GLOBAL MULTIDISCIPLINARY PERSPECTIVES JOURNAL

Integrating Indigenous Knowledge into the Climate–Water–Energy–Health–Food Nexus for Sustainable Smallholder Livestock Livelihoods in Sub-Saharan Africa

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Article Info

ISSN (online): 3107-3972
Impact Factor (RSIF): 8.08
Volume: 03
Issue: 02
March-April 2026
Received: 10-01-2026
Accepted: 12-02-2026
Published: 15-03-2026
Page No: 56-66

Abstract
Indigenous Knowledge Systems (IKS), often overlooked in formal development discussions, offer a significant resource for enhancing the resilience of smallholder households reliant on livestock. By delivering strategies rooted in local contexts for managing resources, mitigating risks, and making adaptive decisions, IKS can play a pivotal role in tackling interconnected challenges within the climate–water–energy–health–food (CWEH–F) nexus. Thus, leveraging and incorporating this knowledge is crucial for fostering sustainable and resilient smallholder livestock production. Across sub-Saharan Africa (SSA), smallholder livestock systems are fundamental to rural livelihoods, significantly contributing to food security, income generation, and nutritional well-being for healthy rural populations. However, these systems face increasing pressures from interacting stressors, such as climate variability, water scarcity, limited energy access, emerging zoonotic diseases, and disruptions in food systems. The CWEH–F nexus offers a systems-oriented framework to address these interdependencies; however, it remains largely disconnected from IKS. This study synthesizes interdisciplinary evidence of the role of IKS in bolstering resilience in smallholder livestock systems. The findings reveal that IKS enhances adaptive capacity through locally grounded practices, such as climate forecasting, adaptive grazing, ethno-veterinary medicine, and communal resource governance. These practices improve resource-use efficiency, reduce vulnerability, and support sustainable livelihood outcomes. Despite these contributions, the integration of IKS into formal nexus frameworks and policy processes remains limited. Key gaps include weak institutional recognition, insufficient gender disaggregated analysis, and challenges in scaling context-specific practices. The study concludes that effectively integrating IKS within the CWEH–F nexus requires adopting hybrid knowledge frameworks, participatory governance mechanisms, and inclusive policy environments. These integrative approaches facilitate the co-production of solutions that are both locally grounded and scientifically informed, thereby enhancing the sustainability of smallholder livestock systems, improving climate resilience, and reinforcing the interdependent resource dynamics that underpin the CWEH–F nexus in Sub-Saharan Africa.

DOI: https://doi.org/10.54660/GMPJ.2026.3.2.56-66

Keywords: Indigenous Knowledge Systems; Livestock Systems; Climate Adaptation; Nexus Approach; Resilience; Sub-Saharan Africa

1. Introduction

The *climate–water–energy–health–food (CWEH–F) nexus* has gained prominence as an integrated, systems-Bonn *2011 Nexus Conference* by Hoff (2011); the nexus framework emphasizes the interdependence of climate, water, energy, and food systems and the need to transcend sectoral silos to reduce trade- The increasing complexity of sustainability challenges in Sub-Saharan Africa has necessitated a transition from sector-specific interventions to integrated systems-based approaches. The CWEH–F nexus provides a comprehensive framework for understanding the interdependencies among critical resource systems (Biggs et

al., 2015; Simpson and Jewitt, 2022). Within smallholder livestock systems, these linkages are particularly pronounced, as livestock production simultaneously depends on water availability, energy access, ecosystem services, and climate stability (Thornton *et al*., 2021).

The CWEH-F nexus approach integrates various sectors to uncover and utilize synergies and reduce conflicts and trade-offs that frequently result from policies focused on individual sectors. This systems-based perspective is particularly vital in rural and resource-constrained environments, where vulnerabilities to climate variability and environmental degradation are pronounced (Nhamo *et al*. 2020). It encourages policymakers and practitioners to adopt cross-sectoral strategies that promote environmental sustainability and enhance community resilience, improve health outcomes, and ensure food and energy security (Decoppet *et al*. 2023) [16]. Building on this foundational work, subsequent research has highlighted the potential of nexus thinking to inform coherent resource planning that advances Sustainable Development Goals (SDGs) and strengthens socio-Chibarabada *et al* 2022; Ningi *et al* 2021; Hirwa *et al* 2021; Nhamo *et al* 2020) [13].

Despite the analytical strength of the nexus framework, its practical application often prioritizes technical and economic dimensions while underrepresenting sociocultural knowledge systems. Indigenous knowledge systems (IKS), developed through long-term interactions between communities and their environments, offer context-specific insights into resource management, climate adaptation, and livestock production (Mapfumo *et al*., 2022; Nyahunda, 2024). IKS has largely been absent in most Nexus models, which tend to emphasize technical, economic, and resources. The exclusion of indigenous knowledge across health, energy, water, and climate dimensions weakens the integration of nexus analyses and underestimates vulnerabilities in smallholder livestock systems. There is a scarcity of longitudinal and experimental studies that could validate IKS contributions and reveal causal influences on nexus outcomes over time. Addressing these gaps is essential for evidence-

In sub-Saharan Africa (SSA), smallholder livestock production is a vital element of rural livelihoods, playing a crucial role in ensuring food security, generating income, enhancing nutrition, and maintaining sociocultural stability. Nearly 70% of rural households rely on livestock for subsistence, with Indigenous Knowledge Systems (IKS) providing guidance for locally adapted husbandry practices, climate risk management, and resource utilization (Herrero *et al*., 2021; FAO, 2023) [27, 23]. By employing indigenous climate forecasting, strategic grazing, and ethno-veterinary practices, smallholder farmers can strengthen their resilience to climatic fluctuations, disease outbreaks, and market disruptions (Thornton *et al*., 2018). Within this framework, IKS acts as a cross-cutting integrator in the CWEH–F nexus, connecting livestock production with interrelated resource systems. Livestock systems depend on water for grazing and animal health, energy for feed processing, and veterinary services, while also contributing to food security and human health through the provision of animal-source foods. Nevertheless, increasing climatic variability and resource degradation pose significant threats to the sustainability of these systems. Thus, incorporating IKS into the CWEH–F nexus presents a system-based strategy to bolster the resilience and sustainability of smallholder livestock livelihoods in SSA.

2. Materials and Methods

A systematic literature review was conducted following the PRISMA 2020 guidelines to ensure transparency, reproducibility, and methodological rigor in identifying relevant studies (Page *et al*., 2021).

2.1. Search strategy

We retrieved peer-reviewed literature from four major scientific databases: Scopus, Web of Science, ScienceDirect, and Google Scholar. We conducted searches using combinations of keywords, including

- “Indigenous Knowledge Systems”
- “smallholder livestock”
- “climate adaptation”
- “water–energy–food nexus”
- “climate–water–energy–health–food nexus”
- “Sub-Saharan Africa”

Boolean operators (AND/OR) were applied to refine the searches.

2.1.1. Inclusion criteria

Studies were included if they:

- Focused on Sub-Saharan Africa
- Examined Indigenous Knowledge Systems
- Addressed livestock production or pastoral systems
- Linked to at least one nexus component (climate, water, energy, health, or food)

2.1.2. Exclusion criteria

Studies were excluded if they:

- focused solely on crop systems
- were not conducted in SSA
- did not address indigenous knowledge
- lacked peer review.

Data synthesis

The selected articles were analyzed using reflexive thematic analysis to classify evidence across five nexus domains: climate, water, energy, health, and food (Braun & Clarke, 2019) [9].

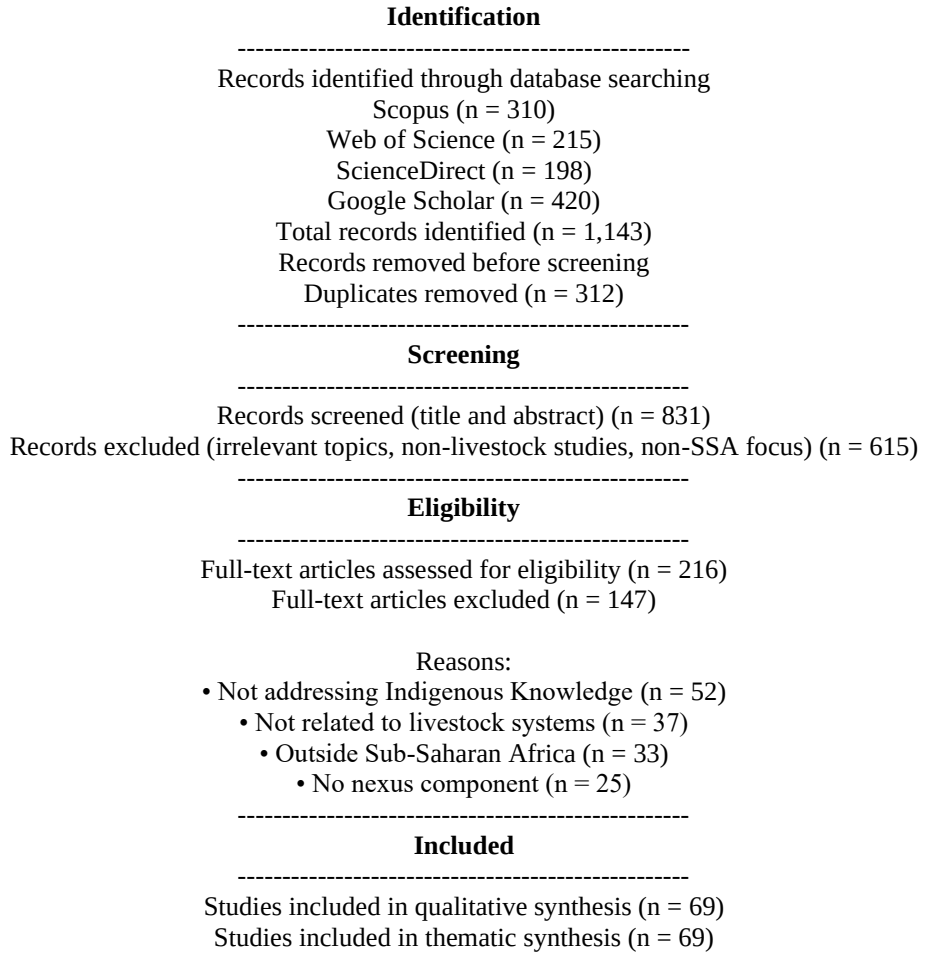

Fig 1: PRISMA 2020 flow diagram illustrating the systematic selection process for studies included in the review on Indigenous Knowledge Systems within the Climate–Water–Energy–Health–Food nexus in Sub-Saharan Africa

3. Results

3.1. Indigenous Knowledge as a Systems Integrator

IKS functions as a cross-cutting integrator within the CWEH–F nexus by strengthening interactions among resource systems and enhancing resilience. To provide a comprehensive understanding of how IKS intersects with multiple resource domains, a conceptual framework was developed (Figure 2). This framework illustrates IKS as a central integrator within the climate–water–energy–health–food nexus, linking resource systems to resilience and livelihood outcomes.

CWEH–F nexus, as illustrated in Figure 2, provides a holistic, systems-oriented framework for addressing resource scarcity and climate change by moving beyond fragmented, sector-specific approaches toward integrated and sustainable resource governance (Biggs *et al*., 2021; Simpson & Jewitt, 2022). Within smallholder livestock systems in Sub-Saharan Africa, the framework highlights the dynamic interconnections among water availability, energy access, animal health, and food production, all of which are highly sensitive to climate variability and extreme events (FAO, 2023; Thornton *et al*., 2021) [23].

Figure 2 conceptualizes these interlinked components as a set of mutually reinforcing subsystems embedded within a broader socio-ecological context shaped by climate change, institutional structures, and market forces. Central to the framework is the integration of IKS, which acts as a cross-cutting enabler that mediates interactions across nexus domains.

Indigenous knowledge contributes context-specific adaptation strategies, including traditional livestock management practices, ethno-veterinary knowledge, water conservation techniques, and climate forecasting based on local indicators (Mapfumo *et al*., 2022; Nhemachena *et al*., 2020).

As depicted in Figure 2, IK strengthens feedback loops between nexus components by enhancing resource-use efficiency, reducing vulnerability, and improving system resilience. For example, indigenous grazing systems and seasonal mobility patterns optimize water and pasture use, whereas traditional animal health practices improve livestock productivity under resource-constrained conditions. These practices support food security and reinforce energy efficiency and health outcomes at the household and community levels (HLPE, 2023; IPCC, 2022).

Furthermore, the framework positions gender and social inclusion, digital access, and institutional support as critical mediating factors that influence the effectiveness of IK integration within the CWEH–F nexus. Figure 2 illustrates how these enabling conditions shape access to resources, knowledge exchange, and adaptive capacity, thereby determining livelihood outcomes. The resulting system is characterized by iterative feedback mechanisms in which improved livestock productivity enhances food security, income generation, and reinvestment into water, energy, and health systems, creating a virtuous cycle of sustainable development (Njuki *et al*., 2022; World Bank, 2021). Overall, Figure 2 demonstrates that integrating IK into the CWEH–F

nexus transforms smallholder livestock systems into resilient, adaptive, and sustainable livelihood pathways capable of responding to the complex challenges of climate change in Sub-Saharan Africa.

Fig 2: Conceptual Framework for IKS into the CWEH–F Nexus for Sustainable Smallholder Livestock Livelihoods in Sub-Saharan Africa

3.2. IKS and Climate Adaptation

IKS constitute a significant and context-specific repository of knowledge, developed and refined by Indigenous communities over successive generations. This body of knowledge encompasses local environmental insights, cultural practices, and resource management techniques that are inherently adapted to the distinct ecological and social conditions of their respective regions. By integrating IKS into climate adaptation strategies, communities can utilize time-tested, place-based insights that enhance resilience to climate variability and change. These systems frequently offer practical solutions for sustainable agriculture, water management, and biodiversity conservation that are both cost-effective and culturally appropriate

Smallholder farmers across SSA employ a suite of indigenous climate indicators—such as animal behavior, plant phenology, atmospheric cues, and astronomical signs—to forecast rainfall, droughts, and other weather events, especially in areas where formal meteorological services are scarce or inaccessible. For example, changes in livestock grazing habits and insect activity are often interpreted as precursors to climatic shifts, informing livestock movement, grazing schedules, and water planning (Ngaruiya *et al*., 2020). These Indigenous Early Warning Systems (IEWS) frequently outperform conventional forecasts in remote pastoral areas by capitalizing on nuanced, long-

Adaptive pastoral mobility, rotational grazing, and seasonal herd diversification are cornerstone strategies supported by IKS that buffer livestock against resource scarcity and climate stressors. By tracking spatial–temporal resource availability and leveraging traditional grazing calendars, pastoralists can avoid overgrazed areas during droughts, optimize pasture regeneration, and align livestock nutritional needs with ecological conditions. These practices contribute to both livestock productivity and ecosystem sustainability, mitigating the cascading effects of climate extremes, such as prolonged drought and pasture degradation. Indigenous livestock breeds harbor valuable traits, such as tolerance to heat stress, water scarcity resilience, and resistance to endemic diseases, which are essential for sustaining productivity under climate variability. Smallholder farmers intentionally select breeding stock based on these adaptive traits, perpetuating herds that are finely tuned to local ecological niches and stress conditions.

Gender roles significantly shape access to, use of, and transmission of indigenous knowledge in livestock systems adaptive capacity (Assan, 2025) [5]. Women frequently undertake essential tasks related to livestock management, such as feeding, milk processing, and the care of small ruminants, thereby establishing themselves as pivotal custodians of IKS. This gender-specific division of labor endows women with distinctive, experience-based insights into micro-level adaptation strategies, including the optimization of feed resources, animal health management, and climate-responsive husbandry practices. Acknowledging and incorporating these gender-specific knowledge systems is thus crucial for enhancing the efficacy of interventions within the CWEH–F nexus and for promoting inclusive,

sustainable smallholder livestock production. (Pedza *et al*., 2025). Addressing these inequalities and integrating gender will effectively address climate change adaptation issues which is critical in the CWEH–F nexus.

There is growing recognition that combining IKS with formal scientific climate data and extension services enhances climate adaptation outcomes. Hybrid knowledge frameworks, where local observations and scientific forecasts are integrated (Nyahunda, 2024; Siatwiinda *et al*., 2025). Despite the proven value of such integration, barriers persist in the documentation, validation, and institutional recognition of IKS, as well as in bridging communicative gaps between local communities and formal climate institutions.

IKS promotes community participation and empowerment, as it is rooted in the lived experiences and collective memory of Indigenous peoples. This localized knowledge complements scientific approaches by addressing data gaps, providing early warning signals, and guiding adaptive responses that are socially acceptable and ecologically viable. Recognizing and incorporating IKS into formal climate adaptation frameworks strengthens adaptive capacity, supports the preservation of cultural heritage, and promotes equitable governance in environmental decision-making processes. Consequently, IKS is indispensable for crafting holistic and sustainable climate adaptation strategies that respect both nature and culture.

3.3. IKS and Water Resource Management

Indigenous Knowledge underpins communal water governance systems, which regulate access, allocation, and use of water resources through socially embedded norms, customary institutions, and traditional leadership structures. Within the conceptual framework (Figure 2), these governance mechanisms are represented as institutional mediators (bottom-left section) that influence the effectiveness of resource management across the nexus. They are linked to the water node through directional arrows, indicating their role in shaping equitable access and sustainable use of water resources.

Customary water governance systems promote collective action, conflict resolution, and equitable distribution, particularly in pastoral and agro-pastoral systems, where water scarcity can intensify competition and trigger resource-based conflicts. These institutions establish rules for water access, seasonal use, and the maintenance of shared infrastructure, thereby ensuring the sustainability of water resources and reducing the risk of overexploitation. As shown in Figure 2, these processes contribute to the social resilience feedback loop, in which effective governance enhances resource sustainability, supports livestock productivity, and strengthens livelihood outcomes.

Recent studies emphasize that integrating indigenous governance systems with formal policy frameworks can improve water security, enhance adaptive capacity, and reduce conflict in climate-vulnerable regions (Nhemachena *et al*., 2020; Cleaver & Whaley, 2022; FAO, 2023) [14, 23]. Moreover, these systems often incorporate principles of inclusivity and local accountability, although their effectiveness can be influenced by gender dynamics and power relations. Therefore, strengthening indigenous water governance within the CWEH–F nexus is essential for achieving equitable, sustainable, and resilient livestock-based livelihoods in Sub-Saharan Africa.

3.4. IKS and Energy Use in Livestock Systems

IKS constitute a socio-cultural foundational element in shaping energy use within smallholder livestock systems in Sub-Saharan Africa, particularly in contexts where access to modern and reliable energy services remains limited. Within the CWEH–F nexus, energy is a key component that underpins livestock production, processing, and value addition. As illustrated in Figure 2, the energy access node (right side) is interconnected with water, food, and health systems through bidirectional arrows, highlighting the dependence of livestock productivity on energy availability and efficiency. Indigenous Knowledge functions as a central integrative mechanism (central oval in Figure 2) that enhances energy sustainability by promoting locally adapted, low-input, and resource-efficient practices.

IKS contributes to circular resource flows, in which livestock by-products, such as manure, are recycled into energy sources, thereby strengthening the energy–food–environment linkage. These processes are represented in Figure 2 through feedback loops, in which efficient energy use improves livestock productivity, enhances food security, and generates income that can be reinvested into sustainable energy solutions. Empirical evidence suggests that Indigenous energy practices significantly reduce reliance on fossil fuels and external inputs, while enhancing resilience to energy shocks and climate variability (Mungai *et al*., 2021; Parawira, 2022; IEA, 2023). Consequently, integrating Indigenous knowledge into the energy dimension of the nexus supports sustainable, low-carbon livestock systems that are both economically viable and environmentally sound.

3.5. IKS and Health (One Health Perspective)

IKS play a critical role in advancing animal and human health within smallholder livestock systems, particularly in resource-constrained settings where access to formal veterinary and healthcare services is limited (Assan, 2025) [5]. Within the One Health framework, which emphasizes the interconnectedness of human, animal, and environmental health, Indigenous Knowledge functions as a cross-cutting driver (central node in Figure 2), linking the health, food, water, and environmental components of the CWEH–F nexus. As illustrated in Figure 2, IKS strengthens bidirectional pathways between livestock systems and the health node, wherein improved animal health enhances food safety, nutrition, and human well-being, while healthy human populations contribute to better livestock management.

Furthermore, IKS enhances feedback loops associated with resilience (bottom-right of Figure 2) by enabling early disease detection, locally adapted treatment practices, and preventive management strategies. These practices reduce dependency on costly external inputs while improving system sustainability. Evidence shows that indigenous health practices, including ethno-veterinary medicine and traditional disease surveillance, contribute significantly to controlling livestock diseases and safeguarding public health in Sub-Saharan Africa (McGaw & Eloff, 2020; Madzimure *et al*., 2021; WHO, 2022). By integrating Indigenous Knowledge into the One Health framework, smallholder systems can achieve cost-effective, culturally appropriate, and ecologically sustainable health outcomes, reinforcing the interconnected pathways between livestock productivity, food security, and human health.

Ethno-veterinary medicine constitutes a key component of IKS that supports the animal health–food security pathway,

as illustrated in Figure 2. Smallholder farmers widely utilize plant-based remedies, herbal extracts, and traditional healing practices to prevent and treat livestock diseases, particularly in areas where access to modern veterinary services is limited or unaffordable (Sithole, 2020). These practices are represented in Figure 2 as adaptive strategies feeding into the health node, with arrows linking improved animal health to enhanced livestock productivity and food availability.

Ethno-veterinary knowledge is deeply rooted in local ecosystems and biodiversity, relying on medicinal plants that are readily available and environmentally sustainable. This aligns with the water–environment–health interactions within the nexus, as the sustainable use of natural resources supports both ecosystem health and livestock well-being. Empirical studies indicate that many plant-based treatments possess antimicrobial, antiparasitic, and anti-inflammatory properties, validating their effectiveness in livestock health management (McGaw & Eloff, 2020; Madzimure *et al*., 2021; Chinsembu, 2022).

Moreover, the use of ethno-veterinary practices reduces reliance on synthetic drugs, thereby lowering costs and minimizing the risks associated with antimicrobial resistance. Within the conceptual framework (Figure 2), this contributes to positive feedback loops, in which improved animal health leads to increased productivity, higher household income, and reinvestment in livestock and health systems. Thus, ethno-veterinary medicine serves as a sustainable, accessible, and culturally embedded pillar of livestock health management in Sub-Saharan Africa (Madisha & McGaw, 2023).

Indigenous knowledge also plays a vital role in managing zoonotic diseases through locally developed practices that reduce disease transmission risks at the human–animal–environment interface (FAO, 2023) [23]. These practices align closely with the One Health approach and are represented in Figure 2 as preventive mechanisms linking the health, environment, and livestock nodes through directional arrows. Common strategies include the isolation of sick animals, controlled grazing to avoid contaminated areas, and hygienic slaughtering and food handling practices, all of which contribute to minimizing the spread of infectious diseases.

These Indigenous practices enhance the health–environment feedback loop by reducing pathogen circulation within ecosystems and improving overall system resilience. For instance, controlled grazing helps prevent overexposure to disease vectors, whereas proper waste management and sanitation practices reduce environmental contamination. Such measures are particularly critical in rural settings, where formal disease surveillance systems are weak or absent (Scoones *et al*., 2021).

Recent studies emphasize that integrating Indigenous disease management practices with formal veterinary and public health systems can significantly improve zoonotic disease control and pandemic preparedness (; WHO, 2022;). Within the CWEH–F nexus framework, these practices strengthen the resilience loop (Figure 2) by safeguarding both livestock productivity and human health, thereby ensuring sustainable livelihoods. Consequently, Indigenous knowledge-based zoonotic disease management represents a cost-effective, locally adaptable, and ecologically sound strategy for advancing One Health outcomes in Sub-Saharan Africa.

3.6. IKS and Food Security

Indigenous Knowledge Systems (IKS) play a central role in enhancing food security within smallholder livestock systems by strengthening the food production–consumption–resilience pathways illustrated in Figure 2. Livestock contributes directly to food availability through the provision of animal-source foods and indirectly through income that improves food access (Assan, 2025) [5]. Within the CWEH–F nexus, IKS operates as a cross-cutting node (central oval in Figure 2) that reinforces linkages among water, energy, health, and food systems through locally adapted practices. These interactions are represented by bidirectional arrows and feedback loops, where improved livestock productivity enhances food security, which in turn supports reinvestment into water, energy, and animal health systems.

Research indicates that practices rooted in Indigenous knowledge, such as adaptive herd management, climate prediction, and integrated crop–livestock systems, play a crucial role in boosting household food security and resilience in the face of climate challenges in Sub-Saharan Africa. Communities utilize Indigenous climate indicators, such as plant phenology and animal behavior, to predict seasonal shifts and adjust planting or grazing schedules, accordingly, thereby reducing climate-related risks and improving agricultural productivity (Egah, *et al*. 2023; Dzviti, *et al*., 2023) [19, 18]. Additionally, adaptive strategies guided by Indigenous knowledge systems (IKS), including changing crop varieties, modifying planting dates, and incorporating livestock into crop systems, have been proven to enhance both food availability and income stability for smallholder households (Siatwiinda, *et al*, 2025; Springer, 2024).

The integration of Indigenous climate services with scientific forecasts further bolsters anticipatory actions, allowing communities to make informed decisions and strengthen their resilience to extreme weather events (Dube, *et al*, 2024) [17]. Furthermore, Indigenous knowledge enhances system sustainability by promoting low-input, ecologically grounded strategies that align with local socio-cultural contexts, thereby strengthening the resilience feedback loop (bottom-right of Figure 1), linking livelihoods, resource efficiency, and adaptive capacity (Nyahunda, 2024; Siatwiinda *et al*., 2025). These studies collectively highlight the crucial importance of IKS in facilitating sustainable livelihoods and climate adaptation strategies for smallholder farmers across diverse agroecological contexts in Sub-Saharan Africa.

3.6.1. IKS and Dietary Diversity and Nutrition

Indigenous knowledge significantly improves dietary diversity and nutritional outcomes by supporting the livestock–food–health pathway, as depicted in Figure 2, where arrows connect livestock systems to food security and human well-being. In Sub-Saharan Africa, traditional livestock-rearing practices emphasize the preservation of a variety of species, such as goats, sheep, and indigenous poultry, which are notably resilient to challenging climatic conditions. These species are well-suited to the region's agroecological diversity, requiring minimal inputs and demonstrating lower susceptibility to disease outbreaks compared to exotic breeds. Consequently, they serve as dependable sources of animal protein and vital micronutrients

for smallholder households (Nxumalo, *et al*., 2025; Melash, *et al*., 2025). The deliberate employment of these robust livestock species bolsters household nutritional security, facilitates income generation, and strengthens overall livelihood resilience in the face of climate stress (Malcom, 2024; Assan, 2025) [5].

By incorporating indigenous knowledge into livestock management, smallholders can sustainably exploit the multifunctional advantages of local breeds while mitigating risks associated with climate-related production (Kom, *et al*., 2024; Mapedza, *et al*., 2025). This diversification strengthens the food security node and enhances the health dimension of the nexus, contributing to improved nutritional status.

Indigenous knowledge-based livestock feeding systems, breeding strategies, and seasonal consumption patterns ensure a continuous supply of animal-source foods, even under climatic stress. Assan, (2025) [5] reported gendered Indigenous Knowledge—particularly women's roles in managing small livestock and household nutrition—acts as a mediating factor (Figure 2: gender and social inclusion) that strengthens intra-household food distribution and utilization. Recent studies highlight that integrating gender and Indigenous Knowledge enhances adaptive capacity, nutritional outcomes, and food system resilience in Sub-Saharan Africa. Additionally, Indigenous livestock management practices improve productivity and reproductive efficiency, thereby increasing the availability of nutrient-rich foods and reinforcing the positive feedback loop between livestock productivity and nutritional outcomes.

3.6.2. IKS and Food Preservation and Storage

Indigenous food preservation and storage practices are critical components of food stability and resilience pathways, particularly within the feedback loops linking food security to sustainable livelihoods (Figure 2). Techniques such as sun-drying, smoking, fermentation, and salting extend the shelf life of livestock products, thereby reducing post-harvest losses and ensuring year-round food availability (Tirivangasi and Rankoana, 2021). These practices are represented in the framework as adaptive strategies that enhance system resilience by stabilizing food supplies during periods of scarcity or climate-induced shocks.

Evidence indicates that a high proportion of rural households rely on Indigenous preservation methods, such as sun-drying, to maintain food reserves and bridge seasonal food gaps (Aworh, 2023) [6]. Importantly, these techniques are energy-efficient and align with the energy–food nexus linkage by minimizing dependence on external energy inputs. Furthermore, Indigenous preservation methods contribute to food safety, cultural continuity, and economic savings, thereby strengthening the livelihood outcomes loop, which connects food security to income generation and resource reinvestment. Thus, these practices play a vital role in enhancing the resilience, sustainability, and inclusivity of smallholder livestock-based food systems in Sub-Saharan Africa.

3.6.3. The role of gender and sociocultural diversity in shaping IKS adoption.

Gender inequalities in access to resources, land, and extension services limit IKS utilization (Huyer *et al*., 2021) [30]. Women possess specialized knowledge in small livestock management and animal health, whereas men typically manage large livestock. Integrating gender-responsive approaches is essential for leveraging indigenous knowledge within the CWEH–F nexus. Gender critically influences the generation and transmission of indigenous knowledge. Sustainable smallholder livestock-based systems are inherently multidimensional, linking environmental integrity, social well-being, and economic viability within an integrated framework.

From an environmental perspective, they focus on optimizing the use of natural resources, reducing greenhouse gas emissions, and preserving biodiversity in livestock production systems (Place, 2024; Nakelse & Dennis, 2024). Socially, they support food and nutrition security, sustain rural livelihoods, preserve cultural values, and promote animal welfare. Economically, livestock systems contribute to household income generation, employment creation, and the long-term productivity and resilience of farming communities. Consequently, sustainability in animal agriculture requires a balanced and integrated approach that simultaneously addresses environmental stewardship, social equity, and economic viability, rather than treating these dimensions independently (Food and Agriculture Organization of the United Nations, 2023).

Smallholder livestock systems are known for their role in contributing to food security; however, they face a plethora of challenges from population growth and climate impacts (Assan, 2023) [4]. Climate change threatens food security by affecting animal farming through worsening weather conditions. Humphary *et al*. (2022) emphasize addressing gender gaps and integrating local knowledge for agricultural development. Gender-specific sociocultural factors interact with climate variations, impacting animal husbandry (All *et al*., 2023). Livestock production contributes to global climate change (Jacquet *et al*., 2023). Global warming affects animal agriculture and exacerbates climate change (Eisen and Brown, 2022) [21]. Kuraz *et al*. (2021) predicted that animal farming will emit 145 GHG (IPCC, 2013).

Climate change disproportionately affects men and women because of distinct roles (UNDP, 2016). Women are particularly vulnerable because they rely on subsistence agriculture (Apira *et al*., 2017) [3]. Climate change impacts indigenous knowledge and gender equality interconnections, influenced by societal factors. Environmental changes challenge smallholder agriculturalists, affecting production in developing countries (Kakota *et al*., 2011). Gender equality enhances women's resilience to climate change. The FAO (2012) [24] emphasizes the importance of gender equity in agricultural development and sustainable livestock production. Boosting food production requires reducing gender inequalities in livestock production and increasing climate knowledge, as these factors negatively impact sustainability.

Climate change disproportionately affects women involved in livestock production compared to their male counterparts, as documented by Laska and Morrow (2006). Chaudhary *et al*. (2022) demonstrated that indigenous knowledge offers valuable insights for addressing climate change. It is imperative for researchers to incorporate indigenous perspectives when establishing sustainable livestock practices (Dakora, 1996) [15]. Eguru (2012) [20] acknowledged the potential of traditional systems in climate planning. Nyong *et al*. (2006) highlighted the application of indigenous knowledge in addressing climate issues in the Sahel region. Furthermore, Svotwa *et al*. (2007), Nyong *et al*. (2006), and Robinson and Herbert (2001) have argued that the integration

of indigenous knowledge with modern scientific approaches enhances the adaptive capacity of livestock to climate change. Indigenous knowledge contributes significantly to animal agriculture through climate forecasting and precipitation prediction (Jiri *et al*., 2016; Mafongoya and Ajayi, 2017). Researchers have recognized the necessity of integrating indigenous and scientific knowledge to effectively address climate change (Chaudhary *et al*., 2022) [12]. Gender equality and traditional wisdom are essential for the sustainability of animal production as they influence both environmental and economic outcomes. Cultural norms dictate gender roles in animal production (Piri *et al*., 2021). Gender-differentiated roles and preferences vary among gender groups (Njuki *et al* 2022).

Gender-based discrimination restricts women's participation in decision-making processes related to animal production, resulting in unequal resource distribution (Assan, 2025) [5]. Development organizations must prioritize gender perspectives in animal husbandry to promote equality. By strengthening gender equality and transforming animal production into resilient approaches, organizations can achieve food production goals (Lecoutere *et al*., 2023). This review examines the relationship between gender roles and indigenous knowledge systems in sustainable animal agriculture. Understanding the intersection of gender and indigenous knowledge systems is crucial for achieving sustainable animal agriculture in the context of climate change.

4. Discussion

4.1. Indigenous Knowledge as a Systems Integrator

This review demonstrates that IKS act as pivotal integrators across the CWEH–F nexus, linking resource systems and strengthening resilience pathways in smallholder livestock systems in Sub-Saharan Africa (SSA). As illustrated in Figure 2, IKS mediates interactions among water, energy, health, and food subsystems, providing context-specific adaptation strategies and reinforcing feedback loops that enhance livelihood outcomes (Mapfumo *et al*., 2022; Nhemachena *et al*., 2020).

The conceptual framework highlights that the CWEH–F nexus is a dynamic, interconnected system in which climate variability, institutional structures, and market forces influence the effectiveness of Indigenous Knowledge integration. By embedding IKS into these linkages, communities can optimize resource-use efficiency, reduce vulnerability to shocks, and improve adaptive capacity (Biggs *et al*., 2021; Simpson & Jewitt, 2022). For instance, traditional livestock mobility patterns, rotational grazing, and ethno-veterinary practices serve as adaptive strategies that enhance productivity while maintaining ecosystem integrity (HLPE, 2023; IPCC, 2022).

Gender, social inclusion, digital access, and institutional support emerge as critical mediators within this framework. Women contribute specialized knowledge related to small ruminant management, household nutrition, and microclimate monitoring. Integrating these perspectives into extension services and climate adaptation planning amplifies the effectiveness of IKS, reinforcing the virtuous cycle between livestock productivity, food security, and resource sustainability (Assan, 2025; Njuki *et al*., 2022) [5].

4.2. Climate Adaptation

IKS provides an empirically validated reservoir of climate knowledge that enhances resilience to increasing climatic variability. Smallholder livestock farmers employ indigenous early warning systems (IEWS) using plant phenology, animal behavior, and atmospheric cues to anticipate rainfall or drought, often outperforming conventional forecasts in remote pastoral areas (Ngaruiya *et al*., 2020; Nyahunda, 2024).

Adaptive strategies, such as seasonal herd diversification, rotational grazing, and spatially informed herd mobility, buffer livestock against resource scarcity. Additionally, indigenous breeds selected for heat tolerance, drought resilience, and disease resistance complement these adaptive strategies, highlighting the importance of conserving locally adapted genetic resources (Siatwiinda *et al*., 2025).

Gender-sensitive adaptation is a crucial factor. Women's knowledge of microclimates and livestock management is often underutilized due to structural inequalities, including restricted access to land, financial services, and decision-making platforms. Addressing these disparities and incorporating gender-disaggregated IKS into climate services improves household adaptive capacity and strengthens resilience pathways (Assan, 2025; Mapedza *et al*., 2025) [5].

Integrating IKS with formal climate information enhances anticipatory planning and creates hybrid knowledge systems that improve early warning, decision-making, and locally relevant adaptation interventions (Nyahunda, 2024; Dube *et al*., 2024) [17]. Nevertheless, challenges remain in validating, documenting, and institutionalizing Indigenous Knowledge, particularly within formal policy frameworks.

4.3. Water Resource Management

IKS are integral to water resource management, as they incorporate communal norms, values, and practices within local governance frameworks in numerous rural communities across Sub-Saharan Africa. Through customary institutions, including community elders, traditional leadership, and collective decision-making platforms, indigenous water governance ensures the equitable distribution and responsible utilization of shared water resources. These systems also offer culturally grounded mechanisms for conflict resolution, aiding in the mediation of disputes over access to rivers, grazing corridors, wetlands, and communal waterpoints. Consequently, water resources are often managed in a manner that reflects local ecological knowledge, seasonal variability, and community livelihood priorities, thereby fostering sustainability and social cohesion (FAO, 2023; Cleaver & Whaley, 2022) [23, 14].

In the context of the CWEH–F nexus framework, indigenous water governance plays a vital role as a connector, bridging the gap between water resources and livestock production, as well as broader livelihood systems. Traditional water management practices, such as seasonal water rationing, protection of wetlands and riparian zones, and maintenance of communal water harvesting structures, help regulate resource use during periods of scarcity. This regulation is particularly important in semi-arid and drought-prone regions, where livestock production depends heavily on reliable access to water for grazing, animal health, and household consumption.

Integrating water management with seasonal cycles and leveraging local environmental knowledge through IKS is essential for fortifying the resilience of pastoral and smallholder livestock systems. This strategic alignment ensures a robust and sustainable approach to resource

allocation, effectively balancing the needs across interconnected nexus sectors. By adopting this method, we can secure a more resilient future for agricultural communities and ecosystems.

4.4. Indigenous Knowledge and Energy Use

Indigenous Knowledge Systems (IKS) in energy-constrained rural settings play a pivotal role in fostering sustainable development by integrating traditional practices with modern sustainability goals. These systems leverage locally available resources and culturally embedded techniques to create low-input-energy solutions that are both accessible and cost-effective. For example, recycling livestock manure into biogas not only provides a renewable energy source but also reduces environmental pollution and enhances soil fertility using digestate as a fertilizer. Similarly, traditional low-input feed processing methods reduce the need for external energy inputs, thereby lowering dependency on fossil fuels and mitigating greenhouse gas emissions. The integration of IKS within the energy dimension of the CWEH–F nexus exemplifies how indigenous practices contribute to circular resource flows, reinforcing the sustainability and resilience of rural livelihoods.

Bidirectional feedback loops between energy, food, and health nodes highlight the multifunctional advantages of IKS. Energy availability directly affects livestock productivity and food processing efficiency, which subsequently influences nutritional outcomes and community health. By optimizing resource utilization through indigenous strategies, these systems maintain economic viability while enhancing environmental stewardship and climate resilience.

The adaptability of IKS to local ecological and socioeconomic contexts ensures that communities can withstand climate-induced energy shocks, such as fuel scarcity or extreme weather events, without compromising food security or health. Therefore, IKS acts as a pivotal integrative framework that not only fulfils the energy requirements of rural areas but also bolsters the overall efficiency and sustainability of the CWEH–F nexus, thereby contributing to the achievement of long-term development goals in vulnerable regions.

4.5. Health (One Health Perspective)

IKS have enhanced the health of both livestock and humans through time-honored practices, such as ethno-veterinary medicine, strategies for disease prevention, and traditional methods for managing zoonotic diseases (McGaw & Eloff, 2020; Madzimure *et al*., 2021; WHO, 2022). In many smallholder livestock systems throughout sub-Saharan Africa, farmers use locally sourced medicinal plants, traditional remedies, and experiential knowledge to treat common livestock ailments, improve animal immunity, and manage parasitic infections. These practices often result from generations of observation and adaptation to local ecological conditions, enabling communities to effectively address disease outbreaks, particularly in areas with limited formal veterinary services. IKS provides a healthcare system that is both accessible and deeply integrated into cultural practices, thus supporting animal productivity and household well-being.

From a One Health perspective, indigenous health practices highlight the essential interconnections between animal health, human health, and environmental sustainability. The well-being of livestock plays a pivotal role in enhancing nutrition and economic stability for rural households, as they provide crucial animal-source foods, such as meat, milk, and eggs, which are indispensable for combating malnutrition and micronutrient deficiencies. Concurrently, traditional livestock management practices, including controlled grazing, herbal disease treatments, and maintaining sanitation around animal housing, are vital in reducing the risk of zoonotic disease transmission between animals and humans. Furthermore, these practices support ecosystem health by promoting the sustainable use of medicinal plant resources and preserving ecological balance within grazing landscapes, thereby reinforcing the feedback loops integral to the CWEH–F nexus.

Indigenous health practices offer a transformative solution for smallholder farmers, significantly reducing reliance on costly veterinary pharmaceuticals and slashing production costs. By embracing plant-based treatments and preventive management strategies, farmers can achieve a more sustainable and environmentally conscious approach to livestock health. When seamlessly integrated with formal veterinary services, scientific research, and public health systems, these Indigenous practices forge powerful knowledge pathways that revolutionize disease surveillance, elevate animal health interventions, and fortify rural healthcare systems. This hybrid approach not only boosts livestock productivity but also fosters resilient livelihoods and champions sustainable development within smallholder livestock systems (Chinsembu, 2022; Madisha & McGaw, 2023).

4.6. Food Security and Nutrition

IKS are instrumental in enhancing food availability, access, and utilization within smallholder livestock systems by incorporating culturally grounded practices that optimize resource use and adapt to local environmental conditions. Key traditional livestock management strategies include herd diversification, in which farmers rear multiple species and breeds to mitigate risk, enhance dietary variety, and stabilize income streams. This diversification ensures that households are less susceptible to disease outbreaks or climatic shocks affecting a single species. Furthermore, breed selection guided by indigenous criteria prioritizes animals inherently adapted to local climatic and ecological conditions, thereby improving the overall productivity, resilience, and sustainability of livestock production. Climate-informed feeding schedules, which align livestock nutrition with the seasonal availability of fodder and water, help maintain animal health and productivity throughout the year, supporting consistent nutritional security for households reliant on livestock products (Egah *et al*., 2023; Dzviti *et al*., 2023; Assan, 2025) [19, 18, 5].

Indigenous preservation and storage techniques, including sun-drying, fermentation, and smoking, play a vital role in reducing post-harvest losses and prolonging the shelf life of animal products. These methods not only ensure food availability during periods of scarcity but also enhance the sustainability of the food system by minimizing waste and preserving the quality and safety of animal-derived foods. The application of these preservation practices reflects the interconnectedness of energy, food, and health within the CWEH–F nexus, demonstrating how IKS reinforces system resilience and supports sustainable livelihoods. By integrating traditional knowledge with contemporary approaches, smallholder communities can enhance food

utilization efficiency, safeguard nutritional outcomes, and build adaptive capacities to withstand environmental and economic challenges (Tirivangasi & Rankoana, 2021; Aworh, 2023) [6]. This comprehensive strategy highlights the significance of safeguarding indigenous knowledge as a valuable addition to enhancing food security and resilience in smallholder livestock systems.

4.7. Gender and Sociocultural Dimensions

Gender dynamics shape the cultivation and application of IKS in livestock management. Women specialize in small livestock, such as poultry and goats, applying detailed knowledge of nutrition, breeding, and health, which supports household nutrition and income. Men focus on large livestock, such as cattle and camels, using distinct management practices. This complementary division diversifies livelihoods and enhances community resilience by expanding adaptive strategies. Recognizing these gendered roles is vital for sustainable livestock interventions in Indigenous communities (Huyer *et al*., 2021; Assan, 2023) [30, 4]. Integrating gender-responsive approaches within the CWEH–F framework promotes equitable access to resources, decision-making, and benefits. Addressing barriers that disproportionately affect women ensures inclusive governance and strengthens IKS resilience, improving climate adaptation, livestock sustainability, and food security. Gender-sensitive interventions are thus crucial for leveraging Indigenous Knowledge toward community well-being and environmental sustainability (Lecoutere *et al*., 2023; Mapedza *et al*., 2025).

5. Conclusion

This review synthesizes the vital role of IKS in strengthening sustainability and resilience among smallholder livestock communities in Sub-Saharan Africa. It situates IKS within the integrated climate–water–energy–health–food nexus, highlighting the need for holistic, context-specific approaches. By embedding IKS within the CWEH–F nexus, this study illustrates the interconnectedness of resource systems and the necessity for integrated, context-specific strategies. The research demonstrates that IKS is instrumental in climate adaptation, water management, energy efficiency, health systems, and food security. Nevertheless, its full potential is hindered by limited policy integration, gender disparities, and insufficient acknowledgment within formal development frameworks. To foster sustainable livestock-based livelihoods, it is crucial to implement inclusive, gender-responsive, and interdisciplinary strategies that merge indigenous and scientific knowledge systems. Policymakers, researchers, and practitioners must collaborate to co-create knowledge, bolster institutional support, and encourage innovative solutions that draw on both traditional and modern practices. Ultimately, weaving indigenous knowledge into the CWEH–F nexus offers a transformative route toward resilient, equitable, and sustainable livestock systems in Sub-Saharan Africa.

Key Highlights

- IKS supports smallholder livestock systems through locally adapted strategies for herd management, climate risk mitigation, and resource utilization.
- The integration of IKS within the CWEH–F nexus underscores the interdependence of these elements in smallholder livestock production landscape.
- IKS enhances resilience by facilitating climate adaptation, promoting sustainable water and energy use, and improving both animal and human health, as well as food security. However, significant constraints persist, including inadequate policy recognition, limited institutional integration, and gender inequality.
- Sustainable livestock development requires participatory, interdisciplinary, and gender-responsive approaches that amalgamate indigenous scientific knowledge.
- Collaboration among policymakers, researchers, and practitioners is crucial for co-producing knowledge and bolstering institutional support.
- Embedding IKS within the CWEH–F nexus offers a pathway toward resilient, equitable, and sustainable livestock systems in sub-Saharan Africa.

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How to Cite This Article
Assan N. Integrating indigenous knowledge into the climate–water–energy–health–food nexus for sustainable smallholder livestock livelihoods in Sub-Saharan Africa. Global Multidisciplinary Perspectives Journal. 2026 Mar–Apr;3(2):56–66. doi:10.54660/GMPJ.2026.3.2.56-66.