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Fourth industrial revolution technologies for climate resilience in Africa: Integrating African indigenous knowledge for smart sustainability

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As Africa confronts intensifying climate risks, emerging conversations around the Fourth Industrial Revolution and Indigenous Knowledge Systems offer promising pathways for resilience. While a handful of studies have explored and discussed this intersection, the conversations remain nascent and are marked by superficial consultations, limited co-design and a lack of clear metrics to assess community involvement or cultural relevance. This study contributes to this conversation, investigating how Fourth Industrial Revolution technologies such as Artificial Intelligence, Internet of Things, blockchain and remote sensing can be meaningfully integrated with African indigenous knowledge, particularly in climate-sensitive sectors like agriculture, conservation and rural livelihoods.

Transdisciplinary Contribution: Using a qualitative transdisciplinary literature review and case studies from across the African continent, the research examines hybrid models that link digital innovation with traditional ecological wisdom. Findings reveal that effective climate resilience requires more than technological deployment; it demands inclusive, ethical frameworks that embed Indigenous Knowledge Systems into digital systems, foster community ownership and support culturally grounded adaptation strategies. The study proposes a conceptual framework and a Community Climate Interpretation Protocol, which introduces a set of simple, locally grounded metrics that empower communities to observe, interpret and respond to weather patterns, using both indigenous knowledge and accessible tools. The context-sensitive co-designed framework offers actionable insights for policymakers, technologists and heritage practitioners. The framework contributes to the growing discourse on decolonising digital sustainability and advancing climate-smart, socially embedded innovation aligned with Sustainable Development Goals 13 (Climate Action) and 2 (Zero Hunger). The model blends a replicable policy blueprint with a practical application that is technologically advanced and socially embedded.

Keywords: 4IR; African indigenous knowledge; climate resilience; Africa; SDGs; smart change; digital transformation; heritage sustainability.

Introduction

Studies in Africa suggest that combining Fourth Industrial Revolution (4IR) technologies with indigenous knowledge can enhance climate resilience through locally relevant early-warning and decision-support systems. Masinde[1] discusses how the Information Technology and Indigenous Knowledge (ITIKI) framework digitalises local drought indicators by integrating wireless sensor networks and artificial intelligence (AI). Thothela et al.[2] further discuss an improved version that uses fuzzy inference systems alongside smart sensors and indigenous practices to assist smallholders in predicting weather patterns, while Agbehadji et al.[3] outline a community co-design model in early warning systems, which leverages digital tools such as blockchain and Big Data to capture and process weather and climate information.

Wanyama et al.[4] and Balogun et al.[5] focus on 4IR applications in smart irrigation and urban digitalisation but do not report indigenous knowledge integration. Across the Indigenous Knowledge Systems (IKS)-related works, the importance of community engagement, demonstrable benefits in early warning and resource optimisation and challenges related to infrastructure, cost and technical expertise are common issues discussed. These findings provide insights into the opportunities and challenges of integrating indigenous knowledge with advanced digital technologies to achieve smart sustainability and climate resilience in Africa. The article specifically seeks to explore how 4IR technologies such as AI, Internet of Things (IoT),

blockchain and remote sensing can be synergistically integrated with IKS to enhance climate resilience, with a focus on AI-driven early warning systems for timely and context-specific climate responses. This objective is explored through answering the key question: how can 4IR technologies be effectively integrated with African IKS to develop locally relevant, ethical AI-driven early warning systems that enhance climate resilience?

Literature review

Recent literature highlights the growing value and urgency of integrating IKSs with modern technologies to address climate vulnerability, particularly among smallholder farmers in sub-Saharan Africa. Kompi et al.[6] argue that although indigenous farming practices have long supported climate adaptation, they remain weakly integrated into contemporary scientific and technological systems because of their qualitative and unstructured nature. Their work advances the proposition that indigenous knowledge can be systematically quantified and translated into data formats compatible with modern decision-support tools, thereby enhancing climate resilience and farmer agency. Similarly, Amare et al.[7] demonstrate that while indigenous knowledge continues to inform local adaptation strategies, the uptake of climate-smart agriculture innovations that meaningfully incorporate such knowledge remains limited in developing countries, constraining broader resilience outcomes. These studies underscore a persistent disconnect between indigenous adaptive practices and formal technological interventions.

More recently, scholarly contributions emphasise integrative and ethically grounded digital approaches as a pathway to overcoming this divide. Khan et al.[8] contend that digital technologies such as mobile applications, geographic information systems and cloud-based platforms offer viable mechanisms for documenting, preserving and sharing indigenous knowledge, provided that partnerships between indigenous communities and technical experts are prioritised. Kemarau et al.[9] further demonstrate that hybrid indigenous and scientific knowledge systems improve the accuracy and social acceptance of climate forecasts, arguing for inclusive frameworks that respect epistemic diversity as a foundation for sustainable climate resilience. Beyond agriculture and climate services, Ajani et al.[10] highlight the role of digital media technologies in revitalising IKS through language preservation. They also cautioned about the need to respect ethical considerations, particularly around intellectual property rights and community ownership in the 4IR context.

Collectively, this body of literature supports the need for socio-technical frameworks that integrate digital innovation with indigenous knowledge in ways that are inclusive, context-sensitive and institutionally supported.

Socio-technical systems theoretical framework

This study views the integration of 4IR into IKS through the lens of Socio-Technical Systems (STS) theory.

This approach provides a promising pathway for enhancing climate resilience in Africa[11] and necessitates a robust theoretical understanding. Early insights from Trist et al.'s[12] STS theory provide a basis for understanding the importance of integrating 4IR into existing community knowledge systems about climate change. The seminal theoretical arguments sought to integrate technology and social employee needs for British coal miners in the 1950s, providing a firm ground for integrating 4IR in the current climate change discourse and practice. Unlike the disruptive effects of technology, such as decreased motivation and productivity because of the introduction of new mining technologies in the 1950s,[12] STS theory emphasises that successful technological interventions are premised on concurrent consideration and optimisation of both the technical components (tools, processes and systems) and the social elements (people, culture and structures) of the environment.[12] This theory fits into this discussion, particularly the arguments for the integration of 4IR into climate resilience and IKS for smart and resilient climate change interventions in Africa. The theory is particularly relevant, as it underscores the importance of aligning modern technological solutions with local social structures, values and participatory practices to ensure meaningful, sustainable outcomes.[12]

The emphasis of STS on the interdependence of social and technical systems in organisational and community contexts demonstrates success factors for integrating 4IR and IKS.[12,13] The adaptation and transformation to hybrid systems require the harmonious interaction between technological advancements and social structures, including cultural norms and local practices.[14] Applied to this study, STS theory offers a scholarly perspective that examines the integration of 4IR technologies with IKS for climate resilience in Africa. The theory foregrounds the argument that 4IR tools and platforms alone cannot deliver sustainable outcomes if deployed in isolation from local cultural practices, governance structures and the lived experiences of local communities. This framing emphasises that smart sustainability depends not only on technical sophistication but also on how 4IR technologies are socially fused, embedded, culturally legitimate and collectively governed.

Thus, 4IR technologies should provide opportunities to improve rather than to erase IKS for climate and weather predictions in Africa. The argument addresses fears that 4IR technologies may undermine IKS in climate resilience projects in Africa. Thus, successful deployment of 4IR technologies in Africa requires careful attention to the social systems within which they are implemented, ensuring that these technologies are adopted in ways that align with local knowledge and practices.[11]

Indigenous Knowledge Systems for climate resilience

Indigenous Knowledge Systems play a pivotal role in climate change adaptation across Africa. These are long-standing

traditions, practices and understandings developed by local communities through direct interaction with their environment, often passed down through generations.[15] These systems encompass ecological observations, weather prediction techniques, resource management strategies and adaptive responses to climate variability, all rooted in specific cultural and geographical contexts.[16,17] Indigenous Knowledge Systems play a vital role in climate resilience by offering context-specific, low-cost and sustainable solutions that can complement modern technological interventions. Traditional ecological knowledge is one model that explains how practices related to sustainable farming, water management and natural resource conservation interact and provide useful information to foster resilience against climatic variations.[18] This model helps explain how indigenous farming practices, for example, have been shown to maintain soil fertility and enhance water retention, crucial elements for sustaining agricultural productivity in a changing climate.[19] Indigenous Knowledge Systems often include methods of disaster preparedness and community-based management that can be directly applied to contemporary climate challenges.[20]

Despite the valuable insights these knowledge systems provide, they often remain underutilised in mainstream climate adaptation strategies, partly as a result of a lack of integration with modern technologies. However, recent studies have indicated that when combined with 4IR technologies, they can significantly improve climate resilience. For instance, integrating indigenous coastal design strategies with modern data systems enhances resilience in coastal regions by combining traditional knowledge with real-time climate monitoring.[21]

Fourth Industrial Revolution technologies

Fourth Industrial Revolution technologies have the potential to transform climate resilience efforts, particularly in data collection, analysis and resource management. In this climate-smart context, the integration of advanced digital technologies into environmental and societal systems to enhance adaptive capacity, efficiency and resilience in the face of climate change constitutes 4IR integration.[22] It leverages innovations such as AI, IoT and blockchain technology to support data-driven, real-time and transparent decision-making. Artificial intelligence enables predictive modelling and automated climate monitoring by analysing large datasets to forecast weather patterns, assess risks and optimise resource use. The IoTs involves interconnected sensors and devices that collect and transmit environmental data, such as soil moisture or temperature, supporting precision agriculture and early warning systems.[22] Blockchain provides secure, decentralised data management, useful for transparent tracking of resource flows, carbon credits or climate finance, thereby fostering trust and accountability in climate-smart initiatives.[23,24,25] Artificial-intelligence-driven weather prediction models, IoT-based smart agriculture systems and blockchain for tracking sustainable supply chains are examples of how technological innovations can provide real-time, data-driven solutions to climate challenges.[17] These technologies provide strategic opportunities to supplement IKS by providing accurate forecasting, early warnings and predictive analytics, which enhance decision-making and community preparedness.[26]

Research methods and design

This study adopted a transdisciplinary, qualitative, systematic literature review to investigate how 4IR technologies are integrated with IKS to enhance climate resilience in Africa. Qualitative synthesis enabled an in-depth, contextualised understanding of complex socio-technical intersections, capturing both technological innovation and culturally embedded practices that cannot be fully understood through quantitative aggregation alone.[27] The literature search involved an extensive review of publications indexed in Scopus, Web of Science, Google Scholar and selected institutional repositories, yielding 50 relevant sources published between 2010 and 2024. These sources included peer-reviewed journal articles, policy reports and documented case studies and collectively informed the theoretical, contextual and methodological framing of the study.

From this broader corpus, a subset of studies was systematically screened for in-depth qualitative synthesis, using eight predefined inclusion criteria: relevance to climate resilience, explicit application of 4IR technologies, integration of IKS, African geographic focus, evidence of community engagement, methodological clarity, innovation or scalability potential and alignment with Sustainable Development Goals.

Each study was analysed by using a structured analytic framework assessing the type of 4IR technology deployed, the nature and application of indigenous knowledge, functional domains, community engagement approaches, reported outcomes and implementation challenges and enablers. This approach enabled systematic cross-case comparison and a thematic analysis.

The flow diagram in Figure 1 illustrates the key steps taken to identify and select appropriate literature and studies used for the deep analysis of this study.

Ethical considerations

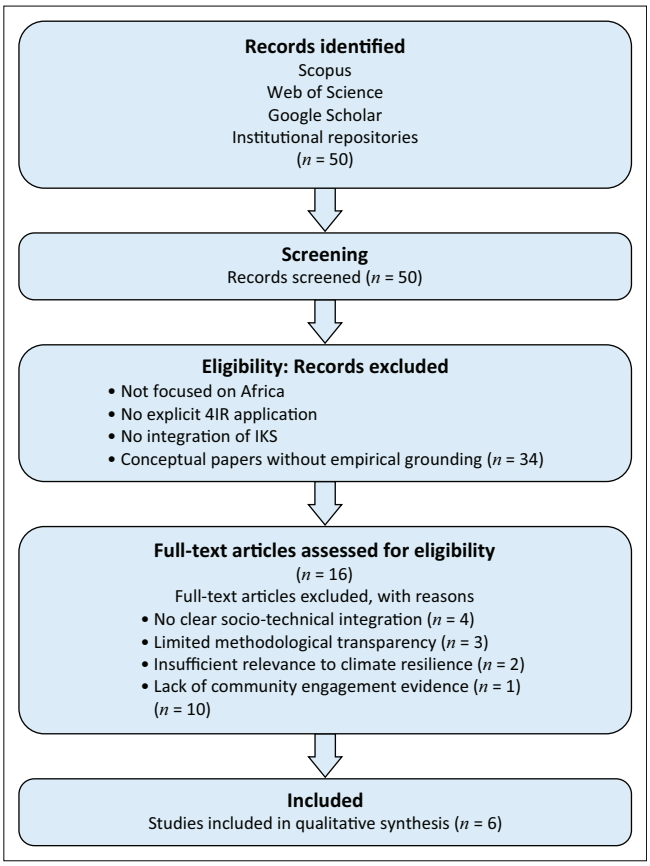
This article followed all ethical standards for research without direct contact with human or animal subjects.

Results

The results presented in this section demonstrate how integrating 4IR technologies such as AI, IoT, blockchain and remote sensing can positively impact rural agriculture, conservation and rural livelihoods through integrated 4IR-IKS hybrid weather and climate predicting systems. Nine themes were identified and presented in the next sections.

Integration frameworks and approaches

Firstly, the identified theme revealed the importance of existing 4IR-IKS integration frameworks and approaches



4IR, Fourth Industrial Revolution; IKS, Indigenous Knowledge Systems.

FIGURE 1: PRISMA flow diagram for methodology.

that provide structured pathways for combining IKS with advanced 4IR tools. A leading example is Masinde's ITIKI framework, developed and piloted in Kenya, Mozambique and South Africa. This framework integrated coded fuzzy logic with local ecological observations to improve drought prediction.[1] It integrated local farmers' traditional indicators, such as bird migrations and flowering patterns, into algorithmic models to generate hybrid early warnings. Through the ITIKI framework, community trust was enhanced when communities saw their knowledge reflected in weather outputs that directly affected them. Similarly, Thothela et al.'s blockchain-enabled platform documented and validated indigenous farming practices in South Africa.[2] Blockchain applications in South Africa showed significant potential to preserve and manage IKS in the agriculture sector. Mavilia et al.[28] concurred that blockchain technology reshaped the agricultural sector as it provided secure environments for storing and exchanging agricultural data. Sakthi et al.[29] also revealed that the integration of blockchain with IoT and Edge Computing helped create smart agricultural knowledge discovery systems. The scholars noted that the integration of blockchain technology was beneficial in offering privacy, security and easy accessibility of information, which guarantees protection of sensitive data from unauthorised access.[29]

Despite the complementary opportunities for 4IR-IKS in traditional agricultural systems, such as informing rural production, storage, processing and marketing practices, scholars found that the fear that technology may erase IKS was real; hence, the call for its preservation to ensure continuity when older generations pass away.[30] The literature further revealed that technology presented opportunities for digital preservation of IKS in Africa through digital archiving and other related information and knowledge management systems.[31] Likewise, ensuring local farmers' information transparency and security through blockchain strengthened their intellectual property rights while creating a reliable repository for integrating IKS into smart agriculture.[23] The current challenge with these hybrid frameworks, despite demonstrated promise, was their reliance on digital infrastructures unavailable in most rural areas in Africa. Hence, scalability remained a challenge.[32]

Fourth Industrial Revolution applications for climate resilience

Secondly, 4IR applications have been developed and deployed for climate-smart resilience in Africa. Several African countries have tested specific 4IR tools to support climate adaptation. For example, in Uganda, Nomugisha et al.[33] developed an IoT-based sensor network to monitor soil moisture and optimise irrigation for maize farming. The Uganda research demonstrated the significant potential of IoT technology in transforming agricultural practices. This comprehensive IoT framework, specifically for climate-resilient maize farming in Central Uganda, addressed challenges including climate change, suboptimal resource use and low crop yields through cost-effective solutions suitable for smallholder farmers. Similarly, Wilberforce et al.[34] found that IoT-enabled smart agriculture frameworks provided useful insights into smart technologies such as Raspberry Pi. This 4IR system integrated sensors for real-time monitoring of temperature, rainfall, soil moisture and pressure, which improved local weather predictions and decision-support systems when connected to systems such as the 'Thing Speak' platform for data analysis and remote access.

More evidence of IoT use in agriculture showed promising results, with Dayoub et al.[35] highlighting precision agriculture's potential to increase yields up to 50%, while reducing costs through real-time data management of soil, water and weather information. Alzubi et al.[36] also revealed how AI and IoT integration enabled sustainable farming practices and highlighted realistic challenges such as data management, interoperability and infrastructure deployment in agriculture.

The above scholarly literature evidence, however, revealed an overarching challenge of costly infrastructure, limiting reach to wealthier farmers. These challenges were also experienced in Malawi, where an AI-powered WhatsApp chatbot, 'Ulangizi', was used to deliver agricultural information to local farmers. Ulangizi, an adviser in the local Chichewa language, delivered real-time advice in vernacular to smallholder farmers adapting to drought and cyclone risks.[37] This pilot project revealed that while this linguistic inclusivity was a success story, access barriers persisted as a

result of limited smartphone penetration and Internet costs, particularly for rural women. Similarly, Ozor et al.[38] revealed successful AI-driven pest and disease detection through Artificial Intelligence for Agriculture and Food Systems Innovation Research Network across eight sub-Saharan countries.[38] This initiative prioritised gender equality, social inclusion and environmental sustainability through participatory design and ethical frameworks.[38] However, the familiar challenges like infrastructure limitations, technological accessibility and resource constraints continued to hinder scalability and effective use.[39] Thus, other studies suggested that Africa needs AI solutions beyond technological determinism and Western-centric worldviews. The suggestions entailed embracing decolonial approaches that acknowledge past power imbalances, gender disparities and race and incorporate IKS.[40] Practical steps to address these gaps included establishing robust policy frameworks, strengthening capacity-building efforts and ensuring input from African innovators, policymakers, and academics to align AI solutions with local needs and values.[41] These exam ples showed that 4IR applications enhanced resilience when they are gender inclusive, localised, participatory and affordable.

Implementation and sustainability factors

Thirdly, the sustainability of integration initiatives often depended on institutionalisation, policy support and resource continuity. Research evidence on IKS in African climate and disaster policies revealed gaps between knowledge, recognition and implementation.[18] Bol et al.[18] found that while policy documents were increasingly referencing IKS, their practical implementation in formal decision-making was limited. This important study across seven African countries representing six climate zones provided useful insights into action points to bridge the knowledge-implementation gaps.[18] Despite this policy gap, IKS have demonstrated remarkable adaptability, evolving with changing climate conditions to develop advanced adaptation strategies enhanced through technology-driven early warning systems, risk management and weather forecasting.[42]

Mwalwimba et al.[43] asserted that flood prediction based on animal movements and ecological cues was widely trusted by farmers, yet the absence of formal recognition meant limited institutional uptake. Similarly, in South Africa, indigenous indicators of drought risk were not systematically integrated into most municipal disaster risk-reduction plans. This left gaps between policy commitments and practice.[44] Similarly, barriers such as colonial influences, inadequate documentation and modernisation were noted as other factors that affected the integration of IKS into integrated planning processes to preserve this knowledge.[44] The studies revealed that despite efforts to bridge this gap, donor dependence in financing limited the sustainability of these efforts. The research evidence further revealed that sustainability ultimately required investments in scientific understanding, observational data, model capability, capacity development, knowledge management and strengthened partnerships for co-production and coordination.[45]

Knowledge co-production and participatory design

Fourthly, research evidence showed that knowledge co-production played a pivotal role in ensuring the credibility and adoption of integrated systems. In sub-Saharan Africa, participatory workshops in which farmers helped shape AI advisory tools resulted in higher uptake of the technology.[38] Farmers valued being part of the design, which increased ownership and cultural fit. In South Africa, Masinde[1] highlighted how involving rural communities in drought prediction through ITIKI not only validated indigenous knowledge but also improved algorithmic accuracy. These findings, aligned with wider African evidence, showed that when co-design is prioritised, both scientific reliability and social legitimacy were enhanced.[46] In information technology for development contexts, Montero et al.[47] and Makate[48] demonstrated that integrating co-creation and co-design within design science research with women entrepreneurs in Tanzania produced meaningfully contextualised solutions and fostered stronger ownership and social acceptance. Similarly, Tsekleves et al.[46] noted that community engagement and integrating women into leadership roles and considering cultural preferences led to more sustainable and effective interventions. Likewise, co-design workshops in South Africa's flood management brought together diverse stakeholders, including flood-prone communities, which enabled the establishment of key risk drivers and fostered genuine collaboration for community-based early warning systems.[49] Conversely, top-down models often failed because they overlooked socio-cultural practices, which were critical for community trust building.

Inclusivity and gendered dimensions

The fifth theme on inclusivity and gendered dimensions revealed how 4IR excluded some community members, particularly women who are not socially integrated into community realities. Studies across sub-Saharan Africa found that digital farming tools often ignored women's access constraints, reinforcing inequalities.[38] Conversely, where gender was explicitly addressed through training and inclusion in design processes, women reported higher yields, better climate adaptation strategies and increased agency in decision-making.[38] As shown earlier, in Malawi, the AI chatbot demonstrated inclusivity by supporting communication in local languages, but affordability remained a barrier, disproportionately affecting women smallholder farmers with less access to digital devices.[37] Evidence across the continent showed that gender-sensitive designs were both an ethical imperative and a determinant of practical 4IR-IKS success in climate-smart and resilient interventions.[38]

Trust, accessibility and localisation

The sixth theme revealed how trust and accessibility were recurrent challenges yet very critical factors in scaling 4IR-IKS integrated systems. The experience with farmers using the AI chatbot in Malawi showed how mistrust of AI led to underutilisation of 4IR investments at the community level.

The theme revealed that any AI-related errors, like misdiagnosis of pests and diseases, resulted in disastrous results like lost yields, which created a mistrust of AI advice. In Uganda, similar experiences were noted, including expressed hesitation in trusting AI or IoT recommendations when they diverged from indigenous indicators.[33,37] Yet, in South Africa, reliance on local ecological signs such as insect behaviour and flowering patterns enhanced trust in hybrid models because farmers saw familiar signals mirrored in digital outputs.[1] Accessibility issues, particularly the costs of smartphones, Internet and sensors, limited uptake in Malawi and Uganda.[33,37] The evidence showed the effects of localisation strategies using low-cost, offline and inclusive language tools as bridges to address trust and access gaps.

Policy and institutional gaps

The seventh theme revealed policy and institutional gaps despite recognition of IKS in national climate policies. A review of climate frameworks in Zimbabwe, South Africa, Kenya and Malawi showed that IKS was often acknowledged rhetorically but rarely embedded in disaster risk–reduction strategies.[18,50] Added to this gap was the weak institutional support, lack of monitoring and inadequate cross-sector collaboration, which limited scaling. As noted earlier, South Africa's climate policies mentioned indigenous practices, yet municipal-level implementation often excluded them as a result of a lack of technical frameworks.[44] Similarly, in Malawi, institutional silos between local disaster committees and scientific agencies hindered integration of traditional flood indicators into formal early warning systems.[43] The system did not bridge the policy–practice gap, which was essential for mainstreaming IKS within 4IR-enabled governance structures.

Evidence of impact on climate resilience

The eighth theme revealed tangible benefits of integrating IKS and 4IR. In sub-Saharan Africa, co-designed AI systems improved crop yields and reduced fertiliser waste.[18] In South Africa, farmers reported more accurate drought forecasts when indigenous cues were blended with fuzzy inference models.[1] In Malawi, the 'Ulangizi' chatbot improved farmer access to climate advice, especially during cyclone seasons.[37] However, the studies also revealed how these impacts were uneven, with marginalised groups often left behind as a result of affordability and infrastructure gaps. Long-term evaluations were rare, making it difficult to establish sustained resilience outcomes.

Intellectual property considerations

Finally, the studies revealed that the integration of IKS into 4IR raised questions about intellectual property, ownership and ethics. Blockchain-enabled frameworks in South Africa showed promise in protecting local knowledge by creating transparent and verifiable records.[2] However, concerns remained about the exploitation of indigenous knowledge by external actors, without adequate benefit sharing. Agbehadji et al.[3] argued that ethical AI in African agriculture must prioritise inclusivity, fairness and respect for traditional practices. Without safeguards, there was a risk that digital platforms would commodify and appropriate IKS, rather than empowering its custodians.

These findings revealed that while the integration of 4IR technologies with IKS holds transformative potential for climate resilience in Africa, its success depended on moving beyond rhetorical inclusion and technological determinism to hybrid systems rooted in local agency, ethical co-design and inclusive governance.

Discussion

The results have shown varied implications, opportunities and challenges in the integration of 4IR technologies into climate preparedness strategies. This includes new possibilities for enhancing early warning systems, agricultural efficiency and community resilience. Masinde's[1] ITIKI system implies that African agricultural and climate programmes could potentially benefit more through combining indigenous drought indicators with real-time sensor data to produce locally relevant alerts. Similarly, Agbehadji et al.'s[3] decentralised early warning architecture may improve transparency and accelerate smart agriculture and climate information through smart sensors, AI and blockchain technologies. These innovations are particularly valuable in regions like rural Africa, where conventional meteorological infrastructure is limited or inaccessible.

However, their real-world performance is often constrained by persistent infrastructure deficits, unreliable power supply and low levels of digital literacy, especially in rural and marginalised communities. A critical gap in the reviewed literature is the limited attention to system robustness, including the risks of false positives and negatives and the lack of interoperability with traditional alert mechanisms such as community radio, oral storytelling and local observation protocols. This gap raises concerns about overreliance on digital precision, without inclusive rollout strategies that accommodate diverse knowledge systems and user capacities.

Moreover, the high capital investment required for deploying 4IR technologies, ranging from sensor networks to satellite-linked platforms, often benefits external suppliers and technology vendors more than the communities they are intended to serve. Agbehadji et al.[3] caution that without clear frameworks for return on investment and long-term sustainability, these technologies risk reinforcing existing inequalities rather than resolving them.

Smart irrigation and precision agriculture platforms, as discussed by Wanyama et al.,[4] offer promising solutions to climate-induced agricultural stress, particularly in semi-arid regions. These systems integrate drones, satellite imagery and AI-powered decision support to optimise water use and improve crop yields.

Yet, their adoption among smallholder farmers remains limited because of the need for stable Internet connectivity, technical expertise and financial resources. Mavilia et al.[28] highlight the blockchain's potential to enhance transparency and market access, but empirical evidence on its long-term impact in low-resource settings is still emerging. Mfitumukiza et al.[32] emphasise that scalability must be grounded in institutional support, subsidy frameworks and adaptation to local socio-economic realities.

The integration of these technologies with IKS must be deliberate, inclusive and economically viable to ensure that they contribute meaningfully to climate resilience. Codified IKS, such as community-based weather interpretation protocols using sky colour, wind direction, animal behaviour and soil texture, can serve as low-cost, culturally embedded tools for identifying and reporting climate risks. These protocols should be linked to simplified monitoring and evaluation frameworks that allow communities to track changes, respond to alerts, and contribute to longitudinal data collection. As this article recommends, governments and private sector actors must prioritise the expansion of public digital infrastructure, including affordable Internet access and digital literacy programmes, to ensure that rural and underserved populations can engage with these technologies meaningfully. Without such foundational investments, the promise of 4IR will remain out of reach for those most vulnerable to climate shocks.

Ultimately, the path to smart climate resilience lies not in choosing between tradition and technology but in weaving them together through ethical co-design, inclusive governance and sustained investment. This requires a shift from extractive innovation models towards community-led adaptation, where local knowledge not only is respected but also actively shapes the tools and systems designed to protect it.

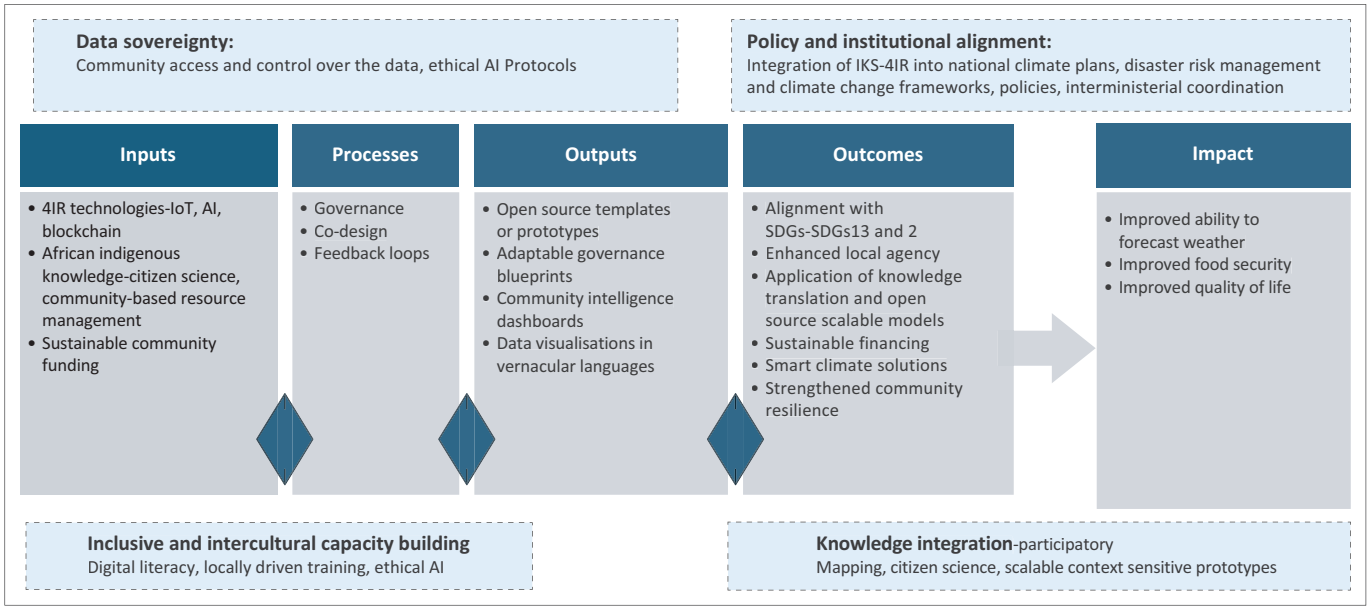
Conceptual contributions of the article: The integrated framework for smart sustainability through tech-indigenous synergy

In response to the fragmented landscape described in previous sections, this article introduces the Integrated Framework for Smart Sustainability through integrated framework for smart sustainability through tech-indigenous synergy (IFSS-TIS) as a conceptual innovation. Drawing on the strengths and limitations of previous models, IFSS-TIS seeks to harmonise co-designed 4IR technologies with indigenous knowledge through a structured, scalable and culturally sensitive approach. The framework is designed to guide policymakers, technologists and community stakeholders in implementing solutions that are not only smart but also sustainable and socially embedded, thereby advancing climate resilience in Africa.

The IFSS-TIS outlines key components for achieving climate resilience:

As Figure 2 shows, incorporating multidimensional frameworks that integrate 4IR technologies with IKS enhances climate resilience in African communities. The introduction of ethical considerations such as data sovereignty and mechanisms for knowledge translation, participatory co-design and intercultural capacity building enhances existing frameworks. It offers a structured pathway from inputs to impacts, harmonising technological innovation with cultural relevance, community ownership and inclusive governance.

Another key contribution is the framework's conscious attempt to position indigenous knowledge not as a passive supplement but as a co-equal input in climate-smart innovation. Thus, introducing novel layers such as community intelligence dashboards and scalability protocols



AI, artificial intelligence; IKS, Indigenous Knowledge Systems; 4IR, Fourth Industrial Revolution; IoT, Internet of Things; SDGs, Sustainable Development Goals.

FIGURE 2: Author's conceptualisation of the Integrated Framework for Smart Sustainability through Tech-Indigenous Synergy.

not only bridges the gap between pilot projects and long-term sustainability but also brings the African epistemic voice in 4IR-IKS discourse and practice.

Likewise, aligning outputs with Sustainable Development Goals 13 (Climate Action) and 2 (Zero Hunger), the model offers relevant policy and practical options that address technological and social issues, which enhances the trust in and use of the system. Thus, this conceptual synthesis provides a foundation for rethinking climate resilience through a socio-technical lens that centres African agency and epistemologies. The next section discusses how this model can be simplified for applied deployment in rural Africa.

Community climate interpretation protocol and metrics

The proposed Community Climate Interpretation Protocol (Table 1) introduces a simple set of locally grounded metrics designed to empower communities to observe, interpret and respond to weather patterns, using both indigenous knowledge and locally accessible tools.

This tool provides practical guidance based on everyday climate indicators such as sky colour, wind direction, animal behaviour, plant responses, soil texture and rainfall patterns to inform communities on weather and climate changes. While not exhaustive and not providing universally understood climate signals, the listed metrics serve to illustrate how a simplified community weather protocol contributes to the transformation of passive community observations into proactive climate intelligence. Pairing each metric with a clear method of measurement and a risk flag system (green, yellow and red) guides community action. This proposed structure is inclusive and democratises smart climate interventions at the community level, enabling community members with low-literacy levels to engage meaningfully with climate signals and fostering a culture of preparedness rooted in local experience rather than external dependency.

The integration of high-tech climate models with indigenous knowledge metrics on climate bridges knowledge gaps between 'outsiders' and 'insiders', thereby improving community resilience to climate shocks based on grassroots realities. This model has the potential to improve community response to climate shocks through activating early climate responses and also complements the inconvenient waiting for delayed or inaccessible forecasts from conventional national weather stations. Communities are empowered as they can activate early responses such as adjusting planting schedules, securing livestock or conserving water based on their own observations. Through an integrated logbook system, the framework ensures that climate champions track, share and act upon climate data collectively and also integrates literacy into daily life, reduces vulnerability to extreme weather and builds local ownership into climate adaptation. Ultimately, existing scientific models could be enhanced if they consider the hybrid proposals making climate resilience smarter, more inclusive, democratic and deeply rooted in community wisdom.

Conclusion

This study affirms that integrating 4IR technologies with IKS presents a transformative opportunity for building climate resilience across African communities. However, the current landscape remains fragmented, with efforts often limited to pilot projects or isolated interventions that lack institutional depth and long-term sustainability. While co-designed tools like ITIKI have demonstrated the value of blending local knowledge with predictive analytics, their implementation is uneven and rarely scaled across regions or sectors. Most 4IR applications are concentrated in agriculture and early warning systems, leaving critical domains such as urban planning, disaster governance and public service delivery under-explored. Moreover, the exclusion of traditional governance structures, gendered knowledge and intergenerational wisdom from mainstream climate strategies continues to undermine the legitimacy and effectiveness of these interventions.

A deeper concern lies in the absence of simplified monitoring tools, longitudinal data and adaptive feedback mechanisms that allow communities to learn from experience and refine their responses over time. Without these elements, climate innovations risk becoming top-down and technocratic, disconnected from the lived realities of those most affected.

TABLE 1: Community climate interpretation protocol.

Metric	Why It Matters	How to Measure It	Risk Flag	Community Action
Sky Colour at Sunrise and/or Sunset	Red and/or orange hues may signal dry spells or wind shifts	Visual observation daily at dawn and/or dusk	Yellow (if persistent)	Begin water-saving measures; delay planting
Wind Direction and Strength	Sudden changes may indicate storms or seasonal shifts	Use flags, smoke trails or tree movement	Red (if strong and erratic)	Secure homes, livestock and crops; alert leaders
Animal Behaviour	Birds flying low or frogs vocalising often precede rain	Observe animal movement and sounds	Yellow (if frequent)	Prepare for rain; check drainage and shelter
Plant Indicators	Early flowering or leaf curling may signal heat stress or seasonal change	Monitor local trees and crops weekly	Yellow or Red (if widespread)	Adjust planting schedules; apply mulch or shade
Soil Texture	Cracking signals drought; sogginess signals flood risk	Touch and observe the soil weekly	Red (if extreme)	Store water, reinforce ditches and avoid planting
Rainfall Patterns	Irregular or intense rain may signal climate disruption	Use buckets or simple rain gauges	Red (if erratic or absent)	Activate community alerts; adjust farming plans
Temperature Extremes	Sudden spikes or drops affect crops and health	Use thermometers or body sensation	Yellow or Red (if prolonged)	Protect vulnerable groups; adjust outdoor work hours

The lack of digital infrastructure in rural areas, coupled with low digital literacy among vulnerable groups, further limits the reach and impact of 4IR solutions. Communities often remain passive recipients of climate information rather than active co-creators and agents in resilience-building. Climate change management strategies must be rooted in local agency, ethical co-design and inclusive governance to fully unlock the potential of 4IR-IKS integration, ensuring that technology amplifies, rather than replaces, the wisdom and adaptive capacity of indigenous communities.

Recommendations

To bridge the gaps identified in this study, governments must take deliberate steps to institutionalise IKS within national climate policies, not as symbolic gestures but as co-equal frameworks for understanding and responding to environmental change. These steps require the development of culturally inclusive monitoring and evaluation protocols that incorporate simplified, community-readable metrics. These metrics should enable local actors to identify and report climate risks, using familiar indicators such as sky colour, wind direction, animal behaviour and soil texture, linked to a risk flag system that guides timely and appropriate responses.

Incorporating these tools within local governance structures will help ensure that climate adaptation is not only technically sound but also socially embedded and locally owned.

In parallel, both government and private sector actors must invest in expanding public digital infrastructure to ensure broader Internet connectivity, especially in rural and underserved areas. This programme includes deploying affordable, solar-powered connectivity solutions and building digital literacy programmes that empower communities to engage with climate technologies meaningfully. Hybrid early warning systems that combine satellite data with codified IKS can be scaled through local innovation hubs, supported by South–South collaboration and regional knowledge exchanges. Practice must prioritise community-centred design, ethical data governance, and the creation of scalable prototypes that reflect the diversity of African contexts.

Ultimately, advancing smart sustainability requires a shift from extractive innovation models towards inclusive resilience-building, in which technology serves as a bridge, not a barrier, to indigenous agency and climate justice.

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CRediT authorship contribution

Zacharia Grand: Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Visualisation, Writing – original draft, Writing – review & editing. The author confirms that this work is entirely their own, has reviewed the article, approved the final version for submission and publication and takes full responsibility for the integrity of its findings.

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Data availability

The data that support the findings of this study are available from the corresponding author, Zacharia Grand, upon reasonable request.

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