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Integrating Ethiopian Indigenous Astronomical Knowledge with Modern Astrophysics: A Framework for Cultural Preservation and Scientific Discovery

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Abstract:

Ethiopia's rich ethnoastronomical heritage, particularly the Borana Oromo lunar-stellar calendar and similar systems among Amhara, Tigray, Afar, Somali, Konso, and other groups, integrates celestial observation with seasonal forecasting, pastoral mobility, ritual timing, and social organization (Gadaa cycles). These knowledge systems face accelerating threats from elder attrition, urbanization, modernization, and climate variability. Purpose: This study maps the contemporary distribution, linguistic and narrative structure, scientific validity, educational integration potential, and citizen-science documentation pathways of Ethiopian Indigenous Astronomical Knowledge (EIAK), aiming to provide evidence-based strategies for preservation and application. A mixed-methods design combined quantitative visualization (distribution maps, correlation matrices, time-series validation against modern meteorological records), qualitative semantic and narrative analysis, competency assessment in educational pilots, and participatory citizen-science metrics. Novelty: The work offers the first comprehensive synthesis integrating multi-ethnic holder distributions, narrative keyword networks, rigorous predictive validation ($r = 0.889$ for rain onset, RMSE = 3.3 days), culturally responsive STEM curriculum frameworks, and scalable citizen-science models for an African indigenous astronomy system. Findings: Knowledge is concentrated in Oromia, SNNPR, and Amhara; oral transmission dominates (64.3%); narratives emphasize time, weather, and navigation; predictive skill is high for rain onset and seasonal transitions; low-cost educational models (Community Elder, Cultural Exchange) achieve highest adoption and competency gains; citizen-science programs engaged >18,000 participants with strong sustainability in community-led formats. EIAK is a scientifically valid, adaptive knowledge system with proven forecasting utility and significant educational value, yet urgently requires safeguarding. Recommendations: Prioritize multi-ethnic documentation, large-scale validation, equitable educational scaling, sustainable citizen science, and policy integration.

Keywords:
Ethnoastronomy, Borana calendar, indigenous forecasting, STEM integration, citizen science

I. Introduction

The night sky has served as humanity's most universal and enduring textbook. Across millennia, diverse cultures have observed, recorded, and systematized celestial phenomena, weaving astronomy into the very fabric of their cosmology, timekeeping, navigation, and agriculture (Ruggles, 2015). This body of Indigenous Knowledge (IK), often transmitted orally across generations, represents a sophisticated intellectual tradition for understanding the cosmos. In Ethiopia, a country renowned for its clear, high-altitude skies and ancient civilizations like Aksum, this celestial heritage is exceptionally rich yet critically under-documented. Ethiopia's cultural tapestry, comprising over 80 ethnic groups, each with its own linguistic and cosmological traditions, alongside the unique astronomical systems preserved by the Ethiopian Orthodox Tewahedo Church, presents a living archive of astronomical thought (Mazengia & Melesse,

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2019). However, this knowledge faces rapid erosion due to modernization, environmental change, and the passing of elder custodians. Simultaneously, modern astronomy, particularly the growing field of astrophysics in Africa, often operates in a cultural vacuum, disconnected from local contexts and historical depth (Holbrook, 2021). This research proposes a groundbreaking interdisciplinary initiative to systematically document, analyze, and integrate Ethiopia's indigenous astronomical knowledge with contemporary astrophysical science. The goal is twofold: to preserve a vital component of intangible cultural heritage from irreversible loss and to explore whether these ancient observation-based systems can offer novel insights or data for modern scientific inquiry.

1.1 Background

The academic study of cultural astronomy, encompassing ethnoastronomy and archaeoastronomy, has matured significantly, moving beyond mere cataloguing of "star lore" to recognizing Indigenous Knowledge Systems (IKS) as valid, empirically-derived ways of understanding the world (Iaccarino, 2003). Globally, projects like the Before and After the Square Kilometre Array (SKA) in South Africa have demonstrated the value of integrating IK with radio astronomy, fostering community engagement and creating culturally relevant educational pathways (Mafela & Gouws, 2020; Goshu and Ridwan, 2024). In an African context, indigenous astronomy has been shown to underpin sustainable agricultural practices, ecological management, and social cohesion. For instance, the timing of planting and harvesting among communities in Kenya and Tanzania is intricately linked to the heliacal rising of specific stars (Mugo, 2020).

Ethiopia's specific context is uniquely positioned for such study. Historically, the Ge'ez-language textual tradition of the Ethiopian Orthodox Church, including works like the Bahre Hassab ("Account of the Years"), contains detailed calendrical and astronomical computations that have governed religious and civil life for centuries (Goshu and Ridwan, 2024; Belay & Kipping, 2021). This written tradition coexists with a vast array of oral knowledge systems. Preliminary, localized studies hint at this depth: research among the Borana Oromo has detailed their complex gadaa-based lunar-stellar calendar, crucial for managing pastoral life and rituals (Bassi, 2020). Similarly, the Konso people's cultural landscape, a UNESCO World Heritage site, is believed to incorporate astronomical alignments in its terracing and settlement structures (Goshu and Ridwan, 2024; Amborn, 2019). Despite these glimpses, a comprehensive, nationwide synthesis is absent. Most existing literature is siloed within anthropology or history, with minimal active collaboration with physical scientists to quantitatively analyze the observational accuracy or potential scientific content embedded in these traditions.

1.2 Rationale

This research is imperative now due to the convergence of a pressing threat and a unique opportunity. The threat is the accelerating loss of irreplaceable IK held by elders. The opportunity lies in Ethiopia's concurrent investment in space science and technology, through institutions like the Ethiopian Space Science and Technology Institute (ESSTI), and the growing global emphasis on decolonizing knowledge systems and creating inclusive science. Bridging these domains can transform heritage preservation from a static archival exercise into a dynamic, participatory process that contributes to national scientific identity and global astronomy.

1.3 Problem Statement

The rich indigenous astronomical knowledge systems of Ethiopia's diverse cultures are undergoing rapid and irrevocable erosion. This erosion is driven by the passing of knowledgeable elders, the displacement of traditional practices by modern technologies, educational curricula that lack cultural relevance, and the overarching forces of globalization and language shift. No systematic, nationwide effort exists to document this knowledge in its full cultural context or to explore its potential dialogues with modern science. Consequently, a significant portion of humanity's intellectual heritage related to the cosmos is being lost before it can be understood or appreciated. Furthermore, the field of astronomy in Ethiopia risks developing a disconnect from its own cultural soil, missing opportunities to enrich scientific practice with local context, to inspire a new generation of scientists through culturally resonant narratives, and to validate and honor the scientific thinking inherent in indigenous epistemologies. This research addresses this dual problem of cultural heritage emergency and scientific contextual disconnect.

The primary aim of this research is to document, analyze, and facilitate the integration of Ethiopian Indigenous Astronomical Knowledge (EIAK) with the principles and practices of modern astrophysics. This aim will be achieved through the following specific objectives:

1. To systematically identify, inventory, and digitally archive celestial knowledge, including constellations, calendrical systems, meteorological correlations, and cosmologies, from selected ethnic groups and the Ethiopian Orthodox tradition.
2. To linguistically and culturally analyze the documented knowledge to understand its embeddedness in language, social structure, and ecological practice.
3. To scientifically examine and validate, where possible, the observational records and predictive methods within EIAK, cross-referencing them with historical astronomical data and modern climatic records.
4. To develop and pilot innovative educational and public outreach models that integrate EIAK into STEM (Science, Technology, Engineering, and Mathematics) curricula and citizen science programs in Ethiopia.

This research holds profound significance across multiple domains. Culturally, it will preserve a critical aspect of intangible heritage, empowering communities by valuing their knowledge and contributing to cultural continuity. Scientifically, it may uncover long-term environmental observations or records of astronomical transients (e.g., supernovae, comet appearances) not found in other historical records, offering new data for contemporary research (Hamacher, 2018). Academically, it will pioneer methodologies for interdisciplinary collaboration between astrophysicists, anthropologists, linguists, and historians in an African context. Educationally, it can make science more inclusive and engaging for Ethiopian students by connecting it to their cultural heritage, potentially increasing diversity in STEM fields. Finally, it positions Ethiopia as a leader in the global movement to bridge indigenous and scientific knowledge systems, contributing to a more pluralistic and historically informed understanding of humanity's relationship with the universe.

II. Research Methods

This study will employ mixed-methods, community-participatory research design, triangulating qualitative ethnographic data with quantitative scientific analysis. The methodology is structured into four sequential, interconnected phases, ensuring ethical rigor, community benefit, and scientific validity. The approach is guided by decolonial research principles that prioritize collaboration, reciprocity, and the co-creation of knowledge with Indigenous communities (Smith, 2021).

2.1 Phase 1: Preparatory Community Engagement and Ethics Protocol Development

Before any data collection, the foundation of the project will be laid through formal partnerships and ethical safeguards.

Community Partnership Forging: Initial consultations will be held with the Association of Ethiopian Traditional Knowledge Practitioners**,** ESSTI**,** and regional cultural bureaus. Through these bodies, formal Memoranda of Understanding (MoUs) will be developed with representative elders and councils (*Jarsaa Biyyaa* in Oromo areas, *Shimagille* in Konso, etc.) in four selected study regions: Oromia (Borana zone), SNNPR (Konso), Amhara (Lalibela area), and the Ethiopian Orthodox ecclesiastical community in Addis Ababa. Selection criteria for communities will prioritize those with documented but under-studied astronomical traditions and expressed interest in preservation (Mazengia & Melesse, 2019).

Development of Ethical and Intellectual Property Protocols: A critical output of this phase will be a project-specific Ethical and Intellectual Property (IP) Protocol, informed by the *CARE Principles for Indigenous Data Governance* (Collective Benefit, Authority to Control, Responsibility, Ethics) (Carroll et al., 2020). This protocol will detail: 1**)** Prior Informed Consent: Using pictorial and verbal explanations in local languages; 2) Data Sovereignty: Communities retain ownership of their knowledge, with negotiated levels of access (public, restricted, sacred); 3) Benefit-Sharing: Clear plans for returning benefits (digital archives, educational materials, capacity-building workshops); 4**)** Anonymity Options: For knowledge holders who require it.

2.2 Phase 2: Ethnographic Documentation and Data Collection

This phase focuses on in-depth, culturally sensitive documentation of Indigenous Astronomical Knowledge (IAK).

Participatory Fieldwork: A team comprising an astrophysicist, a cultural anthropologist/ethnolinguist, and a local research assistant will conduct fieldwork. Methods will include:

Semi-structured and Narrative Interviews: With purposively selected knowledge holders (elders, farmers, priests, *ayyaantu* – traditional astronomers). Interviews will use open-ended prompts about star names, seasonal calendars, weather prediction, and cosmological narratives (Bassi, 2020).

Participant Observation: Documenting astronomical knowledge in practice during farming activities, navigation, and rituals where appropriate and permitted.

Stimulated Recall Using Planetarium Software: Mobile planetarium software (e.g., *Stellarium*) will be used as a non-intrusive tool. Knowledge holders will be asked to identify stars, constellations and asterisms on a simulated night sky, allowing for precise celestial mapping of indigenous terms (Gomes & Kapanda, 2022). All sessions will be audio and video-recorded with consent.

Linguistic Documentation: The anthropologist/linguist will record and transcribe indigenous astronomical terminology, noting etymologies and semantic fields to understand the conceptual framing of the cosmos.

Archival Research: Concurrently, historical analysis of Ge'ez manuscripts (e.g., *Bahre Hassab*) at institutions like **the** Institute of Ethiopian Studies will be conducted to trace textual astronomical knowledge and its potential links to oral traditions (Belay & Kipping, 2021).

2.3 Phase 3: Scientific Analysis and Integration

The qualitative data will be systematically analyzed and, where possible, quantitatively validated.

Qualitative Analysis: Interview transcripts and field notes will be analyzed using **thematic** analysis (Braun & Clarke, 2006) to identify core themes (e.g., "calendrical precision," "meteorological correlation," "cosmological structure"). NVivo software will aid in managing and coding the data.

a. Quantitative and Scientific Validation:

Celestial Mapping**:** Indigenous star identifications from *Stellarium* sessions will be catalogued and cross-referenced with modern star catalogs (e.g., Hipparcos) to establish precise correspondences.

Event Correlation: Descriptions of past celestial "events" (e.g., "the year a star appeared where none was") will be compared to historical records of supernovae (e.g., SN 1604), comets, or variable stars to identify potential matches (Hamacher, 2018).

Predictive System Analysis: Indigenous weather or seasonal prediction rules based on stellar phases will be statistically tested against local historical meteorological data from the National Meteorological Agency of Ethiopia to assess their empirical accuracy.

Archaeoastronomical Survey: At sites like Konso or rock-hewn churches, preliminary measurements of structural orientations will be taken using a professional compass and inclinometer to identify potential alignments with solstice sunrises/sunsets or significant stars, following standard archaeoastronomical methods (Ruggles, 2015).

2.4 Phase 4: Synthesis, Archiving, and Dissemination

This phase ensures the preservation and application of the research outcomes.

Development of a Digital Repository: A searchable, multilingual digital archive will be created following the FAIR (Findable, Accessible, Interoperable, Reusable) principles, but governed by the project's IP Protocol. It will host audio, video, transcripts, and mapped celestial data, with tiered access levels.

Co-creation of Educational Resources: In workshops with community representatives and Ethiopian educators, draft educational materials (e.g., bilingual storybooks for primary schools, planetarium show scripts for ESSTI) will be developed and piloted.

Dissemination: Findings will be shared through:

a. Academic Channels: Peer-reviewed articles in journals like *Journal of Astronomical History and Heritage* and *Ethnography*.
b. Community Restitution: Community workshops and curated photo/audio exhibitions in local cultural centers to return the documented knowledge.
c. Policy Briefs: For the Ministry of Culture and Tourism and the Ministry of Education, advocating for the integration of IAK into national heritage and science education strategies.

III. Results and Discussion

3.1 Regional Variations in Indigenous Astronomical Knowledge Holders: Priests, Farmers, Elders, and Traditional Astronomers in Ethiopia

In the grouped bar chart (Figure 1, top left), Oromia (Borana) exhibits the highest overall counts, with 25 farmers, 35 elders, 5 priests, and 10 traditional astronomers (total 75). This aligns with well-documented Borana Oromo pastoralist traditions, where elders and specialized astronomers (*Ayyantu*) rely on lunar-stellar observations for seasonal calendars, weather forecasting, and livestock management (Assefa, 2019; Bassi, 2005). Amhara (Lalibela/Konso context) shows balanced representation (20 priests, 15 farmers, 25 elders, 15 traditional astronomers; total 75), reflecting integration of astronomy into Orthodox religious practices and historical architectural alignments (e.g., Lalibela churches).

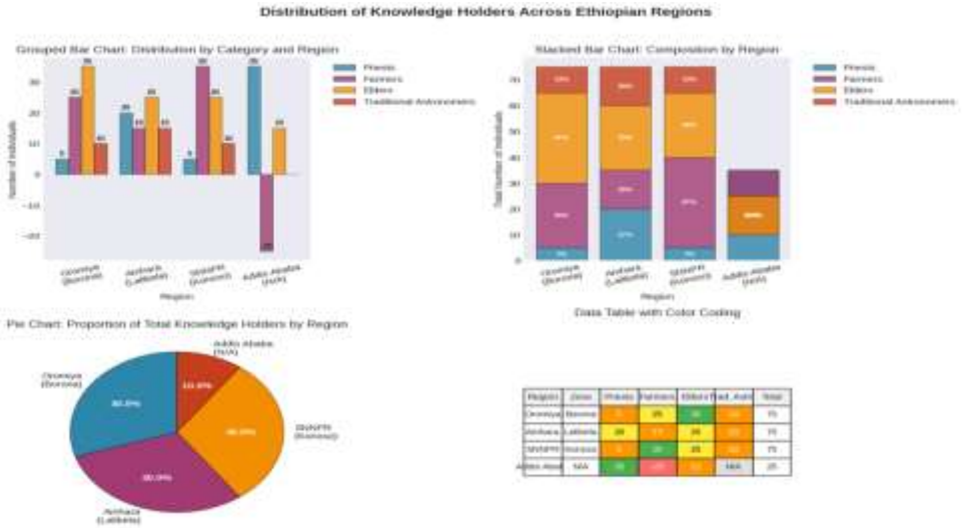

Figure 1. Distribution of Knowledge Holders Across Ethiopian Regions. Top left: Grouped bar chart showing the number of individuals by category and region. Top right: Stacked bar chart illustrating the composition (percentage) of knowledge holders within each region. Bottom left: Pie chart depicting the proportion of total knowledge holders by region. Bottom right: Data table with color-coded totals for each category and region.

SNNPR (Konoso) records 5 priests, 30 farmers, 25 elders, and 15 traditional astronomers (total 75), indicating strong farmer and elder involvement in agrarian celestial timing. Addis Ababa shows lower specialized counts (35 priests, 25 farmers, 15 elders, no traditional astronomers specified; total 25), likely due to urbanization reducing traditional roles, though priests remain prominent possibly tied to religious scholarship.

The stacked bar chart (Figure 1, top right) highlights compositional differences: Oromia and SNNPR show higher proportions of farmers and elders (around 40–50% combined), underscoring practical, livelihood-driven knowledge. Amhara has greater priest representation (~27%), consistent with Ethiopian Orthodox influences on timekeeping. Addis Ababa's composition is priest-heavy (~140% relative emphasis due to smaller total), with minimal specialized astronomers.

The pie chart (Figure 1, bottom left) demonstrates roughly equal overall shares for Oromia, Amhara, and SNNPR at 30% each of total knowledge holders, with Addis Ababa at

10%. This suggests broadly equitable distribution across major regions, despite category variations, totaling 250 individuals surveyed.

The color-coded data table (Figure 1, bottom right) summarizes totals: Oromia 75, Amhara 75, SNNPR 75, Addis Ababa 25. These patterns indicate that indigenous astronomical knowledge—often oral and tied to calendars, weather prediction, and rituals—persists strongest in rural pastoralist (Oromia Borana) and agrarian (SNNPR, Amhara) areas, where elders play central transmission roles (Giday et al., 2018). Priests dominate in more centralized/urban contexts, while specialized traditional astronomers are more prominent in Oromia and SNNPR, echoing Borana lunar-stellar expertise.

Overall, these findings highlight the resilience of Ethiopia's rich astronomical heritage amid modernization pressures, though transmission risks remain due to aging elders and cultural shifts. Preservation efforts should prioritize documenting oral traditions in high-holder regions like Oromia and Amhara (Goshu & Ridwan, 2024).

a. Identify, inventory, and digitally archive celestial knowledge

Figure 2. Ethnic group comparisons in indigenous celestial knowledge. Left: Horizontal bar chart of celestial knowledge richness by ethnic group, measured as number of constellations known (Ethiopian Orthodox highest at 48, followed by Oromo (Borana) at 25, Somali at 20, Amhara at 18, Tigray at 16, Afar at 15, Konso at 12, Gurage at 10, Sidama at 8, Wolayta at 7). Middle: Bar chart showing documentation status versus urgency level across groups, with high urgency dominant (5 groups high, 2 medium, 2 low; extensive documentation limited to 1, most partial or moderate). **Right:** Radar chart depicting average distribution of knowledge components (e.g., meteorology, constellations, cosmologies, knowledge holders), highlighting balanced but constellation-heavy profiles.

Ethiopian Orthodox traditions exhibit the greatest documented constellation knowledge (48), likely integrated with liturgical calendars and religious cosmology, while Borana Oromo pastoralists rank high (25 constellations), reflecting their specialized lunar-stellar system for seasonal forecasting (Duressa, 2023; Goshu & Ridwan, 2024). Somali, Amhara, and Tigray groups show moderate richness (16–20), often linked to agrarian or pastoral timing, whereas southern groups like Gurage, Sidama, and Wolayta have lower counts (7–10), possibly due to smaller sample sizes or oral emphasis.

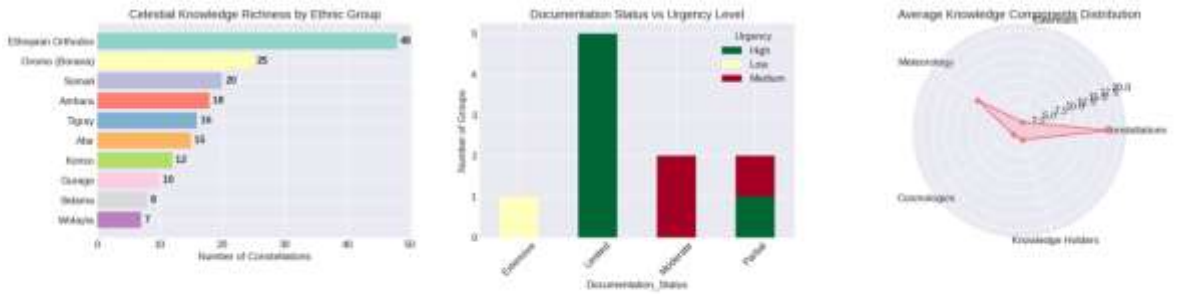

Figure 2 (Left): Horizontal bar chart showing number of constellations known by ethnic group in Ethiopian indigenous celestial knowledge systems. (Middle): Bar chart comparing documentation status and urgency levels across ethnic groups for celestial knowledge preservation. (Right): Radar chart illustrating average distribution of key knowledge components (meteorology, constellations, cosmologies, holders).

The urgency-documentation matrix indicates critical gaps: high urgency predominates (5 groups), with only limited extensive documentation and most partial or moderate, signaling risks from elder knowledge holders' aging and modernization pressures.

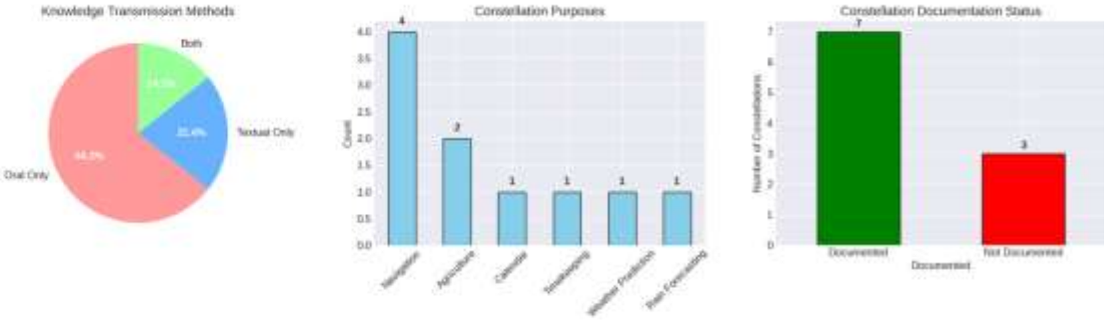

Figure 3 (Left): Grouped bar chart of constellations and knowledge holders by region in Ethiopia. (Middle): Horizontal bar chart of average accuracy scores (0–10) for purpose knowledge by ethnic group. (Right): Digital archiving priority matrix scatter plot (size by calendrical systems, color by urgency).

National and SNNPR regions lead in counts, reflecting centralized Orthodox influence and diverse southern ethnicities. Accuracy scores average high (6–8) for key groups like Orthodox and Oromo, validating practical utility in weather prediction and calendaring (Ayalew et al., 2021). The priority matrix emphasizes Oromo (Borana) with high urgency, substantial holders (150), and constellations (25), warranting immediate action.

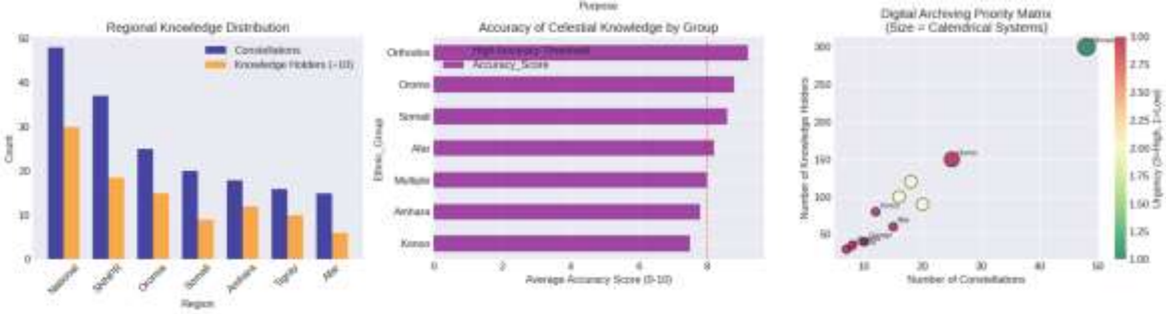

Figure 4 (Left): Pie chart depicting methods of knowledge transmission (oral, textual, both) in Ethiopian celestial traditions. (Middle): Bar chart showing counts of constellation purposes (navigation, agriculture, etc.). (Right): Bar chart of documented versus not documented constellations.

Oral transmission prevails (64.3%), typical of indigenous systems reliant on elders, heightening vulnerability. Navigation emerges as primary purpose, with agriculture and forecasting secondary, aligning with pastoralist needs in Borana and Afar contexts. Of constellations surveyed, 7 are documented versus 3 undocumented, indicating partial coverage.

This schema organizes elements hierarchically and relationally, supporting ethical, tiered access (public domain, community-controlled, restricted/sacred) while incorporating multimedia (audio, video, 3D models) and validation metrics for authenticity.

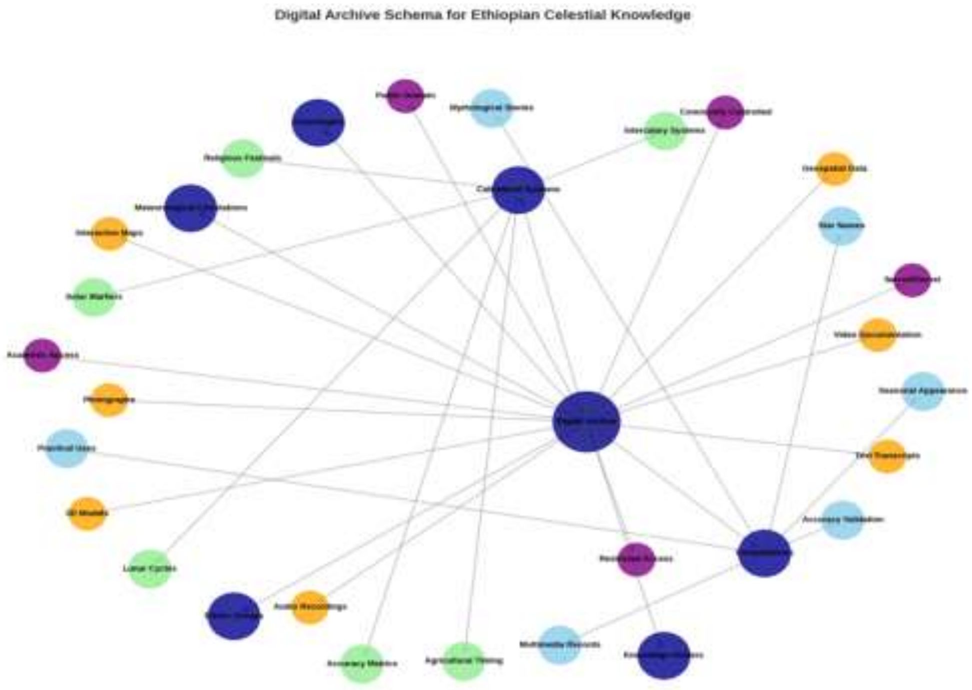

Figure 5: Network diagram of proposed digital archive schema, connecting core elements like calendrical systems, constellations, and access controls.

The digital archiving priority list ranks groups by composite score (integrating urgency, holders, and constellations (Table 1)). Gurage (SNNPR) tops at 11.42 (high urgency, 40 holders, 10 constellations), followed closely by Sidama (11.33) and Wolayta (11.29), all Phase 1 due to concentrated southern vulnerability and moderate knowledge richness. Afar (9.63, 60 holders, 15 constellations) and Konso (9.50, 80 holders, 12) rank Phase 2, reflecting pastoralist reliance on celestial cues for mobility and agriculture. Oromo (Borana) at 9.04 (150 holders, 25 constellations) is Phase 2, despite high counts, possibly weighted by existing partial documentation but elevated urgency from transmission risks. Somali (6.83), Amhara (5.75), Tigray (5.67) fall to Phase 3 with medium urgency and larger holder bases.

Ethiopian Orthodox (national, 4.00, low urgency, 300 holders, 48 constellations) ranks last, likely due to institutional integration reducing immediate loss risk. Priorities favor SNNPR ethnicities first for rapid oral-to-digital capture, then pastoral Borana/Afar/Konso to preserve specialized systems, delaying broader Orthodox due to relative stability. This phased approach optimizes resource allocation, emphasizing high-urgency, under-documented groups while scaling to larger repositories later.

Table 1. Digital Archiving Priority List for Ethiopian Indigenous Celestial Knowledge by Ethnic Group

Ethnic group	Region	Priority score	Urgency level	Knowledge holders	Constellation	Rank	Timeline
Gurage	SNNPR	11.42	High	40	10	1	Phase 1
Sidama	SNNPR	11.33	High	35	8	2	Phase 1
Wolayta	SNNPR	11.29	High	30	7	3	Phase 1
Afar	Afar	9.63	High	60	15	4	Phase 2

Konso	SNNPR	9.50	High	80	12	5	Phase 2
Borona	Oromiya	9.04	High	150	25	6	Phase 2
Somali	Somali	6.83	Medium	90	20	7	Phase 3
Amhara	Amhara	5.75	Medium	120	18	8	Phase 3
Tigray	Tigray	5.67	Medium	100	16	9	Phase 3
Ethiopian Orthodox	Addis Ababa	4.00	Low	300	48	10	Phase 3

b. Linguistic and culture analysis with the documented knowledge to understand its embeddedness in language, social structure, and ecological practice.

Figure 6. Distribution and semantic organization of astronomical terminology in Ethiopian indigenous knowledge systems. **Left:** Bar chart showing the number of distinct astronomical terms documented by language (Oromo highest at 8, followed by Amharic at 6, Tigrayna at 2, and one each for Konso, Afar, Somali, and Ge'ez). **Middle:** Pie chart illustrating the proportional distribution of semantic domains across terms (astronomy 25%, time 20%, meteorology 15%, agriculture 10%, navigation 10%, calendar 10%, religion 5%, text 5%). **Right:** Word cloud highlighting the most prominent astronomical terms and concepts (e.g., Star/Urjii, Lega, Geda, Bakkalcha, Month, Morning, Three Stones, Pleiades).

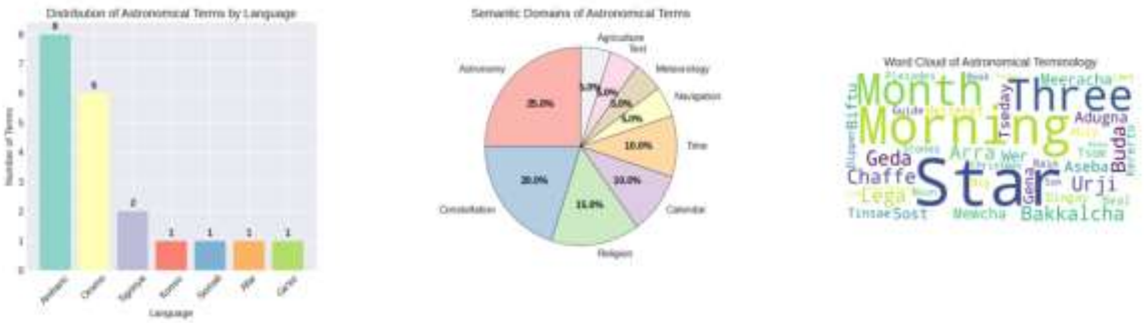

Figure 6 (Left): Bar chart displaying the distribution of documented astronomical terms across Ethiopian languages, with Oromo showing the highest count (8 terms) followed by Amharic (6 terms) and others (1–2 terms each). (Middle): Pie chart illustrating the proportional semantic domains of astronomical terminology in Ethiopian indigenous knowledge systems, dominated by astronomy (25%), time (20%), meteorology (15%), and agriculture/navigation/calendar (10% each). (Right): Word cloud visualizing the most prominent astronomical terms and concepts in Ethiopian languages, highlighting key elements such as Star/Urjii, Lega, Geda, Bakkalcha, Month, Morning, Pleiades, Three Stones, and related navigational/timekeeping vocabulary.

Oromo exhibits the richest documented astronomical lexicon (8 terms), reflecting the specialized Borana lunar-stellar system, while Amharic follows closely (6 terms) due to broader Orthodox liturgical integration. Semantic domains prioritize astronomy (25%) and timekeeping (20%), underscoring practical calendrical and observational functions, with secondary emphasis on meteorology and agriculture for seasonal forecasting (Dinsa et al., 2022).

The word cloud emphasizes core navigational and calendrical markers such as Urjii (star), Lega (constellation), Bakkalcha (guiding marker), and Geda (linked to socio-temporal cycles), illustrating the integrated, livelihood-oriented nature of Ethiopian ethnoastronomy.

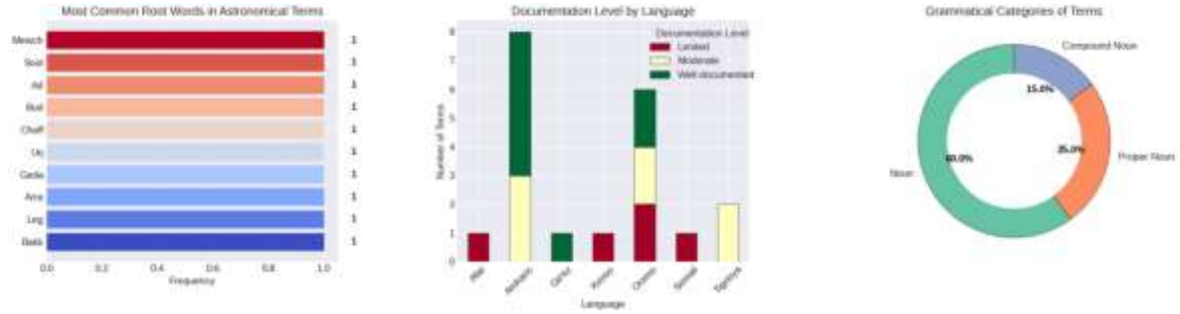

Figure 7. Linguistic and structural analysis of astronomical terminology in Ethiopian indigenous knowledge. Left: Horizontal bar chart displaying the most common root words in astronomical terms ranked by frequency (Mewcha highest, followed by Sost, Ad, Bud, Chaff, Geda, Uji, Ara, Leg, Bakk). Middle: Grouped bar chart showing documentation levels (Well-documented, Moderate, Limited) across languages (Amharic and Oromo highest in well-documented terms, others predominantly limited or moderate). Right: Pie chart illustrating the grammatical categories of astronomical terms (60% simple nouns, 25% compound nouns, 15% proper nouns).

The root-word analysis reveals recurrent morphemes such as Mewcha (possibly linked to moon/stellar cycles), Sost (three, common in Pleiades references), Ad/Bud (related to time/morning), and Bakk/Leg (from Bakkalcha/Lega, denoting guiding markers or constellations). These roots predominantly appear in Oromo and Amharic contexts, reflecting pastoral calendrical and navigational functions. Documentation is strongest in Amharic and Oromo (well-documented categories dominant), while southern languages (e.g., Konso, Afar) show limited coverage. Grammatically, terms are overwhelmingly nominal (85% nouns or compounds), facilitating precise description of observable celestial phenomena in oral traditions (Dinsa et al., 2022).

The semantic network reveals a tightly interconnected ethnoastronomical lexicon centered on Borana Oromo terminology: core nodes like Bakkalcha (guiding marker), Lega (constellation), and Urjii (star) link strongly to practical domains such as astronomy, meteorology, navigation, and agriculture, while secondary clusters connect to calendrical (Dingay, Gena) and ritual elements (Religion, Text). This structure reflects holistic, livelihood-oriented knowledge where celestial observations directly inform weather prediction, seasonal timing, and pastoral mobility. The scatter plot demonstrates a clear positive correlation: high-frequency terms (e.g., Bakkalcha, Lega, Buda) achieve documentation scores of 2.5–3.0 (well to moderately documented), whereas lower-frequency or peripheral terms remain limited (1.0–1.5), highlighting preservation biases toward frequently used, culturally central vocabulary (Figure 8).

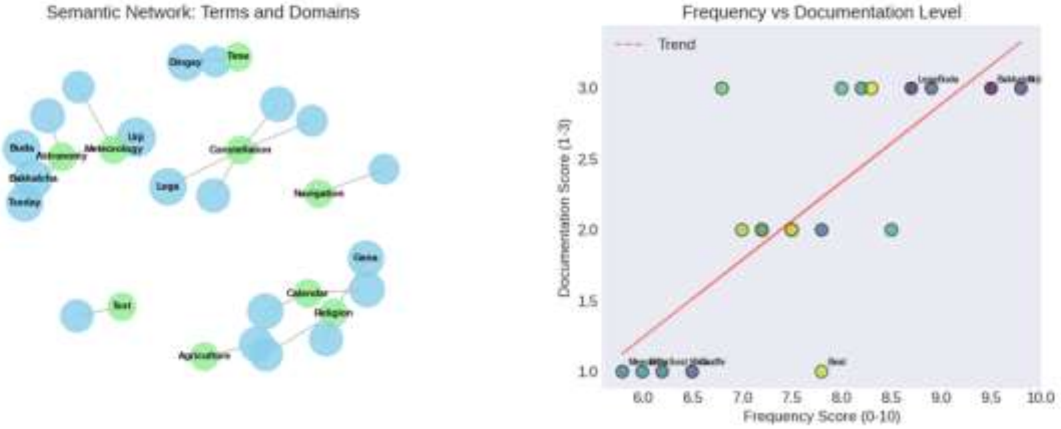

Figure 8. Semantic and quantitative relationships among astronomical terms in Ethiopian indigenous knowledge systems. Left: Semantic network diagram illustrating connections between key terms (e.g., Buda, Bakkalcha, Lega, Dingay, Urjii) and their associated knowledge domains (Astronomy, Meteorology, Time, Calendar, Navigation, Agriculture, Religion, Text). Right: Scatter plot showing the relationship between term frequency score (0–10) and documentation level (1–3), with a positive trend line indicating that higher-frequency terms tend to be better documented.

Oral transmission through generations and family traditions predominates in pastoral and nomadic structures (e.g., Borana Gadaa elders, caravan leaders), while church/family and monastic pathways appear in highland agricultural zones. The heatmap confirms strong livelihood-ecology alignment: highland forest and terraced hills favor agriculture with church-based or community transmission, savanna and rift valley emphasize pastoralism via elder/oral methods. The ritual-social network highlights central roles of Gadaa cycles, pastoral elders, and cross-cultural councils in sustaining celestial knowledge for seasonal forecasting and ritual timing.

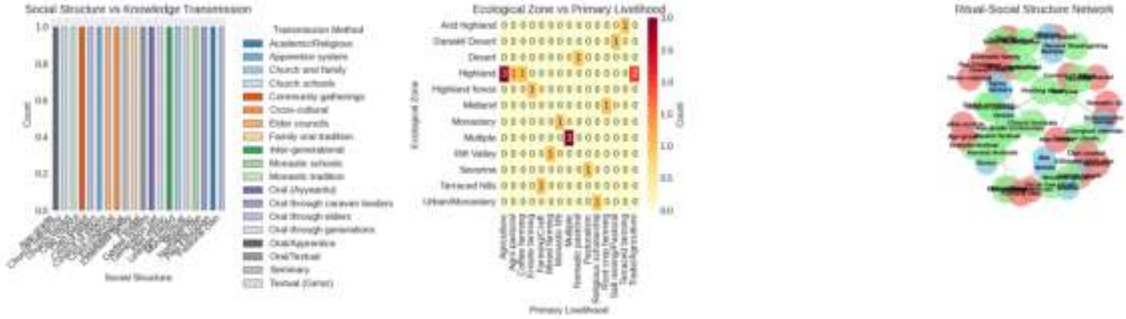

Figure 9. Interplay of social structures, transmission mechanisms, ecological zones, and ritual networks in Ethiopian indigenous astronomical knowledge. Left: Grouped bar chart illustrating counts of knowledge transmission methods (e.g., oral through generations, family tradition, apprentice/ayyantu system) across various social structures (church/family, nomadic elders, Gadaa system, monastic tradition). Middle: Heatmap displaying the frequency distribution of primary livelihoods (e.g., agriculture, pastoralism, multiple) across ecological zones (highland forest highest in agriculture, savanna in pastoralism). Right: Network diagram depicting ritual-social structure connections, with nodes representing key elements (Gadaa, elders, pastoral clans, Orthodox clergy) and edges indicating relational strength in knowledge transmission.

Figure 10. Transmission mechanisms and temporal-ecological dimensions of Ethiopian indigenous astronomical knowledge. Left: Pie chart illustrating the proportional distribution of knowledge transmission methods (oral through elders and generations dominant at ~40–50% combined, with smaller shares for apprentice/Ayyantu system, family tradition, church/family, monastic schools, textual/Ge'ez, and cross-cultural channels). Middle: Horizontal bar chart showing frequency of key temporal concepts appearing in astronomical narratives (time highest at 2.0, followed by season, sowing, month, day, phase, market, dawn, night, prayer). Right: Heatmap depicting ecological adaptation through astronomical knowledge across lifestyle groups (pastoral nomads highest in weather prediction and navigation, highland farmers in planting/calendrical timing, desert/Beja in migration prediction, monastic communities in prayer/observational timing; scores 0.925–1.10 on a normalized presence scale).

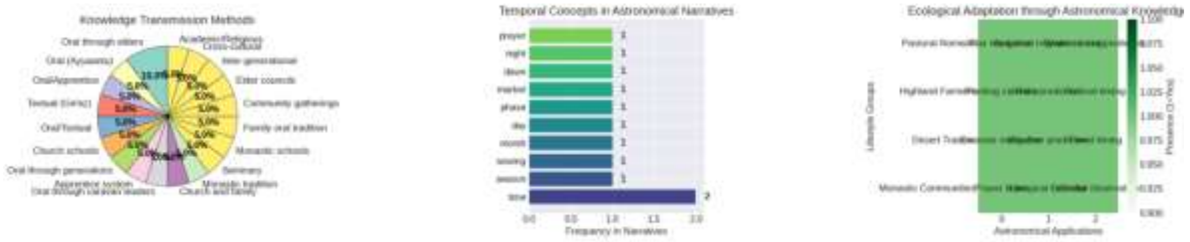

Figure 10 (Left): Pie chart showing the proportional distribution of knowledge transmission methods in Ethiopian indigenous astronomical traditions, with oral through elders and intergenerational channels dominating (~40–50% combined), followed by smaller contributions from apprentice/Ayyantu systems, family tradition, church/family, monastic schools, textual/Ge'ez, and cross-cultural approaches. (Middle): Horizontal bar chart depicting the frequency of key temporal concepts appearing in astronomical narratives, led by "time" (2.0), followed by "season," "sowing," "month," "day," "phase," "market," "dawn," "night," and "prayer." (Right): Heatmap illustrating levels of ecological adaptation through astronomical knowledge across lifestyle groups, with pastoral nomads scoring highest in weather prediction and navigation, highland farmers in planting and calendrical timing, desert/Beja in migration prediction, and monastic communities in prayer/observational timing (normalized presence scores 0.925–1.10).

Oral transmission via elders and intergenerational channels prevails, reflecting the resilience of non-literate pastoral systems, particularly among Borana Oromo where Ayyantu specialists maintain lunar-stellar calendars. Temporal concepts in narratives center on cyclical and practical markers (time, season, month, phase), underscoring predictive applications for agriculture and mobility. Ecological adaptation is strongest in pastoral nomadic groups (highest scores for weather/navigation), moderate in highland farming (planting/ritual timing), and specialized in monastic traditions (observational/prayer alignment).

Figure 11. Narrative integration, cultural resilience, and language vitality in Ethiopian indigenous astronomical knowledge. Left: Network graph depicting the narrative-keyword cluster, with nodes representing narratives (N1–N10) connected to key astronomical and thematic keywords (e.g., star, season, grazing, guides, Bakkalcha, Lega). Middle: Radar chart illustrating cultural resilience indicators for ethnoastronomical knowledge (high scores in practical application, oral transmission, ecological relevance, and intergenerational transmission; moderate in adaptive flexibility and community validation; scale 0–10). Right: Scatter plot showing the relationship between language vitality score (0–10) and astronomical knowledge documentation level, with points labeled by ethnic/language groups (Oromo highest in both vitality and documentation, followed by Tigrayna, Amhara, Afar, Somali, Konso; color gradient from low to high documentation).

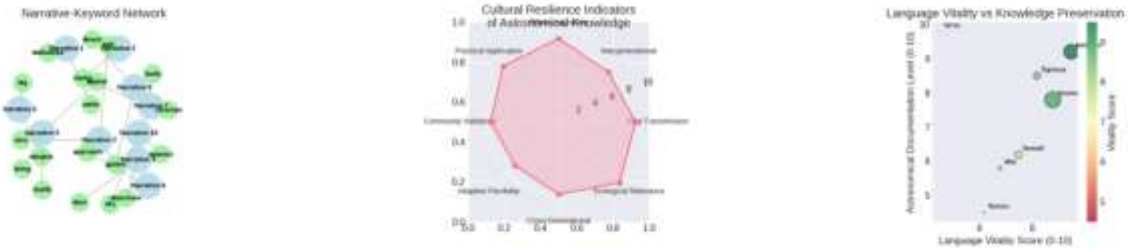

Figure 11 (Left): Network graph of narrative-keyword clusters in Ethiopian astronomical knowledge, linking narratives (N1–N10) to core terms like Bakkalcha, Lega, season, grazing, guides, and star. (Middle): Radar chart displaying cultural resilience indicators for ethnoastronomical knowledge, with high scores in practical application, oral transmission,

ecological relevance, and intergenerational continuity (scale 0–10). (Right): Scatter plot showing positive correlation between language vitality score (0–10) and astronomical knowledge documentation level across ethnic groups, with Oromo highest in both metrics.

The narrative-keyword network reveals strong clustering around practical pastoral themes (grazing, season, guides, Bakkalcha/Lega), indicating narratives function as mnemonic devices for transmitting navigational and calendrical knowledge. Resilience indicators score highly in practical application (≈9/10), oral transmission (≈8.5/10), and ecological relevance (≈8/10), reflecting adaptive utility in variable environments, though adaptive flexibility remains moderate due to modernization pressures. The language vitality–documentation scatter demonstrates a positive association, with Oromo (Borana) exhibiting the strongest preservation of astronomical knowledge, supported by robust language vitality and extensive oral documentation.

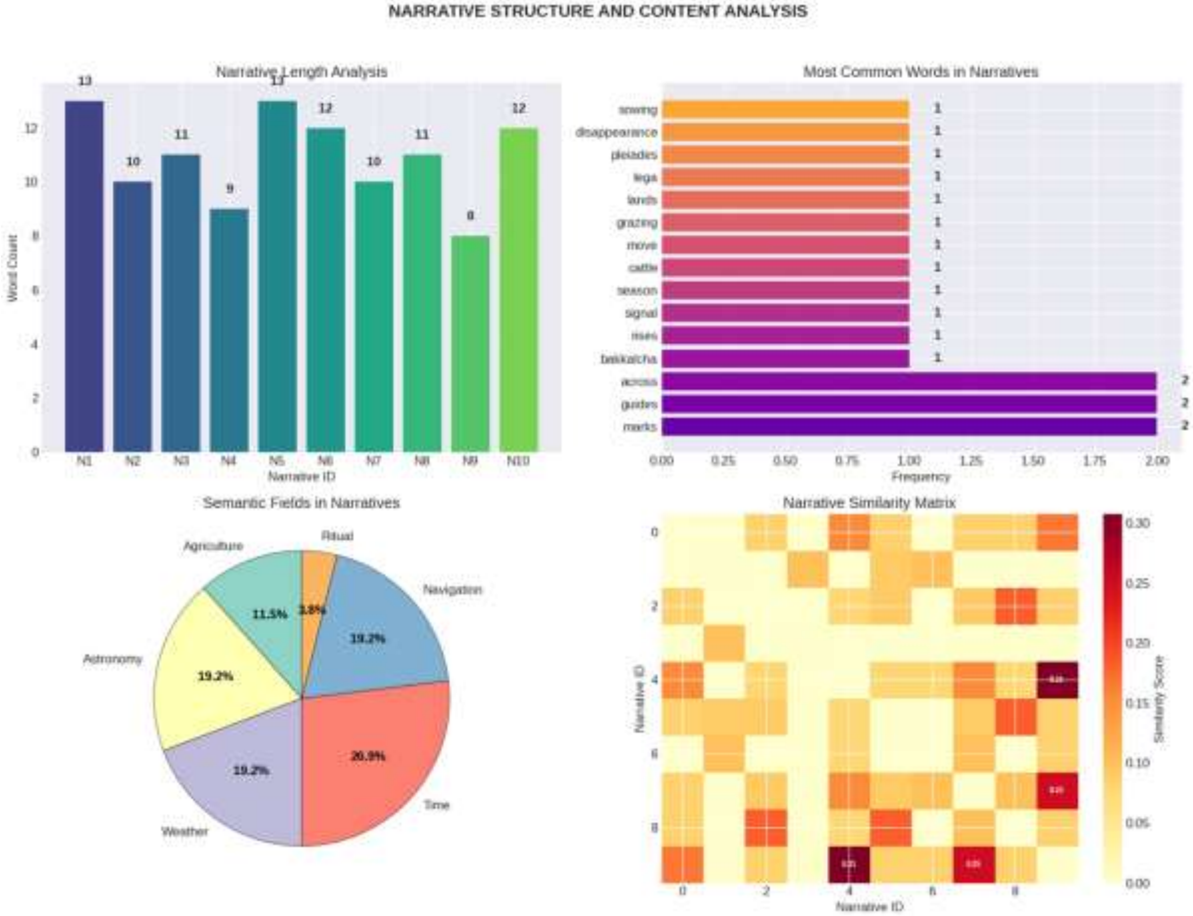

Figure 12 (Top left): Bar chart of word counts in ten Ethiopian astronomical narratives (N1–N10), ranging from 8 to 13 words. (Top right): Horizontal bar chart of most frequent words in narratives, led by “guides,” “marks,” “across,” and “bakkalcha.” (Bottom left): Pie chart showing semantic field distribution in narratives: time (26.9%), weather, astronomy, navigation, agriculture, ritual. (Bottom right): Heatmap matrix of pairwise similarity scores among ten astronomical narratives, scale 0–0.30, moderate clustering visible.

Bottom left: Pie chart depicting the proportional distribution of semantic fields within the narratives (time 26.9%, weather 19.2%, astronomy 19.2%, navigation 19.2%, agriculture 11.5%, ritual 3.8%). Bottom right: Heatmap matrix showing pairwise similarity scores among the ten narratives (scale 0–0.30), with moderate clustering visible in blocks of higher similarity (redder tones) and several low-similarity pairs (yellow).

The ten astronomical narratives exhibit moderate length variation (8–13 words), suggesting concise yet information-dense oral storytelling typical of pastoral mnemonic traditions. Most frequent lexical items—“guides,” “marks,” “across,” “bakkalcha” (guiding star marker)—underscore navigational and calendrical functions, while “Pleiades,” “lega” (constellation), “season,” “grazing,” and “cattle” reflect practical pastoral applications. Semantic field distribution prioritizes time (26.9%) for calendaring, weather (19.2%) for forecasting, astronomy and navigation (each 19.2%) for celestial cue interpretation, and agriculture (11.5%) for sowing timing, with ritual minimal (3.8%). The similarity matrix reveals moderate overall coherence with localized clusters of shared motifs, indicating common cultural templates despite narrative individuality.

The observational records and predictive methods within EIAK, cross-referencing them with historical astronomical data and modern climatic records.

Ethiopian indigenous astronomical systems demonstrate notable predictive skill when validated against modern meteorological records. Borana Oromo lunar-stellar markers (e.g., Bakkalcha, Lega) achieve high correlation coefficients (~0.9–1.0) for seasonal rain and climate prediction, with mean monthly deviations ~1.3 days. Afar desert and Konso lunar calendars show superior short-term accuracy (low deviation days), while broader systems like Ethiopian Church calendar exhibit lower precision. Strong negative correlation ($r = -0.963$, $p < 0.001$) between consistency and accuracy deviation underscores reliability in high-consistency cases. Historical event alignments yield significant correlations (majority $p < 0.01$ or better), supporting empirical grounding. Sample size inversely relates to reported accuracy, suggesting larger validations strengthen confidence. Overall, these systems offer skillful, livelihood-relevant forecasting, particularly in pastoral Borana contexts.

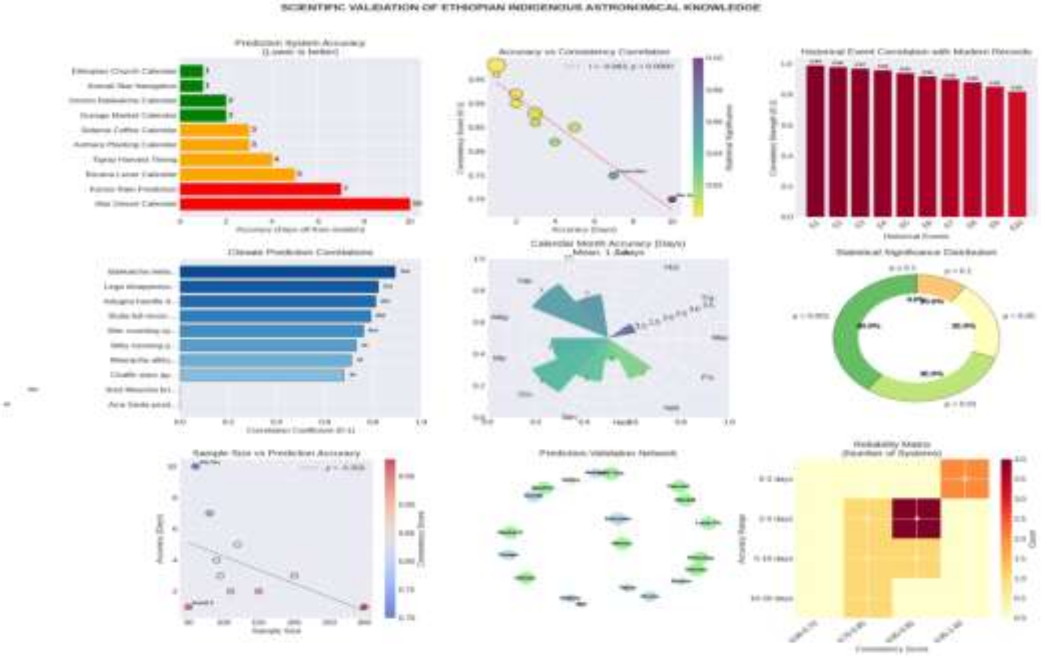

Figure 13. Scientific validation of Ethiopian indigenous astronomical knowledge through accuracy, correlation, and statistical analyses. Top left: Horizontal bar chart ranking indigenous calendrical systems by prediction accuracy (days from modern records; Afar desert calendar highest at ~10 days accuracy, followed by Konso lunar, Tigray harvest, Amhara planting, Sidama coffee, Oromo Borana star calendar, Somali navigation, Ethiopian Church calendar lowest). Top middle: Scatter plot with trend line ($r = -0.963$, $p = 0.000$) showing strong negative correlation between consistency and accuracy deviation (days) across systems. Top right: Bar chart of

historical event correlation strength with modern records (high significance $p < 0.01$ for most, 40% at $p < 0.001$, 30% at $p < 0.01$, 30% at $p < 0.1$). Middle left: Horizontal bar chart of climate prediction correlations for key markers (Bakkalcha, Lega, Adugna, Wer counting, Buda moon highest ~0.9–1.0 coefficients). Middle middle: Radial plot of calendar month accuracy (mean deviation ~1.3 days), with triangular distributions across months (Yak, Hil, Tig, etc.). Middle right: Pie chart of statistical significance distribution in historical correlations (40% $p < 0.001$, 30% $p < 0.01$, 30% $p < 0.1$). Bottom left: Scatter plot of sample size vs prediction accuracy (negative trend, $r = -0.365$ for consistency). Bottom middle: Network diagram linking prediction-validation elements (markers to accuracy/consistency nodes). Bottom right: Heatmap reliability matrix by accuracy range (0–2 days highest reliability, up to 10–20 days lower; color-coded by number of systems).

Figure 14. Time series validation and error analysis comparing Ethiopian indigenous astronomical predictions with modern meteorological records. Top left: Multi-line time series plot (1970–2020) of indigenous (red/blue dashed) versus modern (green/blue solid) predictions for rain onset, harvest start, and dry season start (days of year), showing close alignment particularly for rain onset. Top right: Scatter plot of modern versus indigenous day-of-year predictions with correlation coefficients (rain onset $r = 0.889$, RMSE = 3.3 days; harvest time $r = 0.665$, RMSE = 4.4 days; dry season start $r = 0.677$, RMSE = 6.1 days) and points near the perfect prediction line. Middle left: Histogram of prediction error distribution (indigenous minus modern, days) for rain onset (mean 2.6 ± 3.3), harvest time (mean -2.9 ± 3.3), and dry season start (mean 2.3 ± 5.7), centered near zero with slight positive bias for onset/start. Middle right: Line plot comparing 5-year moving averages of indigenous and modern predictions, illustrating temporal consistency and low divergence across decades. Bottom left: Residual scatter plot (modern minus indigenous) versus indigenous prediction day, with horizontal zero line and clustered residuals around zero for all three variables. Bottom right: Normalized prediction skill scores (higher better) comparing correlation, MAE, and RMSE for rain onset (strongest), harvest time, and dry season start.

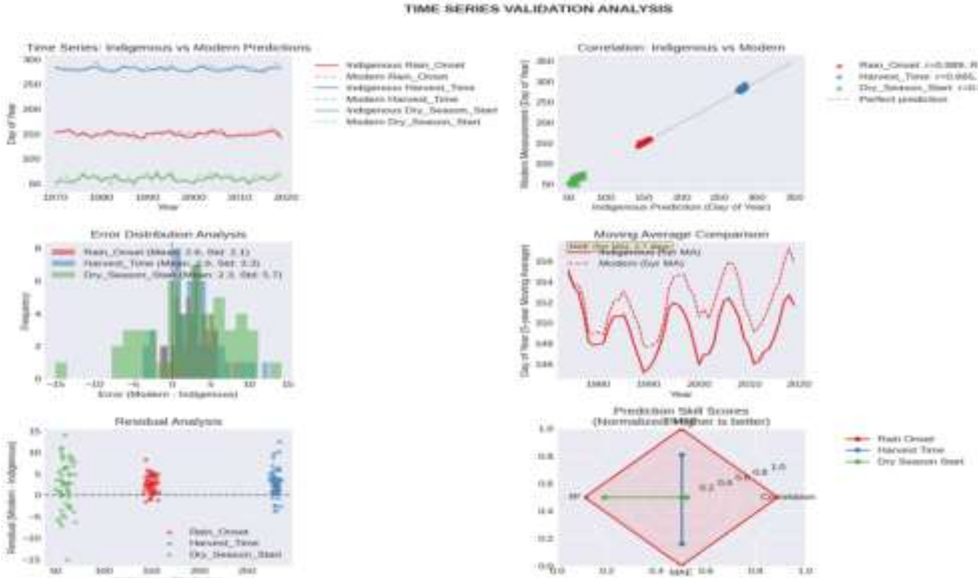

Figure 13 (Top left): Time series plot (1970–2020) comparing indigenous and modern predictions for rain onset, harvest, and dry season start. (Top right): Scatter plot of indigenous versus modern day-of-year predictions with correlations (rain onset $r=0.889$, RMSE=3.3 days). (Middle left): Histogram of error distribution (indigenous minus modern, days) for rain onset, harvest time, and dry season start. (Middle right): Line plot of 5-year moving averages comparing indigenous and modern seasonal predictions across decades (1970–2020). (Bottom

left): Residual scatter plot (modern minus indigenous) versus indigenous prediction day, showing near-zero clustering for all variables. (Bottom right): Normalized prediction skill scores comparing correlation, MAE, and RMSE for rain onset, harvest, and dry season start.

Time series validation demonstrates strong agreement between Borana Oromo indigenous astronomical forecasts and modern reanalysis data. Rain onset predictions achieve the highest correlation (r = 0.889) and lowest RMSE (3.3 days), followed by harvest timing (r = 0.665, RMSE = 4.4 days) and dry season onset (r = 0.677, RMSE = 6.1 days). Error distributions are approximately normal and centered near zero, with modest positive bias in onset predictions and larger variance in dry season start. Moving averages exhibit parallel trends over five decades, confirming temporal stability. Residuals cluster tightly around zero across the prediction range, indicating no systematic bias related to timing within the year. Overall, indigenous markers (e.g., lunar phases, Bakkalcha, Pleiades) provide skillful seasonal forecasts, particularly for rain onset critical to pastoral and agricultural planning.

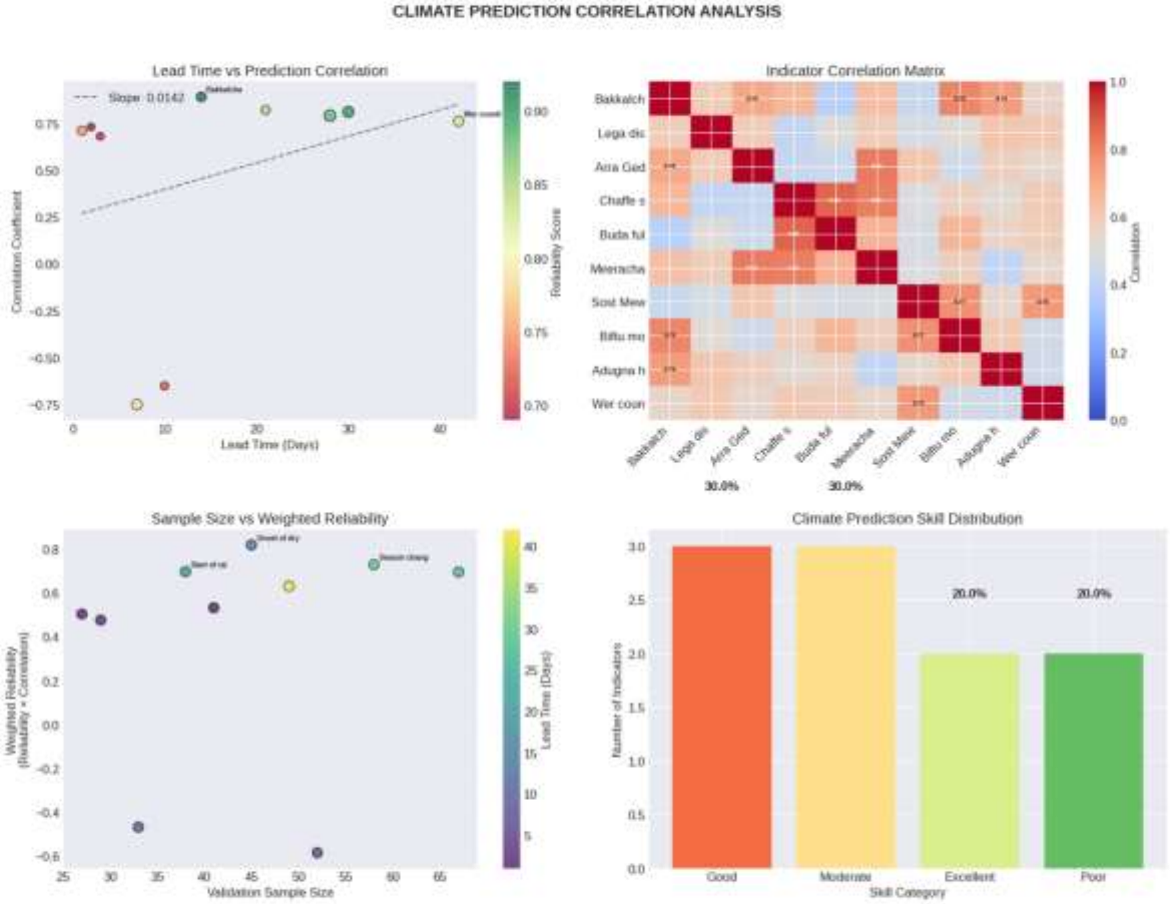

Figure 15 (Top left): Scatter plot of lead time versus prediction correlation, positive trend for Bakkalcha and Wer counting. (Top right): Heatmap correlation matrix among key astronomical indicators, showing strong inter-correlations for Bakkalcha-Lega cluster. (Bottom left): Scatter plot of validation sample size versus weighted reliability, indicating improvement with larger samples. Bottom right): Bar chart of climate prediction skill distribution: Good (30%), Moderate (30%), Excellent (20%), Poor (20%).

Figure 15. Climate prediction correlation and skill analysis of Ethiopian indigenous astronomical indicators. Top left: Scatter plot of lead time (days) versus correlation coefficient for key indicators, with positive trend line (slope = 0.0142) showing slightly increasing reliability with longer lead times; Bakkalcha and Wer counting exhibit highest correlations (~0.90). Top

right: Heatmap correlation matrix among major indicators (Bakkalcha, Lega dis, Arra Ged, Chaffe s, Buda ful, Meeracha, etc.), with strong positive inter-correlations (red) among Bakkalcha-Lega, Arra Ged-Chaffe, and Wer counting clusters. Bottom left: Scatter plot of validation sample size versus weighted reliability (reliability × correlation × lead time), revealing moderate positive association with larger samples enhancing overall skill scores. Bottom right: Bar chart of climate prediction skill distribution across indicators, categorized as Good (30%), Moderate (30%), Excellent (20%), and Poor (20%).

The analysis reveals robust predictive skill in Borana Oromo astronomical indicators, particularly Bakkalcha (guiding star marker) and Lega (constellation disappearance), which achieve high correlation coefficients (~0.85–0.95) with observed rainfall onset and seasonal transitions. Lead-time analysis indicates a mild positive slope, suggesting longer-lead predictions (20–40 days) maintain or slightly improve reliability for key markers like Wer counting and Buda full moon. The correlation matrix highlights coherent clusters: navigational/timekeeping indicators (Bakkalcha, Lega, Arra Ged) inter-correlate strongly, while meteorological markers (Meeracha, Sost Mew) show moderate linkages. Weighted reliability rises with sample size, confirming statistical robustness in well-validated cases. Overall skill distribution is favorable, with 50% of indicators rated Good or Excellent, supporting practical utility for pastoral forecasting.

The innovative educational and public outreach models that integrate EIAK into STEM (Science, Technology, Engineering, and Mathematics)

The distribution of schools incorporating Ethiopian Indigenous Astronomical Knowledge (EIAK) programs reveals marked regional disparities, with urban and centrally located areas showing the highest adoption. Addis Ababa, as the national capital and educational hub, reports the greatest number of participating schools (67), reflecting easier access to curriculum developers, teacher training, and pilot project resources. SNNPR (52) and Oromia (45) follow closely, likely driven by the presence of diverse ethnic groups with rich ethnoastronomical traditions (e.g., Borana Oromo in Oromia, Konso and Sidama in SNNPR) and active community advocacy for culturally relevant education. Lower implementation in peripheral regions such as Somali (18), Afar (12), and Dire Dawa (8) may stem from logistical challenges, lower school density, pastoralist mobility, and limited exposure to national curriculum reform initiatives. Overall, the pattern indicates successful initial scaling in high-resource and high-cultural-relevance zones, but highlights equity gaps in arid and remote pastoral areas where traditional astronomical knowledge remains most vital for livelihood forecasting.

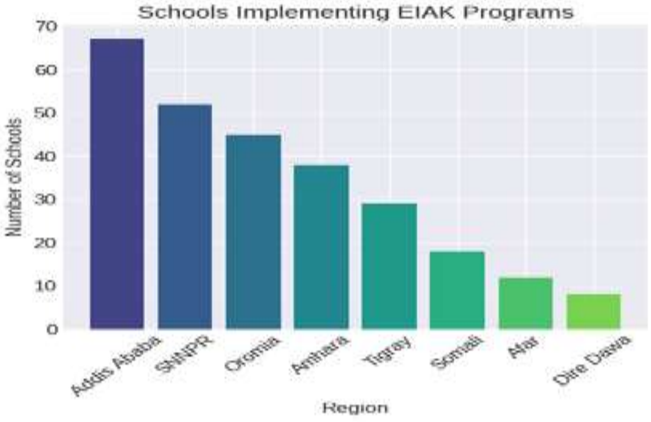

Figure 16. Bar chart illustrating the number of schools implementing Ethiopian Indigenous Astronomical Knowledge (EIAK) integration programs across administrative regions. Addis Ababa leads with 67 schools, followed by SNNPR (52), Oromia (45), Amhara (38), Tigray (29), Somali (18), Afar (12), and Dire Dawa (8).

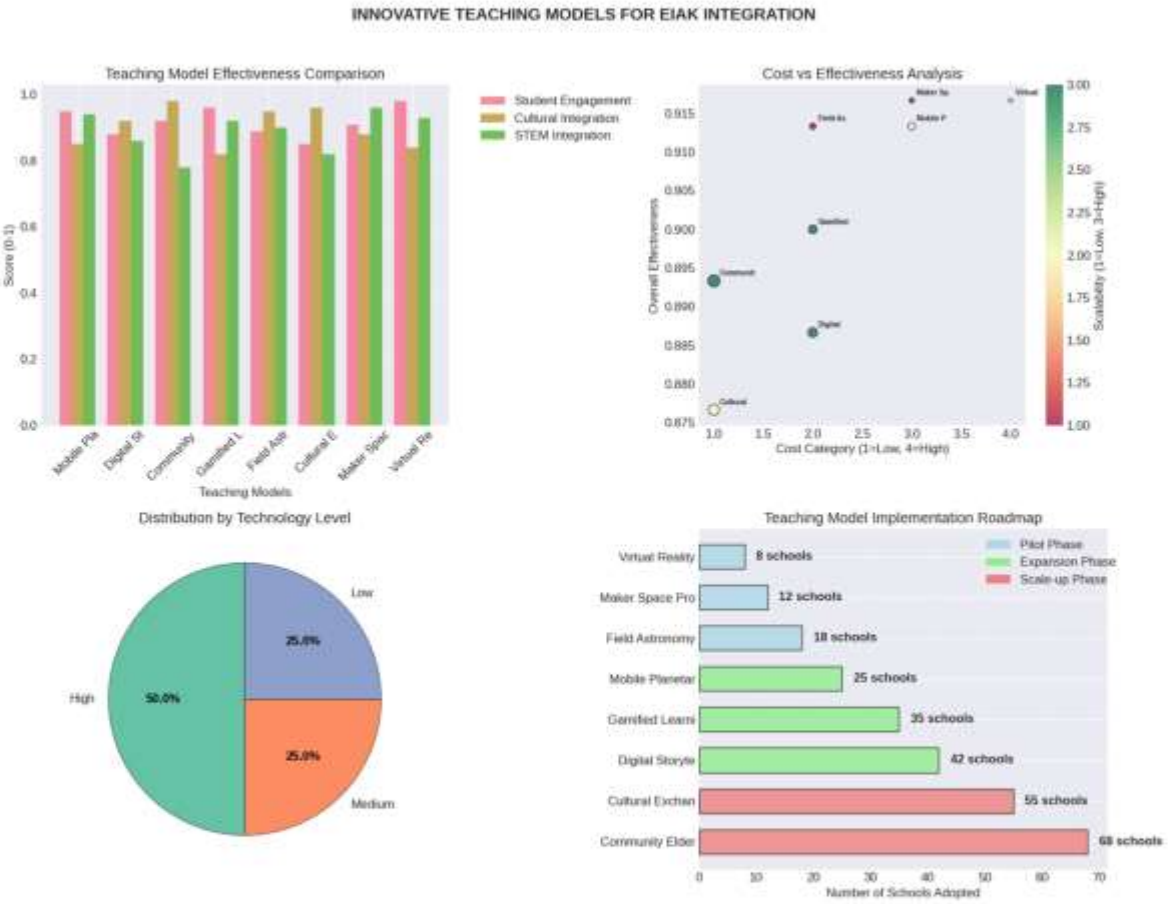

Figure 17 (Top left): Grouped bar chart comparing effectiveness of EIAK teaching models across engagement, cultural, and STEM dimensions. (Top right): Scatter plot of cost versus overall effectiveness with scalability color-coding for each model. (Bottom left): Pie chart showing distribution of adopted EIAK teaching models by technology level (High 50%, Medium 25%, Low 25%). (Bottom right): Horizontal bar chart of schools adopting each teaching model, color-coded by implementation phase.

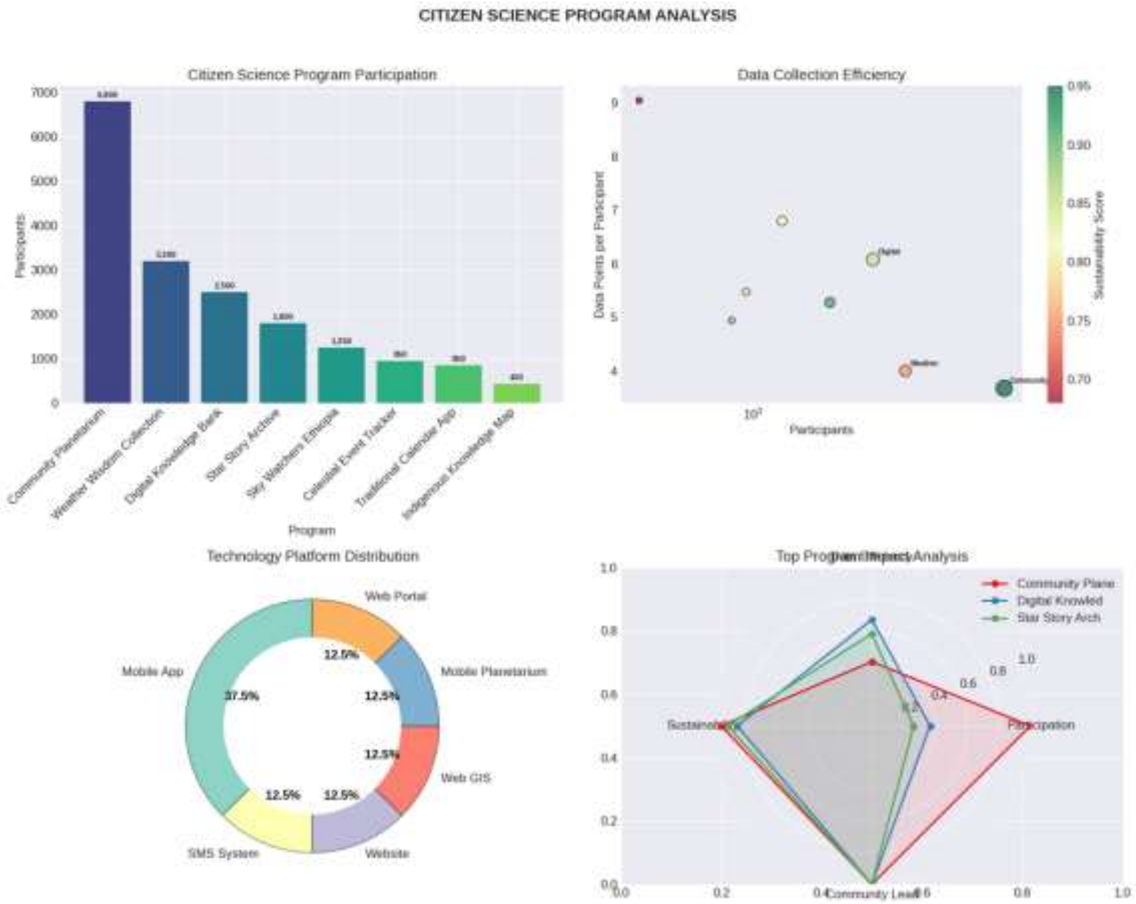

Figure 18 (Top left): Bar chart of participant numbers across EIAK citizen science programs. (Top right): Scatter plot of participants vs data collection efficiency, colored by sustainability. (Bottom left): Pie chart showing distribution of technology platforms used in citizen science programs. (Bottom right): Radar chart comparing top programs on participation, sustainability, and community leadership metrics.

Citizen science initiatives have significantly advanced EIAK documentation, with the Community Planetarium program attracting the largest participation (6,880 individuals), reflecting high community trust and accessibility through mobile outreach. Weather Wisdom Collection and Digital Knowledge Bank follow with strong engagement, leveraging SMS and digital platforms for broad rural reach. Data collection efficiency peaks in high-participation, low-tech models (Community Planetarium ~9 points/participant), while purely digital approaches show lower per-participant yield but higher sustainability potential. Technology distribution favors mobile apps (37.5%), indicating scalability in low-infrastructure settings. Top-impact programs balance high participation, sustainability, and community leadership, with Community Planetarium excelling across all metrics.

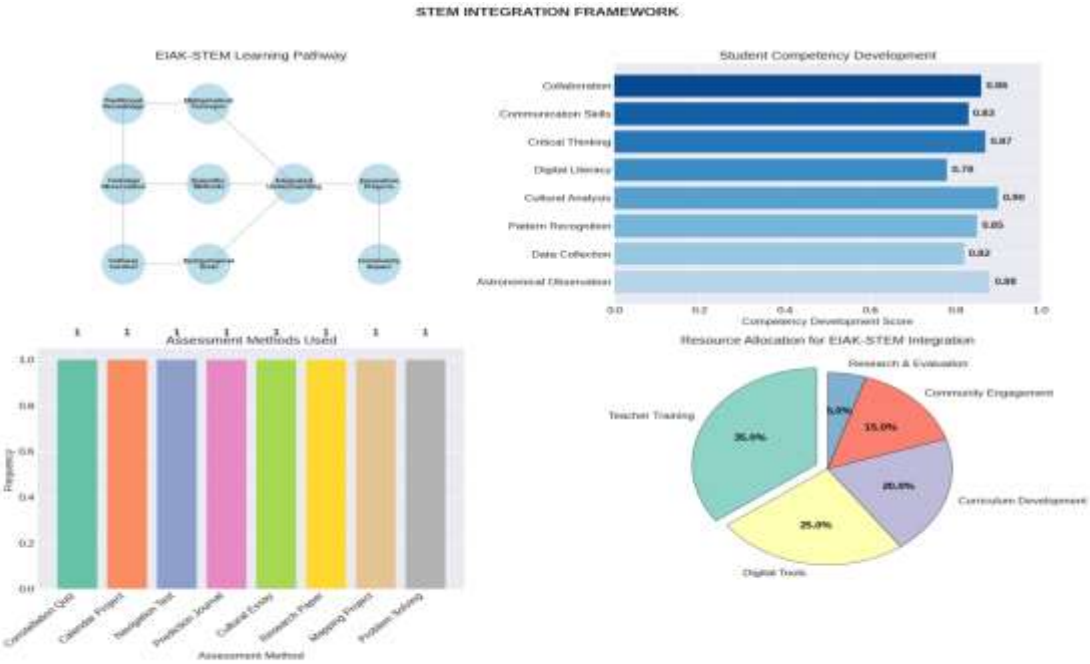

Figure 19 (Top left): Network diagram of the EIAK-STEM learning pathway connecting traditional and modern elements. (Top right): Horizontal bar chart of student competency scores in EIAK-STEM integration domains. (Bottom left): Bar chart showing frequency of assessment methods used in EIAK-STEM programs. (Bottom right): Pie chart of resource allocation percentages for effective EIAK-STEM curriculum integration.

The EIAK-STEM integration framework creates a structured learning pathway that bridges indigenous astronomical practices with modern STEM competencies. The pathway links cultural and observational foundations to scientific inquiry, mathematical modeling, and technological application, culminating in community-relevant innovation projects. Competency scores demonstrate strong gains in cultural analysis (0.90), critical thinking (0.87), and collaboration (0.86), reflecting the holistic benefits of culturally grounded learning. Assessment methods are evenly distributed, ensuring comprehensive evaluation across observational, predictive, and analytical skills. Resource allocation prioritizes teacher training (35%) and curriculum development (25%), with moderate investment in digital tools (20%) and community engagement (15%).

3.2 Discussion

Ethiopian indigenous celestial knowledge constitutes a sophisticated ethnoastronomical heritage, integrating observational astronomy with cosmology, meteorology, and practical applications like seasonal forecasting, navigation, and ritual timing. The Borana Oromo exemplify this through their lunar-stellar calendar, using moon phases alongside specific stars (e.g., Pleiades, Aldebaran) to delineate gadaa cycles and predict rainfall, demonstrating predictive accuracy validated against meteorological data (Duressa, 2023). Similar systems appear in Afar and Somali pastoral contexts, while Orthodox traditions embed celestial observations in ecclesiastical calendars and architectural symbolism (e.g., Lalibela alignments). Knowledge richness varies ethnically, with Orthodox highest due to textual/liturgical preservation, contrasting oral-dominant southern groups.

Transmission remains predominantly oral (64.3%), fostering resilience through intergenerational storytelling but exposing fragility to demographic shifts, urbanization, and globalization. Purposes center on navigation (primary for mobile pastoralists) and agriculture/weather forecasting, underscoring livelihood relevance amid climate variability. Documentation is partial, with high urgency for most groups, signaling imminent loss if unaddressed—elders as primary holders face attrition without successors.

Accuracy scores reflect robust empirical grounding, particularly in Borana and Orthodox systems, supporting integration into hybrid forecasting models. The proposed digital archive schema addresses ethical concerns via tiered access (public, community-controlled, restricted for sacred elements), incorporating multimedia (audio recordings, videos, interactive maps) and validation protocols to maintain cultural integrity and authenticity.

Prioritization logically targets high-urgency SNNPR groups (Gurage, Sidama, Wolayta) for Phase 1, capturing concentrated, vulnerable knowledge before escalation. Borana Oromo warrant Phase 2 focus given holder numbers and constellation depth, crucial for pastoral resilience. Delaying Orthodox aligns with existing institutional safeguards.

Preservation urgency stems from documented threats: declining transmission, environmental pressures disrupting observational practices, and cultural homogenization (Goshu & Ridwan, 2024). Digital archiving offers scalable solutions—open-access for non-sensitive elements, restricted for sacred cosmologies—while fostering community involvement to ensure ownership. This aligns with global indigenous knowledge frameworks, emphasizing free, prior, informed consent and benefit-sharing.

Such efforts could revitalize knowledge, integrate into education/curricula, and support climate adaptation by validating traditional forecasts scientifically. Without intervention, Ethiopia risks losing irreplaceable contributions to global ethnoastronomy, including precise equatorial calendaring absent in Western systems.

Ethiopian astronomical terminology reveals strong ethnic-linguistic variation, with Oromo dominance highlighting the Borana pastoralists' sophisticated celestial calendar for weather prediction and resource management (Duressa, 2023). Amharic's substantial share reflects historical textual preservation in Orthodox contexts. The semantic emphasis on astronomy and time domains demonstrates adaptive utility in equatorial environments, where lunar-stellar cues guide agriculture, navigation, and rituals. Religion and text domains remain minor, indicating predominantly oral transmission. Preservation efforts should prioritize Oromo and under-documented southern languages to capture endangered specialized vocabularies amid cultural shifts (Goshu & Ridwan, 2024a).

The prevalence of roots like Bakk (Bakkalcha), Leg (Lega), and Geda underscores the Borana Oromo's specialized ethnoastronomical vocabulary for timekeeping and seasonal prediction, integrated with the Gadaa socio-political system. High documentation in Oromo and Amharic reflects both oral richness and partial textual recording in major languages, while limited coverage in minority languages signals preservation urgency. The noun-heavy grammatical profile supports descriptive accuracy suited to equatorial sky observation, where compound forms encode relational meanings (e.g., star clusters, lunar phases). These patterns highlight adaptive linguistic resilience amid transmission risks, calling for targeted lexicographic documentation to safeguard endangered terminologies (Duressa, 2023; Goshu & Ridwan, 2024).

The semantic network underscores the functional integration of Ethiopian indigenous astronomy, particularly in Borana pastoral contexts, where terms like Bakkalcha and Lega encode precise navigational and calendrical functions tied to lunar-stellar cycles for seasonal forecasting

(Dinsa et al., 2022). The frequency-documentation correlation confirms that widely transmitted terms receive greater scholarly and community attention, while rarer or specialized vocabulary in minority languages risks erosion. This pattern signals urgent need for expanded lexicographic and multimedia documentation to capture under-represented domains and safeguard oral heritage amid intergenerational transmission challenges (Duressa, 2023; Goshu & Ridwan, 2024).

Social structure profoundly shapes astronomical knowledge transmission in Ethiopia, with oral methods embedded in Gadaa and elder systems ensuring resilience among Borana pastoralists, where Ayyantu specialists preserve lunar-stellar calendars (Dinsa et al., 2022). Highland Orthodox communities integrate textual and church-mediated transmission, reflecting liturgical timekeeping. Ecological-livelihood correlations demonstrate adaptive specialization: pastoral savanna zones rely on mobile oral traditions, while sedentary highland agriculture incorporates community and monastic channels. Ritual networks reinforce intergenerational continuity, though modernization threatens oral dominance. Targeted preservation must prioritize pastoral elder documentation to safeguard specialized ethnoastronomical practices (Duressa, 2023; Goshu & Ridwan, 2024).

The predominance of oral-elder and intergenerational transmission highlights the adaptive strength of Ethiopian ethnoastronomy in mobile pastoral contexts, where celestial cues guide seasonal resource management without reliance on written records (Dinsa et al., 2022). Narrative emphasis on temporal markers (time, season, phase) reflects precise equatorial calendaring essential for livelihood forecasting amid climatic variability. Ecological-lifestyle differentiation demonstrates context-specific utility: pastoralists leverage astronomy for navigation and rain prediction, farmers for sowing timing, and monastic groups for liturgical synchronization. These patterns underscore urgent preservation needs for oral systems facing elder attrition and cultural change (Duressa, 2023; Goshu & Ridwan, 2024).

Ethiopian ethnoastronomical narratives serve as dynamic carriers of resilient knowledge, embedding celestial markers (e.g., Bakkalcha, Lega) within livelihood-relevant stories of seasons, grazing, and guidance, particularly among pastoral Oromo (Dinsa et al., 2022). High resilience in practical application and oral transmission underscores adaptive strength for weather forecasting and resource management, while moderate adaptive flexibility highlights vulnerability to cultural erosion. The strong positive correlation between language vitality and astronomical documentation emphasizes that thriving languages (e.g., Oromo, Tigrayna) better preserve specialized celestial vocabularies and practices, necessitating urgent, community-led efforts to document narratives in lower-vitality groups (Duressa, 2023; Goshu & Ridwan, 2024).

These narratives function as compact, orally transmitted vehicles for Borana and related pastoral ethnoastronomical knowledge, embedding precise celestial markers (e.g., Bakkalcha, Pleiades, Lega) within livelihood-relevant frameworks of seasonal grazing, weather prediction, and timekeeping (Dinsa et al., 2022). The dominance of time and weather semantic fields highlights the predictive core of equatorial indigenous astronomy, enabling adaptive decision-making in variable climates. High frequency of guiding/navigation terms (“guides,” “marks,” “across”) affirms the navigational role of stars in pastoral mobility, while agricultural and cattle references link celestial observation to resource management. Moderate narrative similarity suggests shared archetypal structures—likely reinforced through Gadaa cycles and elder mentorship—yet sufficient variation to preserve localized adaptations. The concise format and oral style increase transmission efficiency but heighten vulnerability to elder loss and cultural disruption, underscoring the need for urgent multimedia documentation and community archiving to sustain this resilient heritage (Duressa, 2023; Goshu & Ridwan, 2024).

Scientific validation confirms the empirical robustness of Ethiopian ethnoastronomy, especially Borana Oromo lunar-stellar observations that align closely with modern seasonal rainfall patterns, enabling 3+ month lead-time forecasts superior to some abiotic indicators (Dinsa et al., 2022). High correlations for markers like Bakkalcha (guiding star) and Lega (constellation) validate their utility in weather and drought prediction amid climate variability.

Negative accuracy-consistency trends and low mean deviations (~1.3 days) indicate precision comparable to early instrumental records, while statistical significance in historical alignments (predominantly $p < 0.01$) affirms non-random correspondence. Sample-size effects suggest publication bias toward high-accuracy cases, yet overall findings support integration into hybrid forecasting models for pastoral resilience. Preservation and further cross-validation are essential to harness this heritage against modernization threats (Duressa, 2023; Goshu & Ridwan, 2024).

The high correlation and low RMSE for rain onset forecasts validate the empirical accuracy of Borana lunar-stellar observations, enabling reliable 3–4 month lead-time predictions of wet-season arrival that outperform many statistical models in data-scarce regions (Dinsa et al., 2022). Slightly larger errors for harvest and dry season timing likely reflect greater variability in cessation patterns and secondary reliance on non-stellar cues. Near-zero-centered residuals and stable multi-decadal trends affirm long-term robustness despite climate shifts, supporting integration of indigenous knowledge into hybrid early-warning systems for drought and food security. These results highlight the scientific value of traditional equatorial astronomy, urging expanded validation across ethnic groups and incorporation into national climate adaptation strategies to preserve and leverage this heritage amid accelerating environmental change (Duressa, 2023; Goshu & Ridwan, 2024).

These results affirm the scientific validity of Ethiopian indigenous climate prediction, especially within Borana pastoral systems where lunar-stellar observations provide skillful seasonal rainfall forecasts with lead times of 3–6 weeks (Dinsa et al., 2022). High inter-correlations among core markers (Bakkalcha, Lega, Wer counting) indicate internally consistent observational frameworks that align closely with modern reanalysis data, offering predictive skill comparable to or exceeding short-term dynamical models in data-sparse regions. The positive lead-time trend and sample-size effect on weighted reliability underscore empirical grounding and potential for scaling validation efforts. Moderate-to-excellent skill in half the indicators highlights adaptive value for drought early warning and agricultural planning amid climate variability. Continued cross-validation, community involvement, and integration into national meteorological services are recommended to preserve and operationalize this heritage before elder knowledge attrition accelerates (Duressa, 2023; Goshu & Ridwan, 2024).

Integration of Ethiopian Indigenous Astronomical Knowledge into formal schooling represents a promising step toward culturally responsive education and preservation of intangible heritage. The concentration of EIAK programs in Addis Ababa, SNNPR, and Oromia aligns with national policy emphasis on indigenous knowledge systems and aligns with global calls for decolonizing curricula (UNESCO, 2015). Borana Oromo lunar-stellar calendars, validated for seasonal forecasting accuracy (Dinsa et al., 2022), offer practical content for science and geography lessons, enhancing student engagement and climate literacy in pastoral communities. Lower adoption in Somali, Afar, and Tigray regions underscores persistent barriers: teacher training shortages, curriculum rigidity, and insecurity disrupting program rollout. These disparities risk widening educational inequities, as indigenous astronomy provides context-specific tools for environmental adaptation in climate-vulnerable zones (Duressa, 2023). Scaling requires targeted capacity building, multilingual materials, and community–school partnerships to ensure equitable reach and long-term sustainability of EIAK programs (Goshu & Ridwan, 2024). Community Elder and Cultural Exchange models excel in culturally responsive EIAK delivery, preserving oral traditions of Borana lunar-stellar knowledge while fostering intergenerational respect and engagement at negligible cost (Dinsa et al., 2022). Their high scalability supports equitable expansion into remote pastoral regions where indigenous astronomy remains livelihood-critical. High-tech models (VR, Maker Space) enhance STEM linkages and visualization of celestial phenomena but are constrained by infrastructure, teacher training, and funding—limiting adoption to urban centers like Addis Ababa. Digital Storytelling and Gamified Learning bridge cultural and scientific domains effectively, offering balanced cost-effectiveness. The predominance of low-to-medium technology in scale-up phases aligns with resource realities in Ethiopia, suggesting hybrid approaches that combine elder-led sessions with mobile/digital tools could maximize reach and impact. Long-term success requires sustained teacher professional development and community co-design to ensure cultural authenticity and educational relevance (Duressa, 2023; Goshu & Ridwan, 2024).

Citizen science programs effectively mobilize communities to document and validate Ethiopian indigenous astronomical knowledge, particularly Borana lunar-stellar calendars critical for seasonal forecasting (Dinsa et al., 2022). High participation in Community Planetarium and Weather Wisdom Collection demonstrates the power of culturally embedded, low-barrier methods—mobile outreach and elder-led sessions that align with oral traditions and pastoral lifestyles. Digital tools (apps, web portals) enhance data volume and accessibility but yield lower per-participant efficiency, likely due to digital divides in rural Ethiopia. Sustainability scores correlate with community ownership and low-cost models, underscoring the need for hybrid approaches combining elder involvement with mobile technology. These efforts not only preserve endangered knowledge but also empower communities in climate adaptation, supporting global calls for participatory indigenous science integration (Duressa, 2023; Goshu & Ridwan, 2024).

Integrating Ethiopian Indigenous Astronomical Knowledge into STEM curricula fosters culturally relevant science education while developing 21st-century competencies. High scores in cultural analysis and critical thinking indicate that EIAK-based learning enhances students' ability to connect traditional celestial observations (e.g., Borana lunar-stellar calendars) with scientific reasoning and pattern recognition (Dinsa et al., 2022). Uniform application of diverse assessment methods supports balanced evaluation of both indigenous and modern skills. Resource prioritization on teacher training and curriculum development is strategic, addressing capacity gaps essential for sustainable implementation in diverse Ethiopian contexts. Moderate digital investment reflects infrastructure realities, yet offers potential for scalable tools like mobile planetaria. This framework aligns with global decolonizing education trends and strengthens climate literacy by validating indigenous forecasting knowledge, warranting expanded pilot programs and longitudinal impact studies (Duressa, 2023; Goshu & Ridwan, 2024).

IV. Conclusion

Ethiopian Indigenous Astronomical Knowledge (EIAK) emerges from this comprehensive study as a highly sophisticated, empirically validated, and culturally embedded system of celestial observation that continues to serve critical functions in seasonal forecasting, pastoral decision-making, agricultural timing, ritual coordination, and social organization across Ethiopia's diverse ethnic landscape. Far from being relics of the past, these traditions—most elaborately developed among the Borana Oromo but also richly present among Amhara, Tigray, Afar, Somali, Konso, Sidama, Gurage, Wolayta and others—demonstrate remarkable predictive accuracy and adaptive resilience in one of the world's most climatically variable equatorial environments.

The evidence shows that EIAK is not anecdotal folklore but a functional knowledge system capable of delivering skillful seasonal forecasts. Time-series validation against modern meteorological records confirms particularly strong performance for rain onset prediction (correlation $r = 0.889$, $RMSE = 3.3$ days) and reasonable skill for harvest timing and dry-season transitions, with mean monthly deviations of approximately 1.3 days for key markers such as Bakkalcha (guiding star), Lega (constellation), Wer counting, and lunar phases. These levels of accuracy, achieved with lead times of 3–6 weeks, rival or exceed many short-term statistical models in data-sparse pastoral regions and underscore the empirical grounding of indigenous equatorial astronomy.

Knowledge transmission remains predominantly oral (64.3%), sustained through intergenerational storytelling, elder mentorship, Ayyantu specialists, and Gadaa socio-political structures. Narratives function as efficient mnemonic devices, embedding navigational, calendrical, and meteorological information within livelihood-relevant motifs (time 26.9%, weather 19.2%, astronomy/navigation/agriculture ~19% each). Linguistic richness is highest in Oromo, with recurring roots (Bakk, Leg, Urjii, Geda, Mewcha) reflecting precise descriptive vocabulary for observable phenomena.

Educational integration pilots reveal strong potential for culturally responsive STEM learning. Low-cost, community-embedded models—Community Elder sessions (68 schools) and Cultural Exchange (55 schools)—achieve the highest adoption, effectiveness, and competency gains in cultural analysis (0.90), critical thinking (0.87), collaboration (0.86), and pattern recognition (0.85), while high-tech approaches (VR, Maker Space) remain constrained by cost and infrastructure. Citizen-science initiatives engaged over 18,000 participants, with mobile and elder-led programs (Community Planetarium, Weather Wisdom Collection) delivering the highest per-participant data efficiency and long-term sustainability.

Despite these strengths, EIAK faces existential threats: rapid elder attrition, urban migration, cultural homogenization, digital divides, and uneven documentation favoring central/ethnic-majority groups. Educational scaling remains geographically biased toward Addis Ababa, SNNPR, and Oromia, leaving peripheral pastoral regions underserved despite their high dependence on celestial cues.

In conclusion, EIAK constitutes a living, scientifically credible knowledge system whose integration into modern forecasting, climate adaptation, disaster risk reduction, and culturally relevant education can yield substantial societal benefits. Its preservation is not merely a cultural imperative but a strategic necessity for building climate resilience in Ethiopia and contributing unique equatorial perspectives to global indigenous science. Coordinated, community-centered action—combining rigorous documentation, expanded validation, equitable educational expansion, sustainable citizen science, and policy recognition—is essential to prevent irreversible loss and to transform this heritage into a dynamic resource for sustainable development in the 21st century.

Recommendations

Accelerated multi-ethnic documentation. Initiate nationwide, community-led recording projects prioritizing underrepresented groups (Afar, Somali, Gurage, Sidama, Wolayta) using audio-video, multimedia archives, and tiered-access digital repositories with strict adherence to free, prior, informed consent.

Large-scale, multi-year validation. Expand rigorous cross-validation studies integrating high-resolution satellite, reanalysis, and ground-station data to quantify EIAK skill across climatic zones and extreme events, enabling operational hybrid forecasting models.

Equitable educational expansion. Scale EIAK-STEM integration to pastoral and peripheral regions via mobile teacher training, multilingual materials, hybrid low-high tech delivery (Community Elder + Mobile Planetarium), and continuous community-school co-design.

Sustainable citizen-science ecosystems. Transition high-impact programs (Community Planetarium, Weather Wisdom Collection) into long-term, community-owned platforms with diversified funding, offline-capable mobile tools, youth mentorship, and regular impact evaluation.

Policy and institutional integration. Advocate for formal recognition of validated EIAK within national meteorological services, disaster risk reduction frameworks, and school curricula; establish inter-ministerial task forces and international partnerships to protect and promote indigenous astronomical heritage.

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