Isinkaye et al. Discover Sustainability (2026) 7:708
https://doi.org/10.1007/s43621-026-03094-z

PERSPECTIVE

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Reimagining smart villages in Africa through synergistic bridging of technology and indigenous knowledge for rural sustainability

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Abstract
Smart Village models are an innovative approach that leverages digital technologies and improved infrastructure to support the development of rural communities. They have emerged as an advanced approach to addressing the continuous problems associated with rural area development. Nonetheless, their sustainability and community approval are hindered by the weak alignment with local contexts and indigenous knowledge (IK), with an emphasis on technological infrastructure. This study presents smart villages as future-ready communities that blend emerging technologies with IK to promote sustainable rural development. It repositions IK as a central organizing lens through which digital technologies are designed, governed, and sustained. Drawing on recent literature and illustrative cases, the study proposes an IK-focused smart village framework that conceptualizes IK as a mediating system for influencing technology adoption, community governance, and sustainability outcomes. The framework highlights how their integration can support eco-inclusive development. Key challenges relating to accessibility, knowledge preservation, and community engagement are discussed. Practical directions are provided for policymakers, technologists, and development practitioners to co-create sustainable smart villages rooted in IK.

Keywords Smart villages, Sustainable development, Indigenous knowledge, Smart technologies, Rural communities

1 Introduction

Rural communities globally face persistent challenges, such as frequent migration of youth to urban cities in search of better opportunities. Also, inadequate infrastructure, limited access to healthcare and education, energy poverty, food insecurity, and digital exclusion are among the reasons for this rapid migration. These rural communities are now severely affected by spatial vulnerability, depopulation, and population ageing [1]. In spite of continued development efforts, the urban-rural divide remains a major barrier to inclusive and equitable growth, especially in the Global South [2]. In response, the concept of Smart Villages has emerged as an integrated and sustainable approach to rural transformation. A Smart Village harnesses digital technologies and community-driven innovation to improve quality of life, promote economic opportunities, and enhance environmental sustainability [3].

The smart village approach emphasizes decentralized solutions, local empowerment, and contextual innovation, distinct from conventional rural development models. It seeks to enable access to key services, such as renewable energy, digital health, smart education, precision agriculture, and clean water, through the application of advanced technologies. These services include, the Internet of Things (IoT), artificial intelligence (AI), blockchain, and mobile platforms [4]. However, technological deployment alone is insufficient. Smart villages also recognize the importance of indigenous knowledge (IK) systems, which have long sustained rural communities through practices rooted in local culture, ecological awareness, and communal governance.

There is rising evidence that technology alone cannot guarantee sustainability but can act as an important enabler of rural development [5]. Also, rural communities are not just blank slates awaiting external innovation, they are repositories of IK systems that have guided sustainable living for generations. These knowledge systems encompass traditional agricultural practices, water conservation techniques, community-based resource management, herbal medicine, and local governance structures [6]. Unfortunately, such indigenous wisdom has often been undervalued or sidelined in favor of external interventions.

In this study, IK refers to the unique, traditional knowledge developed and maintained by communities indigenous to a specific geographic area, which is formed through long-standing cultural practices and local environmental conditions. Although IK is sometimes used interchangeably with "local knowledge," we distinguish it here by its deep roots in ancestral traditions and its strong connection to specific cultural identities and territories. In contrast, local knowledge may include more recent, non-indigenous adaptations.

Reimagining smart villages, therefore, requires a paradigm shift. One that bridges modern technological solutions with IK. This form of integration holds enormous potential. For instance, digital platforms can document, preserve, and scale indigenous agricultural practices. Renewable energy solutions can be tailored to traditional lifestyles. Internet connectivity can expand access to education and telemedicine. When coupled with indigenous health practices, it creates a more grounded and trusted healthcare ecosystem. Similarly, smart water management systems can be enhanced by local knowledge of seasonal patterns and ecological dynamics. Rural communities can foster solutions that are efficient, sustainable, and socially inclusive when advanced technology is aligned with the IK system.

This study is therefore very vital as existing smart village models mostly adopt a technology-first approach. They paid little attention to the lived realities and wisdom of rural populations. When technology and indigenous practices are integrated, rural development initiatives can foster community ownership, enhance resilience, and ensure long-term sustainability. Furthermore, this study contributes to global development priorities related to the Sustainable Development Goals (SDGs), specifically focusing on poverty alleviation, zero hunger, health, education, clean energy, climate action, and sustainable communities. Its relevance is both local, as it empowers rural populations to co-create solutions and global, as it provides a framework for inclusive, adaptable, and sustainable rural transformation.

Reimagined smart villages go beyond the simple application of technology. They become living laboratories of co-creation, where local communities can dynamically shape innovation processes. Understanding how IK systems interact with smart village initiatives is therefore very crucial. This study draws on a qualitative narrative review of recent literature to inform the development of an indigenous knowledge–focused smart village framework. The framework conceptualizes IK as a mediating system that influences technology adoption, community governance, and sustainability outcomes.

The remainder of the paper is structured as follows: Sect. 2 outlines the methodological approach adopted in developing the proposed framework, Sect. 3 reviews the conceptual foundations of knowledge systems and rural sustainability. Section 4 provides an overview of smart technologies in rural development. Section 5 describes the framework for the proposed IK informed smart village. Section 6 outlines challenges and opportunities in implementing smart villages with IK. Finally, Sect. 7 concludes the study and presents future research directions.

2 Methodology

This study adopts a qualitative narrative review to examine the intersection of smart village initiatives, IK systems, and digitally enabled rural development. The literature used was sourced from academic databases, including Scopus, Web of Science, Google Scholar, IEEE Xplore, and ScienceDirect. The search utilized a combination of keywords and Boolean operators to identify relevant studies. Key terms included are *'smart village'*, *rural development'*, '*indigenous knowledge*', '*digital infrastructure*', '*governance*', and '*sustainability*', which were combined using AND/OR operators to refine results.

There were no strict temporal boundaries applied. Articles were selected based on their relevance to the objectives of the study and their contribution to understanding culturally grounded, community-driven development approaches. Non-scholarly sources and studies lacking a clear rural or community focus were excluded. A total of 83 publications were included in the review, with 65 peer-reviewed journal articles, 11 conference papers and proceedings, and 7 books or book chapters.

The selected literature was thematically analyzed to identify key concepts, recurring patterns, and knowledge gaps relating to IK integration, digital governance, and smart system deployment. Insights from this analysis informed the development of the IK–based Smart Village (IKSV) framework.

3 Conceptual foundations of knowledge systems and rural sustainability

This section reviews key concepts that underpin the integration of technology and IK in Smart Villages. These concepts are necessary for understanding how technological innovations align with local practices and informal institutions to promote sustainable rural development. The idea of knowledge in rural development is generally classified into codified and tacit forms. A codified form of knowledge can be stored and reused by people. It describes the kind of information that is formally documented, standardized, and easily shared through digital systems or written records [7]. On the other hand, tacit knowledge is knowledge that resides in a human brain that cannot easily be codified or captured. It is learned by members of an organization through experience and often transmitted informally through observation, mentoring, and community interactions [8]. Indigenous knowledge systems are predominantly tacit. It reflects generations of locally adapted practices in agriculture, resource management, and social organization.

Informal institutions play a central role in determining how knowledge is generated, shared, and applied in rural settings [9]. They include social norms, customary rules, and communal organizations. These institutions influence the acceptance of technological innovations and determine the pathways through which both codified and tacit knowledge are transmitted within communities [10]. Knowledge transmission occurs through both formal channels, such as training programs, digital platforms, and educational initiatives, as well as informal interactions embedded in daily life, which may include mentorship, storytelling, community gatherings, and cooperative labor arrangements.

Integrating technological and IK is key to promoting sustainable rural development. When technological interventions are aligned with local norms, ecological conditions, and community practices, they are more likely to be adopted and yield lasting benefits. For instance, IoT-enabled irrigation systems can be enhanced by local knowledge of seasonal water availability and soil types. Renewable energy solutions can be tailored to existing household routines and traditional energy usage patterns. Likewise, mobile applications that document and disseminate indigenous agricultural practices can complement precision agriculture tools. This can help in creating a synergistic ecosystem that harnesses the strengths of both knowledge types.

Recent research shows that successful rural digitalization relies on integrating codified knowledge with the tacit wisdom of indigenous communities [11]. This integration depends on informal institutions, such as local networks and customary governance, which control the success of technological interventions [12]. Participatory, community-centered approaches help ensure that smart village initiatives are embraced as extensions of local identity rather than external impositions [13].

The literature reveals that sustainable smart village development depends on technology and on careful integration of digital innovation with IK systems. This is mediated through local institutions and participatory knowledge transmission processes.

4 Overview of smart technologies for rural development

Smart technologies, including artificial intelligence (AI), the Internet of Things (IoT), Blockchain, mobile applications, sensors, and data analysis, have a tremendous impact on the security, efficiency, and productivity of daily life, especially in rural areas. This impact extends across various domains, including healthcare, transportation, energy, agriculture, education, infrastructure, and mobility. The successful implementation and adoption of smart technology depend on the target community, local economic conditions, institutional structures, and socio-cultural contexts.

Nearly half of the world's population is estimated to live in rural areas. The economies of these regions play a crucial role in eradicating poverty and other deprivations, including food security and access to quality employment opportunities [14]. Rural development in developing economies is a catalyst for sustainable national development [15]. A proper implementation of smart technologies has the potential to turn these rural areas, plagued by deficiencies in infrastructure, education, healthcare, and more, into more conducive areas of abode.

4.1 Smart technology implementations in rural Africa

In Africa, smart technologies are now being adopted as practical tools for handling long-standing rural development challenges. These technologies are helping rural communities improve livelihoods and promote sustainable development. The following examples illustrate how smart technologies have been implemented in different African rural contexts to support areas such as health, agriculture, community empowerment, energy access, as well as connectivity and digital inclusion.

4.1.1 Healthcare

Smart technologies are currently being deployed to address rural development challenges in Africa, with applications tailored to local socio-economic and environmental contexts. For instance, telemedicine enables rural dwellers to consult specialists as if they were physically available [16]. IoT-powered wearable devices and monitoring systems have been deployed to monitor and manage the health, lifestyle, and environment of rural dwellers, enabling timely intervention in case of a medical emergency.

There is a high prevalence of tropical and non-communicable diseases in Africa. Being a developing economy, most African citizens have limited access to basic healthcare. In South Africa, specialized IoT-powered hospital management systems are used to collect patient information [17]. Similarly, the Rwandan government uses Zipline Drone Delivery & Logistics, which provides drones for transporting medical supplies to hospitals in rural communities [18]. AI-powered software for infectious disease diagnosis (TB, HIV, Ebola, and COVID-19) developed by SystemOne is currently used in 19 African countries, with Telecom26 addressing the problem of unreliable bandwidth and patchy connectivity [19]. The Ebola outbreak in West Africa necessitated the use of mobile phone data and call records to track the movements of contact persons [20]. Despite studies showing the potential of blockchain technology in addressing issues such as missing files or records, its application in healthcare in Africa remains rare. For instance, the Medixus group in Kenya has enhanced collaboration between health workers through a blockchain-powered Electronic Medical Records (EMR) platform, ensuring the availability of patient data [19]. The Egyptian Telemedicine Network (ETN) was developed in Egypt to provide medical services, including radiology, electronic stethoscopes, telepathology, and ECG.

Additionally, in 2009, the authorities developed a Teleconsultation service for infectious diseases, such as hepatitis [21]. In Senegal, a scheme was developed to transmit biomedical images between major hospitals in the country. A service that provides scheduled consultations and referrals was developed in Ethiopia [22]. Table 1; Fig. 1 illustrate how these technologies are combined to enhance healthcare delivery and access. They are actively changing the narrative and the future of healthcare by providing innovative and efficient healthcare management.

Table 1 Enhancement of healthcare delivery through smart technologies

Author	Focus	Application
[23]	Access to healthcare	Accessibility of healthcare services to rural people.
[24]	Improving patient outcomes	Improvement of patient health outcomes.
[25]	Reducing health care costs and increasing efficiency	Optimization of resources in the healthcare system.

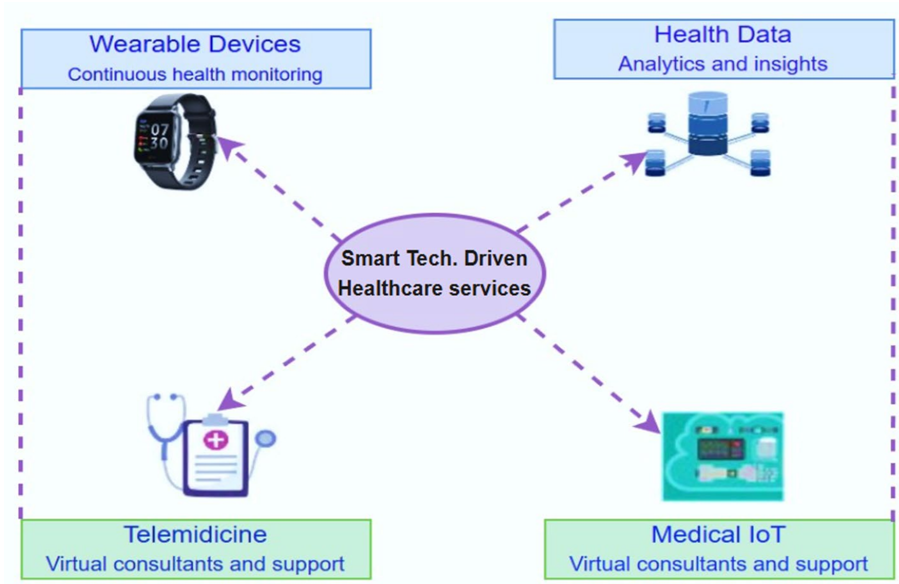

Fig. 1 Smart technology-driven health care services for smart village model

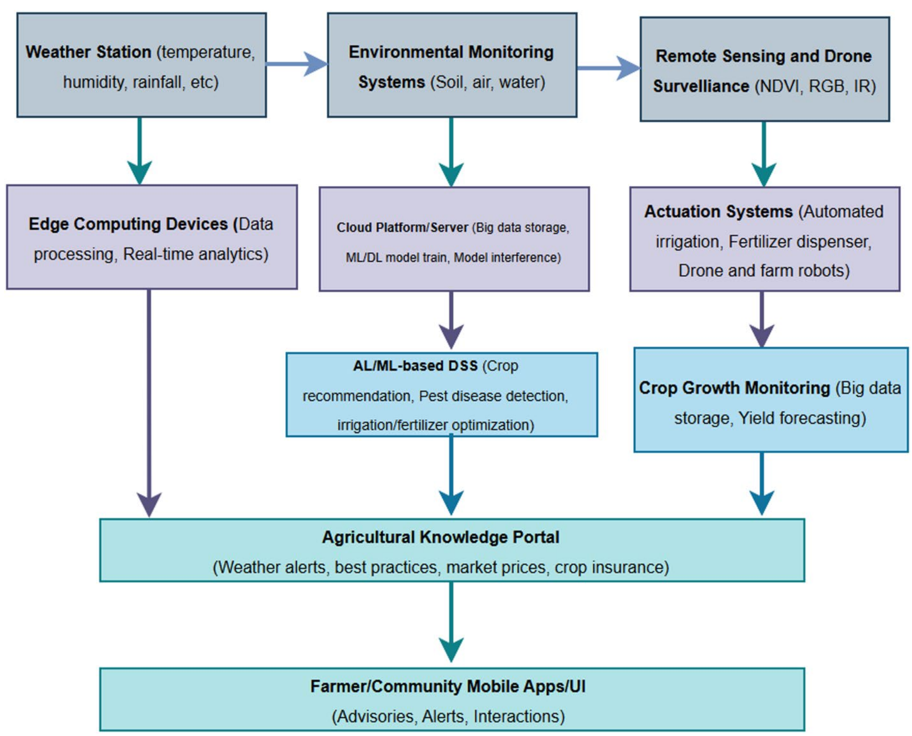

Fig. 2 A model of precision agriculture for a smart village

4.1.2 Agriculture

Smart technologies have significantly impacted the way agriculture is practised in precision agriculture, as shown in Fig. 2. Driven by IoT devices, drones, and sensors, precision agriculture enables farmers to optimize resource use and increase crop yields. Real-time disease prediction for timely intervention is enhanced using drones equipped with multispectral cameras.

South Africa has long used IoT sensors to assist small-scale farmers in water conservation. This is also found in Senegal, where these sensors are utilized for efficient irrigation in tomato farms [26]. These are the different areas in which IoT technology has been applied in agriculture, including farm monitoring and management [27], as well as livestock monitoring and irrigation management [28]. IoT has also been applied to greenhouse environmental control, agricultural machinery, and drones [29], effectively changing agriculture. Figure 3 illustrates the focus areas from the literature where IoTs have been successfully applied in precision agriculture.

Fisheries in Ghana utilize tracking devices and gateways to manage oxygen levels efficiently, temperature, and pH levels [30]. The “Blockchain for Agrifood” project in South Africa is used in the wine production supply chain [31]. The potential of machine learning for crop yield prediction is abundant in the literature. Several AI models have been developed with high accuracy in predicting crop yield in East African countries [32].

4.1.3 Environmental management
Environmental management in rural communities encompasses agriculture, renewable energy, safe water conservation, and infrastructure. Smart technologies also play a vital role in environmental management in rural areas. This ranges from IoT devices and sensors that monitor soil conditions to weather patterns and water quality. The goal is to ensure sustainable resource management.

Access to clean and sustainable water is a significant challenge in Africa, which is home to many rural dwellers [33]. Rwanda utilizes sensors to monitor the water pumps in various locations that supply clean water to its communities. Additionally, the country has an early climate warning system that utilizes IoT and open-source data [34]. Similarly, the Niger utilizes smart meters for effective distribution of potable water. Sustainable

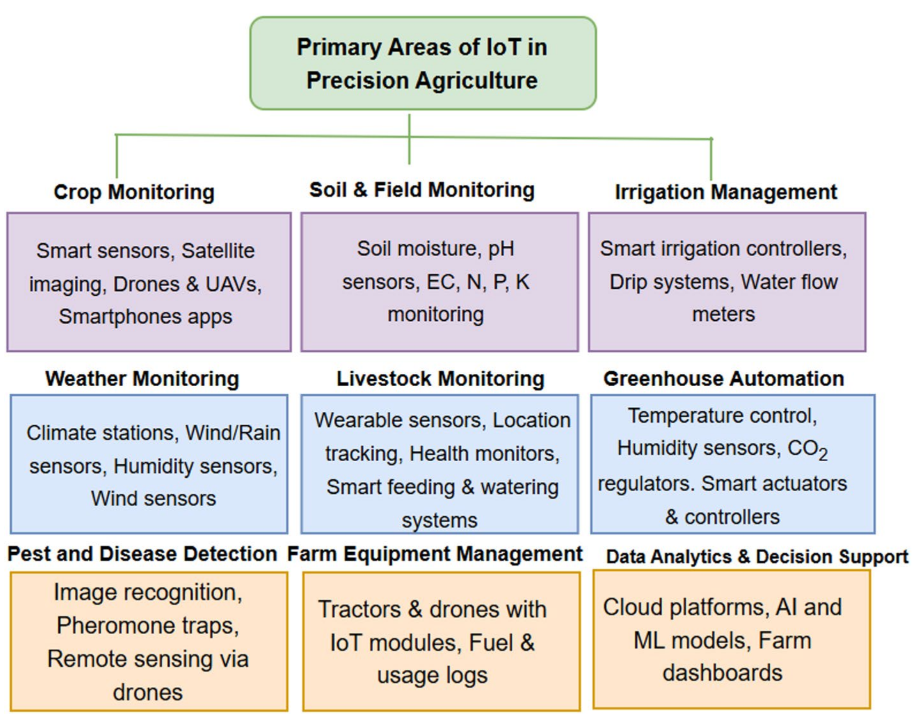

Fig. 3 Internet of things applications in precision agriculture

energy is a big problem in rural Africa. IoT for waste management is implemented in Togo and Nairobi, where sensor-enabled smart trash bins and waste management trucks [30]. The Ubutaka blockchain technology application monitors and manages city land sales [35].

4.1.4 Connectivity and digital inclusion

A significant challenge in rural areas is access to digital information, education, infrastructure, and commerce, which heavily depends on internet connectivity. Smart technologies have been used innovatively to address these challenges. These include satellite-based internet services, wireless technologies, and digital literacy programs for enhanced digital skills.

A project collaboration between the United Nations Industrial Development Organization (UNIDO) and the Japan International Cooperation Agency (JICA), in partnership with the Kenya Electricity Generating Company, utilizes sensors to collect data from turbines and generators, ensuring the efficient operation of power plants [21]. Wildlife surveillance in South Africa is done using drones [36]. AI has also impacted urban planning in Africa. For instance, a monitoring project was commissioned in South Africa to use machine learning to identify informal settlements and structures in satellite imagery. To enhance payment services, a blockchain-powered system is used by DafriXchange and DafriBank to enable Fiat-to-crypto transactions [21].

4.1.5 Key gaps in smart technology implementation

Despite the successful implementations highlighted in Sect. 4.1, inadequate infrastructures, such as access to the internet, electricity, and transportation, are critical limitations that affect the application of smart technologies in rural areas. Also, smart technologies are not inexpensive, and their cost can be a drain on rural dwellers. This can limit the potential benefits of adopting such technology.

Most smart technologies require some level of digital literacy, which may be lacking in the rural population. Additionally, culture and social norms significantly influence the acceptability or otherwise of these smart technologies. If not properly handled, these issues can lead to resistance and slow down technology adoption. Finally, government policies, or a lack thereof, affect the implementation of smart technology. For instance, incentives and favourable regulations provided by the government can go a long way in encouraging rural communities to adopt smart technologies.

4.1.6 Proposed solutions to accelerate smart technology integration

Aside from investing in infrastructure development, which can be expensive for the government, public-private partnerships can be used to meet expanding infrastructure needs. These smart technologies can be affordable in these communities by providing loans at low interest rates, subsidies, and grants through Microfinance institutions and crowdfunding platforms.

Rural communities have unique characteristics that can be explored and incorporated into training programs to enhance education, digital literacy, and technical skills. Before any smart technology is deployed, the community must be engaged and sensitized to overcome resistance. From conception to implementation, community leaders must be engaged, and afterwards, continuous awareness campaigns must be conducted to highlight the benefits of the smart technologies to be deployed.

In conclusion, one of the significant catalysts for rural transformation is smart technologies. They have the potential to tackle long-standing challenges and promote sustainable growth in rural communities. This potential can be hindered by inadequate infrastructure, poverty, educational and digital illiteracy, and cultural and social barriers. However, confronting these challenges could lead to the successful adoption of these technologies, allowing rural communities to benefit from smart technologies and achieve sustainable development.

4.2 Smart village frameworks and implementation models

As the concept of smart villages gains prominence in academic and development contexts, several frameworks and models have been proposed to guide their effective implementation. These frameworks serve as strategic guides that outline the essential components, processes, and enabling factors required for successful smart village development. Table 2 presents a comparative review of selected frameworks. It highlights their key components, implementation approaches, primary focus areas, success factors, and contextual scope.

Table 2 highlights some of the smart village models and focuses on regions and rural village development approaches. The common theme is that they strongly emphasize how technology can be utilized for expansion. For instance, research by [37] discusses areas like ICT, digital literacy, energy resources, and the application of low-cost technology. These models use digital technologies and smart infrastructure to enhance rural livelihood. Aside from this, they highlighted the significance of making the technology locally acceptable. Also [40], considered evolving technologies such as blockchain, pointing out the need for scaling up and ensuring their integration into existing rural systems.

Most models focus on good governance, community empowerment, and sustainability. For instance [38], focused on participant participation, intersectoral coordination, and multi-level government involvement. Their frameworks are human-centered towards capacity building, open communication, and responsive policymaking. Also [3], underlines sustainability, green technology, and resource conservation measures.

Although these existing smart village frameworks provide good guidance, they tend to emphasize technological, governance and socio-economic dimensions as critical components of success. There are limited consideration of localized socio-cultural contexts and the integration of IK systems. This gap highlights the need for context-sensitive frameworks that align technological interventions with community-specific practices and knowledge, an issue addressed by the present study through its proposed framework.

4.3 The role of IK in promoting local innovation and sustainability

Although regional and global smart village case studies revealed the effectiveness of digital and renewable technologies in rural development, many initiatives are largely technology-driven and externally designed. Such approaches may face limitations in acceptance, long-term sustainability, and community ownership when local contexts are not sufficiently considered.

Table 2 Existing smart village frameworks/models

References	Key components	Implementation approach	Framework focus	Key success factors	Contextual scope
[37]	Governance, energy, economy, ICT, people, environment, and tourism.	Systematic meta-analysis	Conceptual smart village model	Affordable and accessible technology, digital literacy (Technological)	Global review of smart village literature
[3]	People, economy, living, energy, environment, mobility, and governance.	Methodological planning, design, and implementation	Contemporary smart village concept	Green technology adoption, environmental awareness (Sustainability and Resource Management)	Global literature and initiatives from different world regions
[38]	Infrastructure, governance, healthcare, education, agriculture, and community empowerment.	Interdisciplinary approaches, stakeholder engagement, empirical studies, and policy interventions	Multifaceted smart village model	Effective communication channels, capacity building (Governance and Community Engagement)	Global case-study synthesis from rural areas
[39]	Village governance, economy, environment, energy resources, human resources, ICT, village farmers, and tourism	Systematic literature review	Conceptual smart village model	Affordable and accessible technology, digital literacy (Technological)	Rural Indonesia
[40]	Blockchain applications in rural development	Review of existing and potential applications	Blockchain for rural development	Integration with existing systems, scalability (Technological)	37 countries worldwide
[41]	Economy, ICT, people, governance, environment, living, and energy.	Systematic review (PRISMA and meta-analyses)	Structured framework for understanding smart villages	Affordable and accessible technology, digital literacy (Technological)	Global rural contexts
[42]	Synchronized SMART village framework	Problem tree analysis; integration of policies with local innovations	Catalytic rural transformation framework	Flexible policy frameworks, multi-level governance (Governance and Community Engagement)	Poptún, Petén, in North-eastern Guatemala
[43]	Technology, society, services, culture, knowledge-based, community-led, human-centric	Scientometric analysis	Knowledge-based, community-led, and human-centric smart village ecosystem	Effective communication channels, capacity building (Governance and Community Engagement)	Haikou Village, Ningxia, China

Therefore, IK, which reflects locally grounded practices and experiential understanding of social and environmental systems, provides a complementary foundation for smart village development. Integrating IK with contemporary technologies can enhance local innovation, strengthen community participation, and support sustainable outcomes in sectors such as agriculture, resource management, and climate adaptation.

Indigenous knowledge forms the basis for decision-making applied to maintain and manage successful coexistence in the local habitat [44]. It reflects the understanding that people within a given locality have regarding their natural environment and how this folk knowledge of cultural beliefs, flora, fauna, and history is harnessed to enhance their lives [45]. This knowledge is acquired through daily interactions with human and non-human elements within the local communities. It is communicated from generation to generation via verbal communication and other socialization practices and channels. It is a tacit knowledge that is dynamic, constantly changing, and learnt through repetition, which aids its reinforcement and retention [46].

Recently, attention has been drawn to integrating indigenous practices into modern techniques for the administration and management of human existence, promoting sustainability. Indigenous knowledge provides the essential means of survival for indigenous people, and it has become an integral part of rural life [47]. It is worth noting that several disciplines, including biodiversity and environmental conservation, health, education, ecology, and land and natural resource management, have been impacted by the use of IK [48]. Indigenous knowledge has been recognized as a major factor in ensuring sustainable development practices in developing countries. It is a force to be reckoned with in avoiding the loss of species and ecosystem biodiversity, with its attendant future implications for the entire planet [46].

4.4 Contributions of IK systems to sustainable development

Indigenous Knowledge systems encompass integrated ecological, cultural, and social practices that have long supported sustainable development in rural communities. Through context-specific and experiential approaches, indigenous communities have successfully managed natural resources, conserved biodiversity, enhanced food security, and adapted to climate variability. This subsection reviews existing literature on the contribution of IK to sustainable development, with particular emphasis on biodiversity conservation, sustainable agriculture and environmental security, food preservation and processing, traditional health practices, and climate change adaptation, as summarized in Fig. 4.

4.4.1 Biodiversity conservation through indigenous practices

An area of use for IK in sustainability is biodiversity conservation. For instance, sacred landscapes are preserved for vulnerable species. This is achieved through restrictions based on myths and taboos. Competition among birds, frugivores, and humans

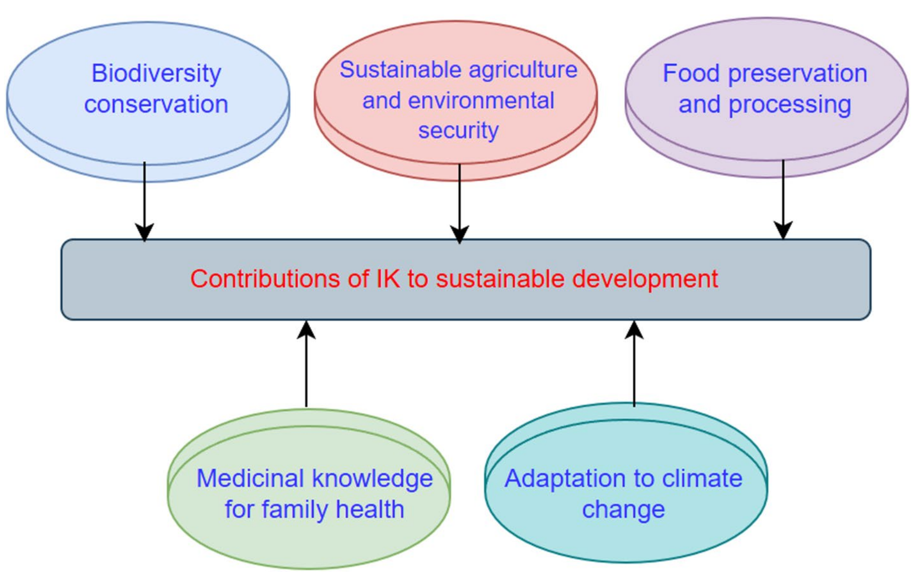

Fig. 4 Contributions of IK to sustainable development

is reduced to ensure a balanced ecosystem. For instance, picking ripened fruits instead of cutting down fruit trees, and cutting only deadwood for firewood, are encouraged to reduce deforestation. Medicinal plants are debarked on only one side, which is shielded from direct sunlight, to regulate the drying rate of debarked trees. This ensures that such trees do not die and are subsequently cut, thereby reducing deforestation. Spiritual beliefs that consider forests as sacred spaces and as resting places for ancestral spirits are upheld to reduce human disturbances to forest biodiversity. This promotes the water cycle and sustainability of the ecosystem [49].

4.4.2 Sustainable agriculture and environmental security

The Southwest Nigerian agricultural system embodies a profound local understanding of land management and ecosystem stability. Women are vital to the application of this knowledge to environmental security and sustainable livelihoods. Non-tillage or minimum-tillage farming methods minimize soil erosion and maintain soil structure. Manual land clearing or controlled burning minimizes the disruption of micro-ecosystems in the soil [50]. Traditional implements, such as digging sticks, hand drills, and planting tools, are designed to create holes with minimal disturbance to the soil, ensuring long-term fertility. Fertiliser is often substituted with organic manure, which is produced by decomposing animal waste and plant remains. Crop rotation and cover cropping also help in recycling nutrients, managing pests, and improving biodiversity in agriculture [51]. Livestock is a source of food and revenue, as well as a means of waste management, by consuming crop remains, and is part of a low-input, circular agricultural system. Such an integrated approach facilitates the preservation of ecology and the maintenance of rural livelihoods, emphasizing the importance of indigenous agricultural knowledge in creating environmental and economic resilience [52].

4.4.3 Traditional food processing and preservation techniques

Age-old food processing and preservation techniques used by indigenous people are also energy-efficient and friendlier to the environment. Sun drying, smoking, and salting are traditional techniques used to extend the shelf life of perishable food products. An example is that meat and fish are smoked to preserve them, and vegetables and edible insects (caterpillars and locusts) are dried in the sun and kept to be incorporated into meals [53]. Others include the use of charcoal for cooling or drying storage sites, or the combination of ashes with kerosene for pest control in stored grains. The low-tech processes do not require electricity and synthetic chemicals. This is why these technologies are suited to the rural environment, where modern infrastructure is not readily accessible [54].

4.4.4 Indigenous medicinal knowledge for family health

The role of traditional medicine in most indigenous societies continues to form an essential part of healthcare. There are local herbal remedies for preventing illness. For example, the Euphorbia kamerunica root is used to treat a depressed fontanel of newborn babies. Boiling the bark of Tetrapleura tetraptera, Bosica anguistifolia, and Spondias mombin are also used to treat navel pain and to treat digestive problems [50], as well as boiling Tetrapleura tetraptera and Citrus aurantifolia to treat newborns. Neem (Azadirachta indica), also known as dongoyaro, is widely used due to its antiseptic, antifungal, and antiviral properties. Neem leaves are used as a paste to treat burns and wounds, and honey is often used as a natural disinfectant and medicinal agent. These practices offer affordable and accessible health services in resource-constrained areas [55].

4.4.5 Adaptation to climate change

Through observing changes such as irregular rainfall, prolonged droughts, and soil erosion, farmers have developed resilient practices. One key strategy has been shifting from monocropping to intercropping and multi-cropping to sustain and maximize food production [56]. Other activities include mulching to maintain the soil's moisture. shading crops to minimize the loss of water through evapotranspiration, and bush fallows for soil rejuvenation by natural means. These are low-cost interventions and are necessary where there are few official reactions to the climate [57]. Case studies demonstrate the application of indigenous systems for biodiversity conservation, sustainable agriculture and food security, population health, and addressing climate change.

4.5 Phases of integrating IK with contemporary technologies

Instead of treating IK as a passive input into digital systems, this model conceptualizes it as an active organizing logic that shapes how technologies are selected, adapted, governed, and sustained in rural contexts. As illustrated in Fig. 5, the phases represent the stages of digitization and also distinct IK-driven mechanisms through which smart village innovations become culturally legitimate, socially embedded, and sustainable.

IK is conceptualized as the central organizing logic that facilitates the design, governance, and long-term sustainability of digital technologies within smart village systems. Instead of functioning as an auxiliary input, IK shapes technological choices through interconnected mechanisms depicted in the figure. These collectively enable culturally grounded, socially legitimate, and sustainable outcomes for smart villages.

4.5.1 Indigenous astronomy

Indigenous astronomy is the traditional knowledge developed by indigenous communities through long-term observation of celestial bodies and their relationship with seasonal and environmental cycles. This knowledge supports rural sustainability by informing planting and harvesting cycles, anticipating seasonal changes, and enhancing climate resilience, especially in contexts with limited access to formal meteorological services. When integrated with modern digital tools and climate data, Indigenous

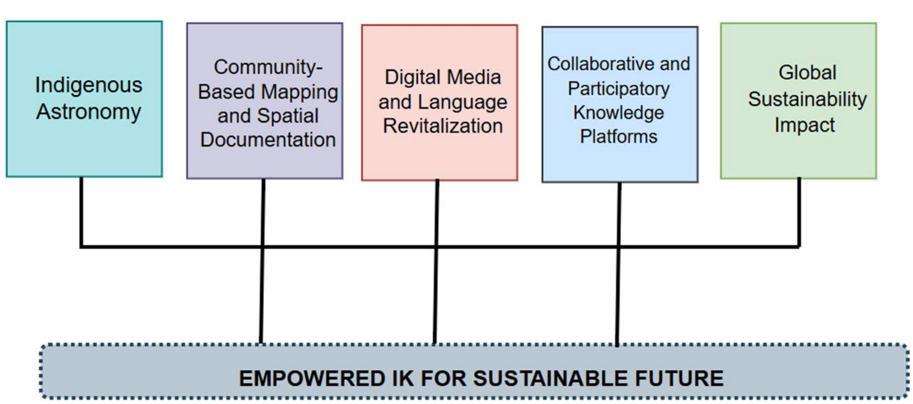

Fig. 5 Phases of integrating IK with contemporary technologies

Astronomy supports context-sensitive and trusted decision-making in rural development. Although related to biodynamic processes, Indigenous Astronomy is broader and predates formalized biodynamic agriculture. The digitization of celestial knowledge contributes to cultural revitalization, economic independence, sustainability, and increased community participation in planning [58].

Analytically, indigenous astronomy serves as a temporal and ecological calibration mechanism, aligning digital climate and agricultural technologies with locally trusted environmental rhythms. This enhances the contextual legitimacy of smart village interventions.

4.5.2 Community-based mapping and spatial documentation

Community-based mapping complements Indigenous Astronomy by preserving cultural heritage and customary land boundaries. Modern GPS mapping, digital cameras, and GIS software capture and spatially index local knowledge, which supports dispute resolution, negotiation, and authenticating land claims [59]. From a conceptual perspective, community-based spatial documentation positions IK as a governance mechanism that mediates how digital mapping technologies shape land rights, resource control, and social accountability within smart village systems.

4.5.3 Digital media and indigenous language revitalization

Digital media plays an important role in safeguarding linguistic heritage and making IK more accessible. Mobile applications, interactive software, and online platforms enable self-paced learning, grammar instruction, and vocabulary acquisition, thereby reaching a wider audience. Social media facilitates community engagement, resource sharing, and knowledge promotion [60]. Digital language platforms can transform IK from a vulnerable cultural asset into an active socio-technical interface that structures participation, intergenerational knowledge transfer, and inclusive access to smart village innovations.

4.5.4 Collaborative and participatory knowledge platforms

Collaborative knowledge platforms allow joint documentation and co-production of cultural wisdom, community contributions, and linguistic expertise [61]. Tools such as language apps, flashcards, pronunciation guides, and interactive exercises promote user-friendly engagement and knowledge revitalization for learners of indigenous languages. This hybrid framing demonstrates that integration is not linear alone, but rather a synergistic interaction between sequential processes and parallel innovations that jointly strengthen the relevance of IK in addressing contemporary challenges. Conceptually, participatory knowledge platforms reframe IK as a co-production mechanism through which digital technologies are socially negotiated, locally adapted, and collectively legitimized rather than externally imposed.

4.5.5 Global sustainability impact

The convergence of these phases creates a hybrid model that links IK with global sustainability outcomes. Integrating Indigenous perspectives ensures solutions are effective, culturally grounded, and context-specific, contributing directly to the United Nations' Sustainable Development Goals (SDGs) [62]. This approach fosters inclusivity, resilience, and adaptability while safeguarding cultural heritage and reinforcing intergenerational continuity. Therefore, the convergence of these IK-driven phases establishes IK as the central organizing logic that links digital innovation to sustainability outcomes that are culturally grounded, socially resilient, and globally scalable.

4.6 Regional and international case studies of smart village achievements

Smart village initiatives now utilize emerging technologies to address social, economic, and environmental challenges in rural contexts. Beyond conceptual frameworks, regional and international case studies demonstrate how these ideas have been implemented in practice. This section reviews selected examples. It highlights the strategies adopted, contextual adaptations, and key outcomes that contributed to their usefulness. The cases are illustrative rather than exhaustive and do not imply prioritization of any region. Their purpose is to showcase diverse approaches of implementing smart village initiatives worldwide.

a. Indonesia context (regional case studies)

Indonesia provides several illustrative examples of smart village initiatives that demonstrate different implementation strategies and outcomes. For instance, the Ketapang Village initiative represents a smart village approach. It focuses primarily on the smart economy with an emphasis on empowering local enterprises, improving market access, and promoting digital entrepreneurship to enhance community welfare. The initiative has contributed to local economic development, but persistent challenges remain. The constraints include limited access to technology and inadequate institutional and government support, both of which limit scalability and long-term sustainability [63].

In contrast, Sinjai Regency adopts a more integrated and large-scale implementation model, where a web-based smart village platform connects 67 villages into a unified system. This platform supports governance, communication, and service delivery. This allows more efficient resource allocation while improving transparency and accountability in local administration. The Sinjai case shows the importance of coordinated digital infrastructure and centralized planning in achieving broader smart village outcomes [64].

Tanete Village, situated in Simbang District, Maros Regency, exemplifies a service-oriented smart village model through its web-based village administration system. The initiative provides online access to essential administrative services, including certificate issuance and population data management. By reducing bureaucratic delays and improving service efficiency and transparency, the Tanete case demonstrates how even small rural communities can successfully adopt digital solutions to modernize local governance when these solutions are appropriately tailored to local needs [65].

The Indonesian case studies collectively indicate that the success of smart villages depends on the deployment of technology, as well as institutional support, the scalability of digital platforms, and alignment with local governance and economic priorities.

b. Global context (international case studies)

Globally, smart village initiatives demonstrate how digital and renewable technologies can be adapted to diverse rural contexts to enhance agricultural productivity, improve service delivery, and foster community resilience. In South Korea, for example, smart village implementations emphasize technology-driven rural transformation through smart farming systems that integrate IoT sensors, automation, and data-driven monitoring of crops and livestock. Aside from agriculture, these villages incorporate smart healthcare services, surveillance systems, and energy-efficient infrastructure to enhance safety and resilience in rural environments. Notable examples include the Busan–Eco Delta Smart Village and the Information Network Village (INVIL) Project. They show how coordinated national policies and advanced digital infrastructure can support comprehensive smart village ecosystems [66, 67].

At a global scale, the IEEE Smart Village initiative represents a community-centered and sustainability-driven model designed to improve livelihoods in underserved and remote communities worldwide. The program combines renewable energy deployment with entrepreneurship, education, and digital infrastructure to foster self-sustaining local ecosystems. A defining feature of the IEEE Smart Village approach is its bottom-up implementation strategy, which prioritizes local capacity building and community ownership as key drivers of long-term success.

Several country-level implementations under the IEEE Smart Village program further illustrate this approach. In Cameroon, a clean-energy-focused smart village model was implemented through the deployment of solar photovoltaic systems and battery-powered mini-grids in all ten regions of the country. Led by Renewable Energy Innovators in Cameroon (REIc), in partnership with IEEE Smart Village, the initiative expanded electricity access to households, schools, healthcare facilities, and small businesses, thereby supporting social and economic development [68].

In India, the smart village concept was applied in Kudagaon, a remote river island in Odisha, through the deployment of SmartAQUAnet™, a solar-powered irrigation system. The project utilized solar microgrids to enable multi-stage water pumping. This is to guarantee reliable and efficient irrigation. Through focusing on agricultural empowerment and self-sustainability, this initiative shows how energy–water–agriculture integration can enhance rural livelihoods in geographically constrained environments [69].

Similarly, in Latin America, a smart village initiative in Poptún, Petén, Guatemala, supported by IEEE Smart Village, adopted a sustainable agriculture–driven approach. The project introduced solar-powered technologies such as a solar-thermal fruit-drying system and photovoltaic-based drip irrigation, within a permaculture farming context. This case illustrates how renewable energy technologies can be integrated with local agricultural practices to foster climate-resilient and economically viable rural development [70].

4.6.1 Implications for Africa

The regional and global examples indicate that successful smart village initiatives are not solely technology-driven. They require institutional support, community engagement, and alignment with local priorities. In African contexts, these lessons suggest that integrating modern technologies with local knowledge and governance structures can enhance rural livelihoods and promote sustainable development.

African rural communities can benefit from scalable digital platforms similar to those in Sinjai or Tanete, which facilitate service delivery, administrative efficiency, and transparency. Renewable energy solutions, as demonstrated by the IEEE Smart Village projects in Cameroon, India, and Guatemala, provide models for off-grid electrification, climate-resilient agriculture, and local enterprise development. Also, integrating IoT-based smart farming systems, solar-powered irrigation, and energy-efficient infrastructure, as seen in South Korea and Indonesia, can improve agricultural productivity and resilience in African villages.

Notably, these examples highlight the need for contextual adaptation: technologies must be tailored to local socio-cultural practices, environmental conditions, and governance capacities. African policymakers and development actors can adopt these lessons by fostering community ownership, building capacity, and forming partnerships with local institutions to ensure that smart village initiatives are both sustainable and impactful. Through combining IK with appropriate modern technologies, Africa can develop smart village models that enhance rural development, food security, and economic empowerment in diverse contexts.

4.7 Key considerations for integrating IK systems

Integrating Indigenous Knowledge Systems (IKS) into contemporary technologies and development frameworks necessitates careful consideration of ideological, epistemological, cultural, and institutional factors. Although IKS is gradually being recognized as a key element for sustainability and cultural stability, its integration is often superficial, with IK placed second to formal scientific and technological systems [71].

One major challenge is the epistemological divide. IK is holistic, relational, spiritual, and place-based and usually transmitted orally through practice and narrative. In contrast, Western science tends to be decontextualized, privileging objective and universalized knowledge. This imbalance reinforces perceptions of science as superior and relegates IKS to anecdotal status, consolidating historical power relations [72]. Furthermore, researchers' lack of cultural competence and inadequate communication creates mistrust and impedes meaningful collaboration. Colonial legacies further undermine indigenous worldviews, though formal education systems often assimilate communities into dominant cultural paradigms, neglecting the epistemological context of IKS [73, 74].

Language plays a vital role in knowledge integration. Indigenous languages are central to cultural identity and knowledge transmission, yet their marginalization in formal education limits both learning and the preservation of IKS [75]. Insufficient access to quality education, inadequate infrastructure, and curricula misaligned with local realities further constrain indigenous learners [76]. Effective integration, therefore, requires dialogue between knowledge systems, promoting bilingual and culturally relevant education while respecting the independence and traditions of indigenous communities.

Beyond these socio-cultural and epistemological considerations, practical implementation factors are also central. Integration efforts benefit from active community engagement, where local actors participate in co-designing, implementing, and monitoring technological solutions. Strong institutional support and governance structures are essential to coordinate resources, ensure scalability, and maintain transparency throughout the implementation process. Technologies must be accessible, adaptable, and contextually tailored to complement indigenous practices, whether in agriculture, energy, or local governance. Examples from Indonesia, South Korea, and Cameroon demonstrate that aligning technology deployment with community priorities and institutional frameworks enhances sustainability and impact.

Capacity building and skill development are essential for equipping communities with the knowledge and competencies to adopt and sustain new technologies while preserving indigenous practices. Likewise, monitoring and feedback mechanisms enable iterative improvements, ensuring that interventions remain responsive to environmental and socio-cultural dynamics.

Finally, successful integration of IKS requires both fair partnerships and institutional change. By combining IK with modern technologies and effective governance strategies, communities can enhance sustainability, resilience, and local innovation. In Africa, applying these lessons can support the development of context-sensitive, culturally respectful, and technologically enabled rural initiatives that improve livelihoods while preserving heritage.

4.8 Conceptual and analytical gaps in IK-Technology integration

The preceding analysis highlights the transformative potential of integrating IK with digital technologies to advance sustainable smart villages. However, a critical review of the literature and existing implementation models reveals persistent conceptual and analytical gaps that must be addressed to translate theory into practice effectively. These gaps lie at the intersection of epistemology, methodology, and impact assessment, which are discussed subsequently.

First, the epistemological-subordination gap presents a fundamental conceptual challenge, rooted in the persistent framing of the IK-technology relationship. As highlighted in Sect. 4.7, Western techno-scientific paradigms often occupy a dominant, normative position, while IK is treated as a complementary or subordinate input to be validated or digitized [71, 72]. This creates an epistemological-subordination gap, where integration risks becoming extractive, mining IK for data points while disregarding its holistic, relational, and spiritual foundations. Therefore, the proposed framework in Sect. 5 aims to reposition IK as the central organizing lens; however, the literature lacks robust models for operationalizing this parity in the design of algorithms, data governance structures, and technology evaluation criteria. Without closing this gap, digital integration may inadvertently perpetuate colonial knowledge hierarchies rather than foster genuine co-creation.

Second, in terms of the contextualization-abstraction gap, digital technologies, by design, often seek scalable and replicable solutions based on abstracted data. Conversely, IK is profoundly place-based, context-specific, and transmitted through embodied practice and narrative [46]. This creates a contextualization-abstraction gap. The process of digitizing IK, transcribing oral histories, mapping sacred sites into GIS, or codifying agricultural practices into decision-support algorithms, inevitably involves simplification and decontextualization. The literature extensively discusses the benefits of such digitization (e.g., preservation, accessibility). Still, it offers scant analytical guidance on managing the inherent losses: the erosion of tacit understanding, the severing of knowledge from its custodians and ceremonial contexts, and the risk of creating sterile digital artefacts divorced from living cultural systems. In light of this, future research that considers implementing the current proposed framework must develop critical methodologies for thick digitization that preserve contextual integrity and respect protocols of access and use.

Third, despite the widespread advocacy of participatory approaches, a significant agency and governance gap exists in how control is exercised throughout the socio-technical lifecycle. Discussions on digital platforms for IK often focus on community engagement or inclusion in projects designed by external actors [13, 38]. There is a lack of exploration of models for community-led technology design and data sovereignty, where communities define the problems, own the platforms, govern the data, and hold intellectual property rights over digitized knowledge. Questions of who builds the algorithms, who owns the servers, who profits from data derivatives, and how informed consent is dynamically managed in a digital ecosystem remain analytically underdeveloped. The principle of digital sovereignty introduced in the proposed framework necessitates the development of concrete legal, technical, and economic models to be implemented. The implications of this for the various layered components, as presented in Fig. 6, are further discussed in the next section.

Fourth, there is a significant gap in impact assessment. The presumed benefits of integration, enhanced sustainability, resilience, and cultural vitality, are often presented axiomatically. However, there is a lack of longitudinal, mixed-methods studies that critically assess both the positive and negative outcomes of such integrations. How does the introduction of digital tools affect intergenerational knowledge transmission pathways? Does precision agriculture augment or atrophy local observational skills and adaptive management practices? What are the metrics for success beyond technological uptake or economic efficiency, metrics that capture cultural well-being, epistemological resilience, and the strengthening of indigenous sovereignty? Without robust, culturally grounded evaluation frameworks, it is challenging to determine whether integration is truly empowering or merely another form of assimilation.

Lastly, it is worth noting that addressing these gaps necessitates a shift from a simplistic integration paradigm to a critical co-production paradigm. This approach entails structuring research and development as an epistemic collaboration between IK and digital systems, recognizing each as a complete and valid knowledge system with its own integrity, protocols, and modes of verification. It further demands reflexive design principles that explicitly acknowledge and interrogate embedded epistemological biases in technological development, while incorporating mechanisms for contextual embedding and continuous community calibration. In addition, a sovereignty-by-design approach is required, prioritizing technical architectures and governance frameworks that embed data sovereignty, community ownership, and ethical reciprocity from the outset.

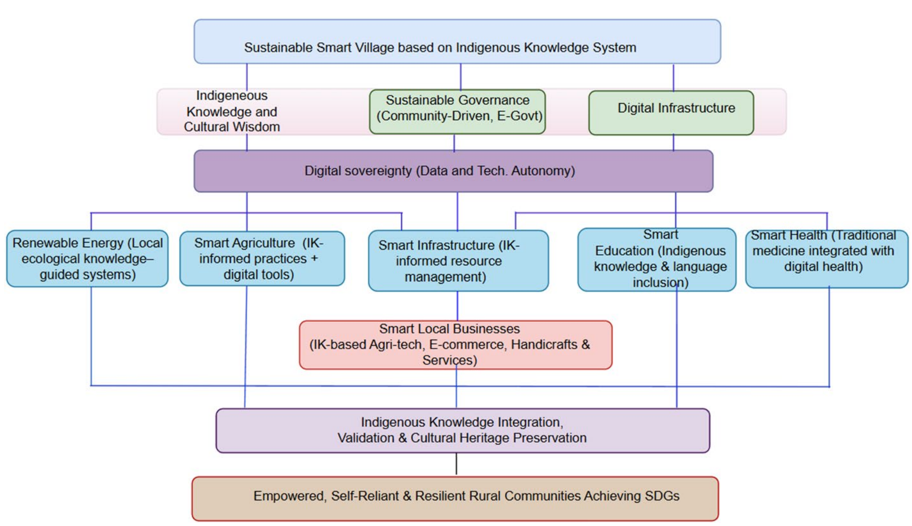

Fig. 6 IK-driven smart village framework for sustainable rural development

Moreover, such a paradigm necessitates pluralistic evaluation frameworks that employ multi-criteria impact assessment tools, valuing ecological, social, cultural, and epistemological outcomes alongside conventional technical and economic indicators.

5 Framework for the proposed IK informed smart village

This section presents a conceptual framework that illustrates how Indigenous Knowledge systems can be systematically integrated with contemporary technologies to enhance sustainable rural development outcomes, grounded in Africa's rich historical and cultural heritage of Indigenous Knowledge.

5.1 Components of the IK-informed smart village framework

A holistic framework for building sustainable smart villages, grounded in IK and cultural wisdom, is presented in Fig. 6. The figure illustrates how indigenous knowledge, governance, and modern digital tools can synergize to empower rural communities while preserving their cultural heritage. The framework is organized hierarchically, moving from foundational principles to practical applications and culminating in long-term outcomes.

5.1.1 Foundational layers

Indigenous knowledge and cultural wisdom constitute the foundational layer of the proposed framework. It functions as a guiding force rather than a standalone component. Instead of operating in parallel with sustainable governance and digital infrastructure, IK provides the philosophical and operational backbone that forms how governance processes are conducted and how digital technologies are designed and deployed. Governance mechanisms are therefore participatory, consensus-driven, and contextually grounded, while digital infrastructure and data practices are aligned with local values, ethical norms, and cultural priorities. In this sense, sustainable governance and digital infrastructure are interpreted and operationalized through the lens of IK. Without this foundation, governance risks becoming top-down and technology risks being misaligned with local realities. Indigenous Knowledge thus legitimizes and contextualizes the "smart" components of the framework, ensuring cultural embeddedness, social acceptance, and long-term sustainability.

5.1.2 Digital sovereignty layer

Digital sovereignty (data and technological autonomy) acts as an important bridging layer between the foundational pillars and the applied smart systems. Although IK provides the philosophical grounding, digital sovereignty ensures that this grounding is operationalized in the digital domain. It emphasizes community ownership, control, and stewardship of data, technologies, and digital platforms. This layer safeguards against external technological dependence, data exploitation, and misappropriation of IK. When IK principles are embedded into data governance, algorithm design, and platform management, digital sovereignty ensures that digital tools reinforce local autonomy, ethical use of data, and long-term sustainability rather than reproducing extractive or externally imposed development models.

5.1.3 Interconnected smart systems layer

This layer comprises interconnected smart sectoral systems that translate IK-driven governance and digitally enabled foundations into tangible development outcomes. These systems function as a synergistic ecosystem guided by IK principles and supported by digital infrastructure rather than operating as isolated interventions. Renewable energy systems utilize local ecological knowledge to design context-appropriate solutions that enhance energy resilience while minimizing environmental disruption. Smart agriculture integrates IK-informed practices with digital tools such as precision agriculture, climate advisories, and GeoAI-based prediction to improve productivity, climate resilience, and food security. Smart infrastructure leverages IK-informed resource management to inform the planning and maintenance of water, housing, transportation, and natural resources. This ensures alignment with ecological limits and cultural values. Smart education embeds IK systems and languages alongside digital literacy to promote cultural continuity and inclusive participation. On the other hand, smart health combines indigenous healing practices with modern healthcare technologies. This allows improved accessibility and trust while preserving culturally embedded health systems. These systems collectively operationalize IK-driven governance and digital sovereignty into sector-specific innovations that are locally relevant, culturally embedded, and socially accepted.

5.1.4 Smart local businesses layer

Smart local businesses form the economic engine of the framework. Rooted in indigenous skills, resources, and knowledge, these enterprises, which include IK-based agri-tech, handicrafts, e-commerce, and local services, translate cultural assets into sustainable livelihoods. Digital platforms enable market access, value-chain integration, and innovation, while IK ensures authenticity, ethical production, and community benefit-sharing. This layer strengthens local economies, reduces rural–urban migration, and reinforces self-reliance.

5.1.5 Ik integration, validation, and preservation layer

This layer provides a feedback and safeguarding mechanism for the entire framework. It ensures that IK used across governance, technology, and economic activities is systematically documented, validated, protected, and transmitted. Validation mechanisms prevent the misuse or distortion of IK, and preservation efforts are supported by digital archiving and storytelling platforms to ensure intergenerational continuity. This layer similarly reinforces trust, legitimacy, and cultural integrity in all smart village interventions.

5.1.6 Outcome layer: empowered, self-reliant, and resilient communities

At the base of the framework is the ultimate outcome of empowered, self-reliant, and resilient rural communities that contribute to achieving the sustainable development goals (SDGs). Empowerment emerges from participatory governance and cultural inclusion; self-reliance from digital sovereignty and local enterprise development; and resilience from the integration of IK with adaptive technologies. The layered structure ensures that development is not merely technologically “smart” but culturally embedded, socially inclusive, and environmentally sustainable.

Table 3 Operational mapping of the proposed IK–technology smart village framework

Framework domain	Relevant IK practice	Enabling technologies	Implementation risks	Suggested indicators
Smart agriculture	Traditional soil health indicators and polyculture planting	IoT Sensors and AI: Cross-referencing soil data with ancestral planting calendars	Loss of Intuition: Over-reliance on digital data may erode oral knowledge transfer	Crop yield stability; % reduction in chemical fertilizer use
Smart health	Ethnobotanical knowledge and community-based care	Mobile Health and ML: Digitizing traditional remedies for accessibility	Biopiracy: Unauthorized commercialization of sacred medicinal knowledge	Integration rate of traditional remedies in village health records
Smart energy	Localized knowledge of wind, sun, and water cycles	Smart Micro-grids: AI-managed renewable energy tailored to village needs	Technical Dependency: High costs and need for external maintenance experts	Energy self-sufficiency ratio (local production vs. grid)
Smart education	Oral storytelling and intergenerational apprenticeship	AR/VR and Digital Archives: Preserving Indigenous languages and sacred histories	Epistemic Injustice: Digital tools "standardizing" and over-simplifying complex IK	Proficiency levels in Indigenous languages among village youth
Smart infrastructure	Traditional architecture and community land management	GIS and Digital Twins: Mapping community growth without infringing on sacred sites	Encroachment: Data mapping used by outsiders to exploit local resources	% of new infrastructure projects adhering to traditional land-use laws

5.2 Operationalization of the proposed framework

To enhance the practical usability of the proposed framework, this subsection presents a concise operational mapping that links each framework domain to relevant IK practices, enabling technologies, implementation risks, and suggested indicators (Table 3). This operationalization translates the conceptual framework into a practical tool suitable for implementation and evaluation in rural sustainability contexts. The table provides a concise guide for applying the proposed framework to support sustainable development and knowledge integration in rural communities.

6 Challenges and opportunities in implementing smart villages with IK

6.1 Current challenges

The integration of advanced technologies into rural development holds great promise for improving the overall well-being within the smart villages. There are diverse interrelated constraints that can emanate when attempting to implement rural sustainability through a balanced combination of advanced technological innovations and IK. Some of these constraints are explained in the following section.

Technological accessibility is a prevalent digital divide that limits inclusive participation in Smart Village initiatives. It presents a situation of inequality in access to modern digital solutions across different social groups [77]. Many rural communities face the challenge of inadequate digital technologies, including internet connectivity, mobile devices, and renewable energy sources, which are essential foundations for smart village infrastructure [78].

In data governance and digital sovereignty, the unprecedented technological advancements and their use on different platforms produce a large volume of sensitive data [79]. Data governance framework should ensure the safe, transparent, and beneficial use of data generated from digital technologies. Weak or absent governance mechanisms can expose communities to data exploitation, thereby undermining trust and autonomy.

Digital **s**overeignty emphasizes the right of individuals, organizations, and communities to exercise complete control over their digital data [80].

For the case of financial sustainability, it is very common for most Smart Village initiatives to start with pilot projects. The projects are primarily funded by international organizations, government grants, and NGOs [81]. A dependence on this funding could expose the smart village initiative to collapse once external support ends.

Preservation of IK in Smart villages utilize modern technologies-driven approaches to improve efficiency and quality of life [82]. These innovations can inadvertently displace or devalue IK systems that have sustained communities for generations. When modern solutions are introduced without the deliberate integration of local systems, they can create a perception that indigenous methods are outdated, inferior, or irrelevant.

Sustained community engagement is one of the most important determinants of the success of any smart village initiative [83]. When a project is launched, there is always a high initial enthusiasm. The novelty of new technologies, training programs, or visible infrastructure improvements usually drives this. However, maintaining that momentum over a long-term period presents a big challenge. Therefore, without sustained community engagement, even the most advanced infrastructure and digital systems may operate far below their potential, or eventually be abandoned altogether.

In addition, rural development policies are often scattered across several ministries, including agriculture, ICT, energy, health, and education, with little coordination. This can lead to duplication and inefficiency. Policies tend to prioritize formal, scientific approaches, which can undervalue traditional practices. This frequently hinders the smooth integration of smart village frameworks. Most of the time, governments lack adequate budgets to fund digital infrastructure, renewable energy, and community capacity-building on a large scale. Policies risk reinforcing inequalities if they fail to actively include women, youth, and marginalized groups in decision-making and benefits distribution. Finally, policymakers face difficulties in measuring multidimensional outcomes such as economic, social, environmental and cultural. This can make it extremely hard to track progress or refine strategies.

These challenges underscore the need to develop eco-inclusive policy frameworks that strike a balance between technological innovation and cultural relevance, equity, and sustainability in the pursuit of reimagined smart villages.

6.2 Opportunities

A reimagined smart village presents opportunities that go beyond mere technology deployment, it provides a pathway that links indigenous wisdom with modern innovations for rural sustainability. One major opportunity lies in enhanced connectivity. When there is reliable internet and communication infrastructure, rural residents can share traditional knowledge. They can also access real-time data on farming, markets, and weather to improve agricultural practices. Telemedicine, e-learning, and digital storytelling are enabled through connectivity, which assists in bridging the digital divide and empowers communities with information, skills, and income-generating avenues previously out of reach.

The reimagined model enables economic diversification. Smart villages can foster rural entrepreneurship, agribusiness innovations, creative industries, and tourism opportunities that align with local culture. This diversification has the potential to reduce overreliance on subsistence farming, open new markets, and strengthen local economies.

Sustainable resource management is another important opportunity. Rural communities can optimize the use of their natural resources by integrating renewable energy systems, precision agriculture, and smart water management tools. This helps to reduce environmental impact. Aside from this, self-reliant communities with lower dependency on external resources are created. This further enhances the contribution to both economic and ecological resilience.

Also, the reimagined smart village supports social inclusion and cultural preservation. Technology-enabled platforms can document, promote, and monetize IK, crafts, and traditions. Hence, cultural heritage can be transferred to future generations. Smart villages become inclusive spaces when communities are actively involved in planning and decision-making processes.

A reimagined smart village can bridge vital service gaps. For instance, it can provide access to improved healthcare and education. Different digital health platforms, telemedicine, and AI-powered diagnostics can be utilized to connect residents with qualified healthcare professionals, regardless of their geographic location. Similarly, education can be transformed through e-learning platforms, virtual classrooms, and digital libraries that bring quality learning resources to every child and adult. Local learning hubs equipped with high-speed internet can enable blended learning, skills development, and vocational training that align with community needs. These innovations can jointly enhance the quality of life and also reduce rural–urban migration.

7 Conclusion and future directions

Rural development discourse is shifting progressively from infrastructure-centric interventions toward culturally grounded, participatory, and community-driven approaches. Within this evolving context, smart villages have emerged as inclusive and adaptive development models with the potential to support sustainability and resilience. However, empirical evidence of their long-term effectiveness remains limited. This study contributes to the growing body of literature by highlighting how smart village initiatives can meaningfully intersect with IK systems to enable context-driven and culturally embedded innovation. Existing studies suggest that integrating traditional knowledge with modern digital technologies can enhance adaptability and resilience in rural communities; however, the magnitude and form of these benefits are strongly shaped by local socio-cultural, institutional, and environmental conditions.

Based on these insights, this study recommends that smart village models be designed to complement rather than replace indigenous practices. The strategic integration of information and communication technologies with IK transfer in education, the alignment of renewable energy systems with community-based management structures, and the expansion of affordable and inclusive digital infrastructure may enhance the relevance and effectiveness of smart village interventions. Additionally, utilizing digital platforms to preserve cultural heritage, strengthen inclusive governance mechanisms, and foster supportive policy and institutional partnerships is crucial for sustaining hybrid development models. Linking indigenous products and services to broader markets through digital tools also holds promise for strengthening rural entrepreneurship.

However, systematic empirical evaluation is required to assess the effectiveness of such strategies across different contexts.

Despite the promising potential of integrating IK and digital technologies within smart village frameworks, there are still key research gaps. Future studies should move beyond conceptual and review-based analyses to empirically assess development outcomes, examine contextual enabling and constraining factors, and identify best practices for implementation. Longitudinal and comparative case studies, as well as mixed-methods approaches, would be valuable for substantiating claims related to resilience, inclusivity, and sustainability.

Also, this study relies on selected secondary sources, which may introduce regional or thematic bias, and does not generate primary empirical data. As a result, causal relationships cannot be established, and the findings cannot be assumed to be universally applicable. Nonetheless, the study provides a structured conceptual foundation that highlights critical directions for future empirical research aimed at advancing culturally grounded and digitally enabled rural development paths.

Acknowledgment
The authors sincerely acknowledge the provision of resources and financial support from the Unit for Data Science and Computing, North-West University, South Africa. This support was instrumental in the successful execution, completion, and publication of this study.

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Folasade O. Isinkaye: Writing—original draft, Writing—review and editing, Investigation, Validation. Jeffrey O. Agushaka: Writing—original draft, Writing – review, Investigation. Abiodun M. Ikotun: Writing—original draft, Writing—review, Investigation. Jumoke Soyemi: Writing—original draft, Writing—review, Investigation. Absalom E. Ezugwu: Conceptualization, Writing—original draft, Writing—review and editing, Supervision.

Funding
This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process
While preparing this work, the authors utilized AI-assisted tools, such as ChatGPT and Grammarly, to enhance the accuracy of the English language. These include spelling, grammar, and punctuation. To ensure accuracy and originality, the authors thoroughly reviewed, revised, and edited the content generated or corrected by these tools. The authors accept full responsibility for the originality of the final content of this publication.

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Received: 14 October 2025 / Accepted: 13 March 2026
Published online: 30 March 2026

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