-level adaptation roof and drainage improvements, emergency stockpiling, afforestation, and collective support during hazards and continues a transition from environment-based to non-traditional livelihood activity already documented at Totopara (Ghosh & Saha, 2017). Growing dependence on a single cash crop, however, runs counter to the diversification generally recommended in the adaptation literature: Kumar et al. (2025) report that monocropping and narrow livelihood options increase vulnerability among tribal farmers. The finding that sustained preparedness followed direct experience of a severe storm rather than the warning that preceded it is consistent with Kasperson et al. (2022), who treat both direct experience and communicated information as pathways through which risk perception forms; the observed pattern of community afforestation and collective coping matches the community- and ecosystem-based adaptation Kumar et al. (2025) describe. Overall, adaptation in Totopara combines autonomous household response, Indigenous practice, and collective action, even as increasing livelihood concentration may be generating new climate vulnerability of its own.

5.4 Strengths and limitations

This study's principal strength is its integrated treatment of Indigenous ecological knowledge, climate-risk communication, and adaptive action through the KCA pathway, rather than as separate processes. The ethnographic design combined in-depth interviews with participatory seasonal calendars, photo-elicitation, communicative-ecology mapping, diary entries written in Bengali, and the Most Significant Change technique, allowing triangulation across multiple data sources, and provides context-specific evidence from a small, geographically isolated PVTG that has received little attention in this literature.

These findings should be read within the study's ethnographic scope. The study was conducted in a single PVTG community using purposive and snowball sampling, drawing on thirteen participants, two of whom also contributed communicative-ecology diaries both drawn from a similar household-farming livelihood context, which may limit the range of occupational perspectives captured through this particular method; the findings are accordingly not intended to be statistically representative or directly generalisable to other PVTGs. The MSC account of post-hazard adaptation drew predominantly on one household's experience of a severe storm and may not represent responses to other hazards or households, and participants' perceptions of changing temperature, rainfall, and seasonality were not independently validated against meteorological records. Larger comparative samples across PVTGs, and integration of ethnographic findings with local climate and hazard data, would help establish how far these findings transfer beyond Totopara.

6. Conclusion

Climate-risk understanding and adaptation among the Toto emerge from the interaction of Indigenous ecological knowledge, contemporary communication systems, and lived experience of hazards. Indigenous indicators continue to inform how weather change is perceived, though their intergenerational transmission appears to be weakening. Formal climate information arrives at the community through a variety of pathways but is limited by coarse district-level forecasting and disrupted networks, and by the lack of established local communication mechanisms, leaving teachers, health workers, volunteers, and elders to act as informal intermediaries. We demonstrate that while greater livelihood reliance on areca nut may be generating new climate vulnerability, adaptation unfolds through household preparedness and livelihood adjustment, afforestation with timber and fodder species, and collective action at the community scale. These findings support the promotion of community-based preparedness mechanisms rather than solely top-down early-warning systems: locally relevant forecasts, voice- and Toto-language warnings, trusted community intermediaries who facilitate dialogue, and the integration of Indigenous knowledge with scientific forecasting.

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