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REVIEW ARTICLE
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Beyond Barometers: Bridging Indigenous Rainfall Prediction and Climate Science for Sustainable Agriculture: A Systematic Review

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ABSTRACT

The increasing unreliability of scientific weather models in localized, rain-fed agricultural systems has prompted growing interest in Indigenous Technical Knowledge (ITK) as a complementary forecasting tool. This systematic review examines the potential of integrating ITK into modern climate science, particularly artificial intelligence (AI)-based models, to enhance sustainable agriculture. Using the PRISMA 2020 framework, the study synthesizes findings from peer-reviewed articles and institutional reports published between 2000 and 2025 across Africa, Asia, Latin America, Oceania, and North America. Four dominant themes emerged: the typology of indigenous forecasting indicators, the challenges of reliability and knowledge erosion, and the prospects for integration with scientific systems. Results reveal that ITK employs a consistent range of bio-indicators, atmospheric cues, and astronomical observations, which, although locally accurate, face increasing disruption due to climate-induced variability. Case studies show that hybrid models-combining traditional indicators with AI and machine learning enhance forecast precision, farmer trust, and decision-making in agricultural planning. However, the review underscores significant ethical concerns around data sovereignty and knowledge appropriation, calling for co-production frameworks that center Indigenous communities as equal stakeholders. The study concludes that the integration of ITK and modern forecasting is not only scientifically advantageous but also essential for preserving cultural heritage and promoting climate resilience. These synergies can help shape climate services that are inclusive and locally grounded, offering support for sustainable agriculture in a rapidly changing global climate.

Keywords: Indigenous Technical Knowledge, Rainfall Prediction, Climate Adaptation, Sustainable Agriculture, Hybrid Forecasting.

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INTRODUCTION

The sustainability of rainfed agricultural systems in the Global South is increasingly challenged by the growing unpredictability of weather patterns (Qader et al., 2021). While satellite-based data and climate models offer broad-scale projections, they often fall short when it comes to local applicability. These tools frequently lack the nuance, cultural resonance, and trust necessary for widespread use among rural farming communities (Guido et al., 2021; Iticha & Husen, 2019).

In contrast, Indigenous Technical Knowledge (ITK) represents a deeply rooted and complex form of environmental understanding developed over centuries. This knowledge has been accumulated over hundreds of years through meticulous environmental observations. It is grounded in generations of keen observation, drawing from combinations of atmospheric phenomena, planetary signs, and bio-indicators to forecast location and season-specific rainfall (Paparrizos et al., 2023; Kaboré et al., 2024).

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This is a dynamic and empirically validated system that is written down in oral traditions and lived experiences (Nunn et al., 2024; Esquete Garrote, 2025). Despite its proven effectiveness, ITK remains largely excluded from formal climate forecasting systems. A significant gap persists in integrating this form of knowledge into contemporary predictive frameworks. While ITK-based forecasting is practised across the globe, its systematic integration into digital climate systems through artificial intelligence (AI) and machine learning (ML) is largely underexplored (Masinde, 2015; Gaur et al., 2024a; Soldatenko & Angudovich, 2024). This integration is not merely a technical endeavour but a necessary step toward ensuring both ecological and cultural sustainability. Recent studies on AI and ITK integration resulted in accurate and relevant weather forecasts. Kitsios et al. (2024) and Lynn et al. (2026) show that AI models that can derive data from indigenous weather indicators surpass traditional forecasting methods. Moreover, these AI-powered models predict precisely, in real-time and in alignment with local environment conditions (Zeiger et al. 2024; Gryshova et al. 2024).

This paper aims to meet the need for co-produced, hybrid forecasting frameworks. This paper synthesizes global case studies of ITK application and examines their methodological convergence with scientific and AI-driven systems. The objective is twofold: (1) to analyze the enduring utility and vulnerabilities of ITK in the context of accelerating climate variability and (2) to propose a conceptual framework for ethically and effectively integrating ITK with modern scientific and AI-based forecasting tools. This review bridges these parallel systems and contributes to the design of culturally legitimate, scientifically robust, and socially inclusive climate services that can underpin sustainable agriculture in a warming world.

MATERIALS & METHODS

This study employed a systematic literature review guided by the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to explore the role of Indigenous Technical Knowledge (ITK) in rainfall prediction and its integration with scientific forecasting systems. The review aimed at addressing the research question:

How does Indigenous Technical Knowledge contribute to rainfall forecasting, and how can it be harmonized with modern climate models to promote sustainable farming systems?

Search Strategy and Study Selection

Relevant literature was systematically sourced from academic databases including ScienceDirect, SpringerLink, ResearchGate, and Google Scholar covering the period from 2000-2025. A total of 684 records were initially retrieved. After the removal of 142 duplicates, 542 titles and abstracts were screened. Of these, 118 full-text articles were assessed for eligibility, leading to a final inclusion of 46 studies. The selection criteria focused on peer-reviewed articles, institutional reports, and case studies from regions where ITK plays a critical role in agricultural practices, particularly Africa, Asia, Latin America, and Oceania. Boolean search strategies were employed using keywords such as "*traditional rainfall prediction*," "*agriculture metrology*," "*hybrid climate forecasting*," and "*sustainable agriculture*."

Data Extraction and Management

Studies were screened for methodological soundness, thematic relevance, and language (English only). Materials such as opinion pieces, non-analytical content, or those outside the scope of climate-agriculture intersections were excluded. Eligible studies addressed cultural adaptability, the comparison between ITK and scientific approaches, and potential integration for sustainable farming outcomes.
Through thematic analysis, four major categories emerged:

- Indigenous forecasting indicators (e.g., animal behaviour, celestial cues),
- Reliability and limitations of traditional methods,
- Challenges in application and preservation, and
- Opportunities for integration with scientific forecasting tools, including artificial intelligence.

A summary of the selected studies is provided in Table 1 below.

The comparative review emphasized regional variations and the adaptive capacity of ITK under climate variability. The methodology ultimately aimed to synthesize existing knowledge, identify research gaps, and support strategies for ethically integrating ITK into contemporary climate services. The flow diagram outlines the process of literature identification, screening, eligibility assessment, and synthesis used in this study (Fig. 1).

RESULTS

A Global Synthesis of Indigenous Meteorological Knowledge

The systematic review of the literature reveals that Indigenous Technical Knowledge (ITK) for weather forecasting is a globally distributed, yet locally specified, phenomenon. The findings, synthesized from studies across five continents, are structured around the typology of indicators, their documented efficacy, and the emerging challenges posed by anthropogenic climate change. The case studies included in the Results section were selected through a rigorous, criteria-based process embedded within the broader systematic literature review. Selection prioritized peer-reviewed publications and institutional reports that provided empirical data on the use of Indigenous Technical Knowledge (ITK) for weather forecasting in agricultural contexts. Geographic representation was also a key criterion, ensuring inclusion of studies from diverse agro-ecological zones namely, sub-Saharan Africa, South and Southeast Asia, Latin America, Oceania, and North America where rain-fed farming systems are predominant. Case studies were further chosen based on their documentation of specific forecasting indicators, degree of methodological detail, and relevance to themes of knowledge integration, reliability under climate change, and sociocultural preservation. This purposive sampling approach enabled the synthesis of globally distributed yet contextually grounded insights into ITK practices.

Table 1: A summary of the selected studies, detailing geographic distribution, knowledge systems analyzed, and contributions to forecasting frameworks.

Region	Country	Knowledge Systems/Sample Indicators	Year	Key Contributions to Forecasting Frameworks
Africa	Ethiopia	Bird migration, tree phenology	2012	Indicators are still used, but their reliability is declining due to climatic shifts (Egeru, 2012).
	Zimbabwe	Lunar phases, star positions, tree phenology, animal behavior	2017, 2020	Mixed-method studies highlight both continued reliance and vulnerability to climate decoupling. (Ayal, 2017)
	Kenya	Cloud morphology, wind dynamics, and animal behaviour	2019	Strong local adherence to traditional signs suggests integration with digital tools (Ndichu, 2019).
	Uganda	Flowering trees, termite activity	2024	Effective at short-term rainfall prediction; recommended for use in hybrid models (Zeiger et al., 2024).
	Nigeria	Thunder patterns, wind movement, and insect appearances	1988	Older documentation underscores enduring practices among farming communities. (Ammarell, 1988)
Asia	India	Cloud morphology, bird migration, monsoon winds	2022	High local trust in indicators; recommendation for AI-based integration (Tirlapur et al., 2022).
	Nepal	Animal behaviour, dew/fog timing	1988	Culturally embedded signs highlight the need for formal documentation (Ammarell, 1988).
	Philippines	Moon halos, wind direction, tides	2021	Utilized in crop planning; underlines potential for digital hybridization (Irumva et al., 2021).
	Indonesia	Moon cycles, bird calls, local calendars	1988	Traditional calendars suggest strong alignment with ecological cycles (Ammarell, 1988).
Latin America	Bolivia	Celestial patterns, llama behaviour, clouds, winds	2017	Cultural embedding of ITK strengthens usability and legitimacy (Whitt, 2017).
	Peru	Pleiades visibility, animal signs, seasonal knowledge (pacha)	2020	Shows strong integration between ecological observation and agricultural timing (Zounon et al., 2020).
Oceania	Fiji	Coconut flowering, seabird behaviour, wind patterns	2024, 2025	Vital for cyclone preparedness; supports incorporation into national early warning systems (Ali et al., 2025; Nunn et al., 2024).
	Vanuatu	Weather lore, cloud formations	2019	Emphasizes ethno-climatological framing; promotes participatory climate tools (Chambers et al., 2019).
	Papua New Guinea	Flora/fauna observation, traditional calendars	2019	Highly place-based; suggests preservation through community-led digitization (Chambers et al., 2019).
	Australia	Sky lore, faunal behaviour ("bush signals")	2009	Traditional ecological knowledge is strongly tied to seasonal agricultural cycles (Clarke, 2009)
North America	Canada	Sea ice, animal migration, wind patterns	2018	Blends cryosphere knowledge with scientific forecasts, applied to navigation and farming in Arctic regions (Panikkar et al., 2018)

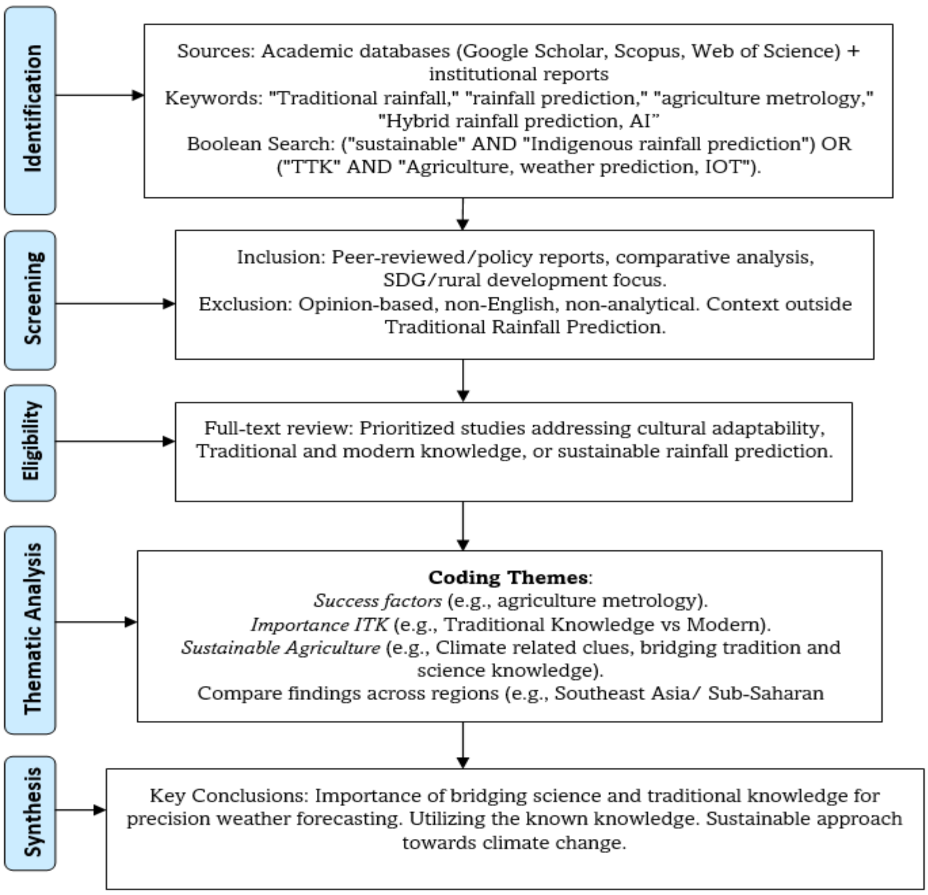

Fig. 1: PRISMA 2020 Flow Diagram of the Systematic Review Process.

A Global Typology of Indigenous Forecasting Indicators

Across diverse geographies and cultural contexts, ITK systems rely on a consistent set of observational domains. Fig. 2 depicts the global distribution of these systems, revealing significant geographic clusters in sub-Saharan Africa, South and Southeast Asia, and Oceania regions highly dependent on rain-fed agriculture. Research synthesis identifies four primary categories of indicators: Astro-meteorological: The observation of celestial bodies,

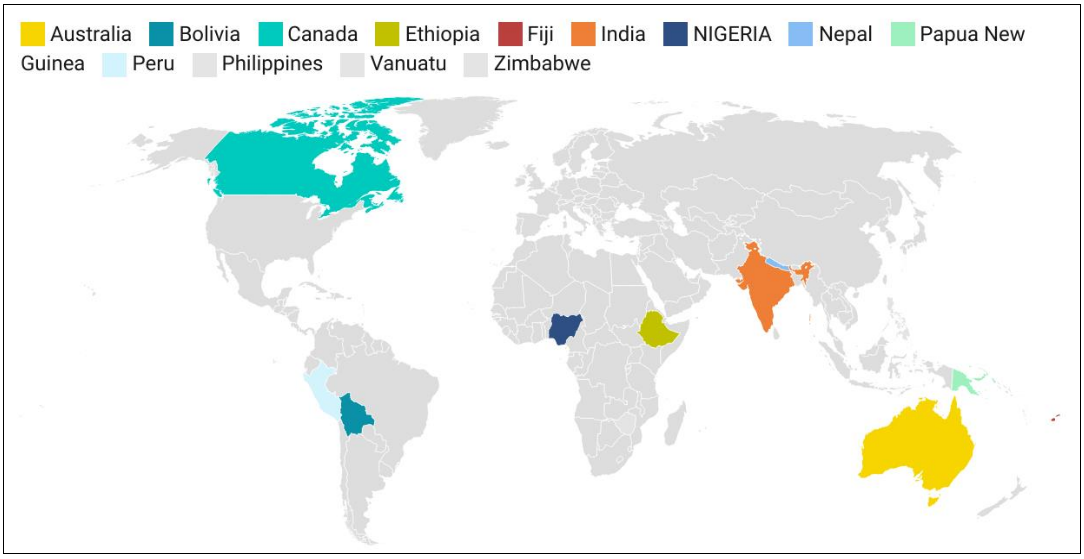

Fig. 2: Global map showing countries with documented Indigenous Technical Knowledge (ITK) systems for agricultural weather forecasting. Geographic clusters appear in sub-Saharan Africa, South and Southeast Asia, and Oceania—regions reliant on rain-fed agriculture.

which includes the moon's halo, the visibility and colour of stars, and specific planetary alignments, which is a common practice for forecasting seasonal shifts, particularly in arid and semi-arid regions of Africa and Asia (Chhangte, 2024; Risiro, 2012; Sekhar et al., 2024; Waktola, 2025).

- *Bio-indicators*: This is the most widely documented category, encompassing the phenology of specific plant species and the behaviour of fauna. For example, afar pastoralists in Ethiopia interpret the migratory patterns of birds and the activity of specific insect species as reliable short-term rainfall predictors (Alsharef & Hassan, 2024). Similarly, Iteso communities in Uganda have historically relied on the flowering of the *Erythrina abyssinica* tree to signal the onset of the rainy season (Egeru, 2012).
- *Atmo-physical Indicators*: This involves the interpretation of wind direction and strength, cloud morphology and colour, and atmospheric humidity. In the archipelagic nations of the Pacific, intricate wind lore forms a cornerstone of marine and agricultural planning (Garibay-Toussaint et al., 2024).
- *Cosmological Frameworks*: In some regions, such as the Yucatán Peninsula, forecasting is deeply embedded within a broader cosmological or spiritual framework, where observations are interpreted through a culturally specific worldview to guide agricultural cycles (Kom et al., 2024).

Case Study: The Rich ITK Corpus of the Pacific Islands

The Pacific Islands demonstrate a highly sophisticated and multi-faceted corpus of ITK, deeply integrated with marine and agricultural livelihoods. As detailed in Table 2, these systems rely on a complex interplay of astro-meteorological, atmo-physical, oceanographic, and bio-indicators from observing the behaviour of seabirds to interpreting wave patterns and cloud morphology (Harrison et al., 2024; Moon, 2024). This rich, localized knowledge is vital for preparing for catastrophic weather events like cyclones in regions with limited modern meteorological infrastructure (Chen & Pietrzak, 2025).

The Dual Threat: Climate-Induced Decoupling and Socio-Cultural Erosion

While the efficacy of ITK is well-documented, our synthesis reveals a consensus in the literature that these knowledge systems face a dual existential threat. The first is the previously mentioned climate-induced indicator, decoupling, where unpredictable weather patterns are weakening the reliability of traditional forecasting methods (Egeru, 2012; Garibay-Toussaint et al., 2024). This challenge is acutely felt in regions like Southern Africa, where farmers report diminishing confidence in historically reliable indicators due to increasing climatic variability (Jiri et al., 2016; Uzoechina, 2025). This erosion of predictive power introduces significant economic risk and uncertainty for all agricultural stakeholders, from farmers to governments (Hammer et al., 2001; Kitsios, 2024; Zeng, 2024).

The second equally critical threat is socio-cultural erosion. However, where indicators remain partially effective, the integrity of ITK is threatened by internal and external social pressures. In Ethiopia, for example, the literature highlights that traditional ecological knowledge is being actively undermined by religious criticism, skepticism from younger generations. The knowledge loss results because they favour modern technology and a systemic lack of formal documentation (Kidemu et al., 2020). Indigenous Traditional Knowledge (ITK) preservation requires more than adapting practices to environmental changes. It requires addressing social dynamics that influence the recognition and respect of ITK within communities and institutions. Crucially, it entails fostering mechanisms for the effective transmission of knowledge across generations to ensure its continuity.

The Rise of Modern Forecasting and Methodological Integration

Concurrent with the challenges facing ITK, literature documents a rapid evolution in scientific weather forecasting, driven primarily by computational power. Modern agricultural meteorology now leverages vast datasets and advanced models to inform decision-making, from crop selection to risk management (Han et al., 2024). This process, which translates large-scale climate data into actionable farm-level strategies, is visually summarized in Fig. 3.

Table 2: A Typology of Indigenous Technical Knowledge Indicators in the Pacific Islands

Method	Description	Associated Island Groups	Reference (s)
Watching the Moon stages	The moon's phases and overall appearance can provide clues about impending weather changes and seasons.	Polynesia, Micronesia	(Cherry & Leppard, 2025)
Animal Behaviour	The behaviour of certain animals, such as seabirds, can signal weather changes. For example, a change in the migration patterns of birds might indicate storms.	Various Pacific Islands (including Hawaii)	(Moon, 2024; Wilson, 2025)
Wind and Cloud Patterns	Specific cloud types and wind direction are indicators of weather changes. For example, the direction of winds and the type of clouds can predict rain or clear weather.	Samoa, Tonga, Fiji	(Harrison et al., 2024; Singh et al., 2024)
Tides and Ocean Currents	Changes in tides or unusual ocean currents can indicate a storm or changes in the weather.	Pacific Islands, especially in coastal regions	(Taira et al., 2024)
Star and Sky Patterns	The position of stars, planets, and the sun's movement across the sky are used for long-term weather predictions. This method was especially useful for navigation.	Polynesia, Micronesia	(Dotte Sarout, 2023)
Tree and Plant Behaviour	Certain trees, such as the coconut palm, are observed for signs of upcoming weather. For example, the way the leaves move, or the direction of the wind can indicate storms.	Samoa, Fiji, Tonga	(Ali et al., 2025; Balick et al., 2024; Singh et al., 2024)
Animal Tracks and Insects	The activity of certain insects (like ants and crickets) and animal tracks can predict weather patterns, including rain or storms.	Solomon Islands Papua New Guinea	(Barry, 2025)
Sound of the Ocean or Winds	The sound of the ocean or the wind, such as increased wind noise or unusual waves, can signal an impending storm.	Cook Islands, Tuvalu	(Taonui, 2006)

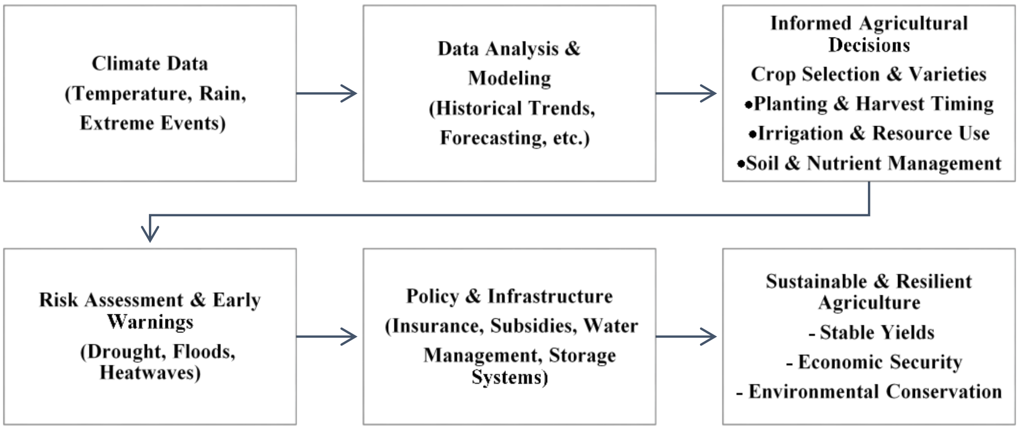

Fig. 3: Schematic Flowchart of Modern Climate Services in Agriculture; Source: (Gryshova et al., 2024; Mukherjee & Fransen, 2024).

Information on the key agricultural decisions, like crop choice and planting times, is important. The flow chart in Fig. 3 illustrates how climate data (e.g., temperature, rainfall, extreme events) is analyzed and modeled. These insights support early warnings for risks such as droughts and floods. Risk assessments guide policy and infrastructure development, including insurance, subsidies, and water management. Together, these steps promote sustainable and resilient agriculture. The outcome is improved yields, economic stability, and environmental conservation.

The use of machine learning (ML) and artificial intelligence (AI) has been the most prominent development in recent years. These methodologies are better because they can analyze extensive observational and model data to identify predictive patterns with greater efficiency than traditional physical models (Soldatenko & Angudovich, 2024). AI-driven tools are now being developed and deployed by major meteorological agencies for multi-year ENSO forecasting, hurricane identification, and high-resolution rainfall prediction (Felsche & Ludwig, 2021; Rolnick et al., 2022; Sun et al., 2022). Additionally, the Internet of Things (IoT) enables a paradigm of "smart agriculture," which allows data-driven insights into climate, soil conditions and value chain management (Gaur et al., 2024b; Johnraja et al., 2024). The development of hybrid knowledge systems is currently the subject of a sizable amount of recent literature. These knowledge systems acknowledge the limitations of purely technical models (e.g., lack of local context) and the challenges facing ITK. These studies propose the systematic integration of ITK with scientific methods, which improve prediction accuracy and enhance community resilience, particularly in agricultural and water resource management (Alessa et al., 2016).

DISCUSSION

This systematic review synthesized the global landscape of ITK for agricultural forecasting, revealing a knowledge system that is both globally prevalent and acutely vulnerable. The findings of the widespread distribution of ITK (Fig. 2), the consistency of its indicators (Table 3 and 4), the dual threats of decoupling and erosion, and the parallel rise of powerful AI tools necessitate a critical discussion of its utility and the imperative for its integration with modern science.

The Paradox of ITK: Enduring Relevance vs. Climate-Induced Instability

A central paradox emerging from this review is the persistent reliance on and trust in Indigenous Technical Knowledge (ITK), even as its biophysical foundations are being destabilized by climate change. While our results confirm that "indicator decoupling" threatens the predictive accuracy of many traditional signals (Jiri et al., 2016), the value of ITK transcends mere meteorological precision. Its continued importance stems from its nature

Table 3: A Global Synthesis of Indigenous Technical Knowledge (ITK) Indicators for Agricultural Weather Forecasting

Region	Country	Primary ITK Indicators Documented	Reference (s)
Africa	Zimbabwe	Astro-meteorological (lunar phases, star positions); Bio-indicators (tree phenology, animal behaviour).	(Ayal, 2017)
	Kenya	Atmo-physical (cloud morphology, wind dynamics); Bio-indicators (animal behaviour).	(Ndichu, 2019; Rankoana, 2023)
	Uganda	Bio-indicators (phenology of specific trees, termite activity).	(Zeiger et al., 2024)
	Nigeria	Farmers use thunder patterns, wind movement, and insect appearances to make farming decisions.	(Ammarell, 1988)
Asia	India	Local farmers observe bird migration, insect behaviour, and monsoon winds (e.g., in Andhra Pradesh and Rajasthan).	(Tirlapur et al., 2022)
	Nepal	Indigenous groups like the Tharu observe animal behaviour and the timing of dew or fog to predict rainfall.	(Ammarell, 1988)
	Philippines	Communities track cloud types, wind direction, moon halos, and tides for crop planning.	(Irumva et al., 2021)
	Indonesia	Farmers use local ecological calendars based on moon cycles and bird calls.	(Ammarell, 1988)
South America	Peru	Andean communities use pacha (seasonal knowledge), star visibility (e.g., Pleiades), and animal signs.	(Zounon et al., 2020)
	Bolivia	Aymara and Quechua farmers observe clouds, wind, and celestial signs for agricultural planning.	(Whitt, 2017)
Oceania	Papua New Guinea	Use of traditional calendars and observation of local flora and fauna to anticipate rain and drought.	(Chambers et al., 2019)
	Vanuatu	Atmo-physical (cloud formations); Ethno-climatological ("weather lore").	(Chambers et al., 2019)
	Australia	Astro-meteorological ("sky lore"); Bio-indicators (faunal behaviour, "bush signals")	(Clarke, 2009)
	Fiji	Atmo-physical (wind patterns); Bio-indicators (flowering of specific coastal plants).	(Nunn et al., 2024)
North America	Canada	Cryosphere (sea ice conditions); Bio-indicators (animal migration); Atmo-physical (wind patterns)	(Panikkar et al., 2018)

Table 4: A Framework of Complementarity between Indigenous and Modern Forecasting Systems

Aspects	Traditional Knowledge Contribution	Modern Knowledge Contribution	Combined Benefit
1. Local Relevance	Provides site-specific, culturally grounded insights	Offers regional/global scale forecasts	Enhances local applicability of scientific forecasts
2. Timeliness of Forecasts	Allows for real-time observation and rapid interpretation	Provides early warnings based on models with satellite data	Makes people more ready for both immediate and distant weather disasters
3. Resource Optimization	Informs optimal timing of planting, harvesting, and irrigation	Supports planning through seasonal climate predictions	Reduces risks and maximizes resource use for higher productivity
4. Farmer Trust and Adoption	Highly trusted and accepted within local communities	Often met with skepticism or limited understanding	Increase adoption of forecasts when both systems are respected and used together
5. Biodiversity Awareness	Linked to ecological indicators (plants, animals)	Often lacks connection to local biodiversity	Promotes sustainable farming practices and ecological balance
6. Climate Adaptation Strategies	Offers adaptive responses passed down through generations	Provides scientific data for long-term climate trends	Strengthens resilience to climate variability and extreme weather
7. Knowledge Continuity	Preserves indigenous heritage and environmental literacy	Advances innovation through technology and research	Fosters intergenerational learning and cross-disciplinary collaboration
8. Limitations Addressed	May lack precision and coverage in extreme events	May miss local context or be inaccessible	Fills knowledge gaps and overcomes individual limitations of each system

as a holistic, culturally embedded system. Unlike top-down scientific forecasts, ITK is inherently place-based, trusted, and directly linked to local decision-making frameworks for land and resource management (Tam, 2024). Therefore, we argue that the primary utility of ITK in an era of climate change may not be its absolute predictive power, but its function as a resilient socio-ecological framework for community-level adaptation.

Recent Advances: Successful Hybrid Models Combining AI and ITK

The new case studies highlight hybrid forecasting models that combine AI and ITK. For example, the ITIKI system of Masinde (2015) used in South Africa and Kenya combined machine learning algorithms with conventional indicators (such as flowering trees and animal behaviour) to provide early warnings for drought. Tam (2024) reported on a cooperative ITK-based livestock prediction pilot in Baringo, Kenya. Early warning systems used satellite data to cross-validate these predictions, which were digitally encoded. The Pacific Meteorological Council's climate resilience platform used natural language processing, combined forecasts derived from satellites with oral climate narratives (Chambers et al., 2019). These initiatives show that hybrid models are being actively tested and implemented with encouraging results in terms of forecast accuracy, farmer uptake, and local legitimacy, demonstrating that they are not merely theoretical goals.

A Framework for Epistemological Integration: Synthesizing Two Worldviews

The central argument of this review is that the path to climate-resilient agriculture lies not in choosing between ITK and modern science, but in their systematic and respectful integration. The weaknesses of one system are often the strengths of the other, creating a powerful potential for complementarity. As synthesized from the literature, Table 4 presents a framework outlining this synergistic relationship.

This framework demonstrates that integration can enhance local relevance, improve timeliness, and crucially build the farmer's trust necessary for adoption (Radeny et al., 2019). The emergence of AI offers a powerful new mechanism to achieve this integration. Rather than replacing ITK, AI can serve as a bridge, translating the qualitative, observational data of ITK into a format that can be processed alongside quantitative scientific data (Price et al., 2025). Table 5 outlines the potential outcomes of such socio-technical integration.

This ITK-AI integration can enrich forecast accuracy, support the digital preservation of at-risk knowledge, and enable the co-design of forecasting tools that are both technically robust and culturally legitimate (Masinde, 2015).

Critical Challenges to Integration: Beyond the Technical

Combining different knowledge systems has great potential; however, putting it into practice is not easy.

Table 5: Integration of ITK with Artificial Intelligence (AI) and its Outcomes

Aspect	Role of Traditional Knowledge (TK)	Role of Artificial Intelligence (AI)	Integrated Outcome
1. Forecast Accuracy	Uses localized, experience-based indicators (e.g., stars, animals, plants)	Analyzes large datasets for pattern recognition and prediction	Enhanced precision in localized and seasonal forecasts
2. Data Enrichment	Offers rich, qualitative ecological data from generations of observation	Converts traditional data into structured formats for model training	Hybrid models that incorporate both cultural and scientific inputs
3. Cultural Relevance	Deeply rooted in local customs and belief systems	Often lacks local context unless specifically trained	Improved trust and adoption of forecasts among local farming communities
4. Climate Adaptation	Adaptive responses to environmental change through observation	Provides simulations and trend analysis for long-term planning	Strengthened community resilience to climate variability
5. Preservation of Knowledge	At risk of loss due to modernization and oral transmission	Capable of digitizing and archiving indigenous knowledge	Long-term preservation and documentation of TK
6. Accessibility and Use	Communicated through oral traditions and community leaders	Can deliver real-time information through apps and devices	Wider dissemination of forecasts to diverse audiences, including rural farmers
7. Participatory Development	Relies on community participation and consensus	Often developed by scientists and data experts	Co-designed systems that are both technically sound and socially acceptable
8. Ethical and Ownership Issues	Concerns over appropriation of indigenous knowledge	Risk of misuse or misrepresentation of cultural data	Necessity for inclusive frameworks ensuring consent, attribution, and fair benefit

One major challenge is the clash between two ways of understanding the world: Indigenous Traditional Knowledge (ITK), which sees knowledge as interconnected and relational, and Western Science, which tends to break things down into separate parts and focuses on measurable evidence. Even more importantly, there are ethical concerns about who owns the knowledge, who controls the data, and the risk of it being misused or taken without proper recognition. For any meaningful collaboration to happen, Indigenous communities must be fully involved as equal partners, not just treated as sources of information. This means setting up clear guidelines for consent, giving proper credit, and ensuring that benefits are shared fairly so that Indigenous knowledge is respected and not exploited (Chambers et al., 2019; Lynn et al., 2026).

Ethical Considerations and Data Sovereignty in Knowledge Integration

Bringing Indigenous Traditional Knowledge (ITK) into modern science raises important ethical concerns that go beyond whether it's technically possible. A major issue is when this knowledge is digitized, used for profit, or misrepresented without proper permission or credit. This can lead to "epistemic extractivism", a form of knowledge exploitation (Chambers et al., 2019; Lynn et al., 2026). Sometimes, AI models use traditional ecological knowledge without clear or transparent rules of data handling, and therefore, data sovereignty becomes a key ethical principle. Indigenous communities should have full control over their knowledge, and any effort to use or share it must follow the principles of free, prior, and informed consent (FPIC). This means that Indigenous peoples must be properly informed and freely agree on how their knowledge will be used before anything moves forward. Co-designed governance frameworks should explicitly define rights of use, authorship, and benefit-sharing. This avoids scenarios where ITK is treated as "open data" for unilateral use. Without this ethical scaffolding, hybrid forecasting does not work as a tool for climate justice; rather, it becomes a new form of digital colonization.

Limitations and Future Research Directions

This review, while comprehensive, is constrained by its reliance on English-language publications, potentially underrepresenting the wealth of knowledge documented in other languages. Furthermore, a publication bias may exist toward successful case studies of ITK. Acknowledging these limitations, our synthesis points toward a clear and urgent agenda for future research:

1. ***Quantifying Indicator Decoupling*:** Empirical studies are urgently needed to systematically quantify the changing correlation between traditional bio-indicators (e.g., plant phenology) and meteorological outcomes under various climate change scenarios. This would allow for the identification of which indicators remain robust and which require recalibration.

2. ***Ethnographic Documentation and Digital Preservation*:** There is a critical need for participatory, community-led projects to document ITK before it is lost. This includes not only the indicators themselves but also the complex cultural and linguistic frameworks through which they are interpreted (Hanson et al., 2025). Getting young people involved in these projects is essential to passing knowledge and skills through intergenerational transmission (Khan & Sharma, 2024).

3. ***Developing and Validating Hybrid Models*:** Action-research projects are required to pilot and assess the performance of co-produced hybrid forecasting models in diverse Agro-ecological contexts. These studies must prioritize ethical engagement and ensure that indigenous partners are treated as co-researchers, not just data sources.

Conclusion

This review underscores the significance of Indigenous Technical Knowledge (ITK) as a culturally embedded and adaptive system with substantial, yet underutilized, potential in contemporary climate governance. ITK is a means of environmental adaptation and preserves ecological knowledge over generations. Therefore, it is essential to recognize, protect, and operate traditional forecasting systems. Institutional mechanisms and supportive legal frameworks must be established by Policymakers which integrate ITK into national climate adaptation strategies. ITK could be integrated into meteorological education, which may include the development of community-based early warning systems and the incorporation of indigenous practices into agricultural extension services. Furthermore, future research should prioritize the development of participatory artificial intelligence (AI) co-design frameworks that treat ITK holders as equal collaborators rather than passive subjects. Such frameworks should aim to produce transparent and interpretable AI models that incorporate qualitative ecological indicators, thereby preserving cultural relevance while enhancing the models' technical accuracy. Ultimately, a transdisciplinary and inclusive approach is required to advance climate-resilient agriculture, one that not only leverages scientific innovation but also upholds social justice and empowers local communities through the meaningful inclusion of Indigenous knowledge systems.

DECLARATIONS

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