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Integrating Indigenous and Scientific Soil Knowledge for Climate-Resilient Environmental Management in Smallholder Agriculture

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ABSTRACT

Climate change is placing increasing strain on smallholder agricultural systems, as described in recent literature, particularly in semi-arid areas with land degradation, soil decline, and climate variability. In these settings, land serves as a critical juncture linking environmental processes, agricultural production, and human decision-making. Although scientific land-use and soil-management approaches rely on measurable, scalable solutions, they often lack consideration of local variations and socio-economic factors. Whereas indigenous knowledge based on land knowledge offers contextual and experiential perspectives yet is rarely incorporated into formal adaptation models. This research uses a conceptual integrative approach by integrating and meshing indigenous knowledge with science for soil and land management for climate adaptation. By studying knowledge systems across various agroecological systems, the study explores areas of overlap and difference between these approaches. These findings highlight the complementary importance of indigenous and scientific perspectives in explaining soil processes. Indicators discovered within indigenous practices, including soil color, plant composition, and biotic activity, map onto scientific indicators such as soil organic carbon, nutrient status, and physical properties. However, the convergence of these knowledge systems is hampered by bureaucratic, policy, and implementation barriers. To overcome such barriers, this study presents the co-created land-based adaptation framework under three domains: indicator integration, practice integration, and scale integration. This framework provides an interpretable, realistic process for integrating traditional and modern indigenous forms of knowledge to improve land and soil management practices in times of climate change. The framework's focus on linking local relevance with scientific rigor aims to develop climate-resilient, context-sensitive, and inclusive agricultural systems.

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1. Introduction

Climate change is increasingly recognised as a significant threat to the sustainability of agriculture, particularly within smallholder farming systems in sub-Saharan Africa. In semi-arid and rural regions such as the Eastern Cape of South Africa, rising temperatures, erratic rainfall, and prolonged droughts exert considerable pressure on already vulnerable agricultural systems, resulting in declining soil productivity and threatening rural livelihoods (Niang et al., 2017). These climatic pressures not only reduce agricultural productivity but also accelerate soil degrade through erosion degradation through erosion biological activity and reduced water holding capacity (Shafiq et al., 2021). As a result, the ability of soils to support crop production and buffer climatic shocks is increasingly compromised, particularly in resource constrained smaller farming systems (Lal, 2015).

Under these conditions, soils function as active agents in climate adaptation by influencing water retention, nutrient cycling, and carbon storage, all of which are critical for crop resilience and productivity (Lal, 2015). Soil health is closely linked to biological processes, particularly microbial activities that support nutrient cycling and ecosystem functioning. Inevitably, there is neglect of indigenous soil conservation practices, leading to further negative impacts on soil microbial communities, which destabilise ecosystems and reduce agricultural sustainability (Matsapa & Thelma, 2025). While soil systems are an important aspect of climate adaptation, most climate change adaptation efforts have been based on input- and technology-led policies that have focused on improved crop varieties, fertilisation, and irrigation. Science-based approaches like Integrated Soil Fertility Management (ISFM) optimise soil productivity by integrating mineral and organic inputs and refining agronomic practices to suit local micro-environments (Otieno & Adamtey, 2021; Vanlauwe et al., 2014).

While these approaches have contributed to significantly to improving agricultural productivity. They are often implemented through top-down and technocratic frameworks that insufficient account for local environmental variability, farmer experience, and socio-economic realities. Consequently, scientific recommendations may lack contextual relevance, reducing their effectiveness and adoption among farmers. Yet these strategies tend to be deployed under top-down, technocratic frameworks that do not sufficiently consider the socio-economic realities and lived experiences of smallholder farmers. Additionally, many soil management programs are still based on Western-centric approaches, use coarse soil data and generic recommendations, and lack farmer involvement in program design.

This disconnect between scientific foundations and practical reality is compounded by the fact that indigenous indicators and local soil classifications are given only weak input into extension and decision-support systems (Kuria et al., 2019; Matsapa & Thelma, 2025; Snapp, 2022). In contrast to scientific knowledge, which is based on systematic observation, experimentation, and empirical verification, indigenous knowledge is cumulative and experiential, transmitted through generations of experience with the land and society (Hualpa et al., 2025). For example, soil fertility is assessed by soil colour, texture, vegetation patterns, and biological activity indicators such as earthworms, all of which provide inexpensive, location-specific approaches to managing farmland (Hualpa et al., 2025).

These indicators facilitate real-time assessment of soil characteristics, thereby informing crop selection and supporting adaptation to environmental changes. However, indigenous knowledge systems are increasingly being undermined. In addition to limited access to land and declining youth engagement in agriculture, the expanding role of input-intensive agricultural systems is undermining intergenerational knowledge transfer (Melash et al., 2023; Mishra et al., 2025). This loss hampers locally rooted soil management practices and diminishes the adaptation ability of smallholder systems to climate change.

An emerging body of literature indicates a marked convergence between indigenous and scientific soil knowledge. For instance, Hualpa et al. (2025) found that farmers' observations of soil texture corresponded well with classifications established by traditional research, in which each group, as measured (with less than 10% difference in descriptions), perceived soil texture. A correlation with measured crop plant behaviours, soil colour, vegetation patterns, and biological activity, as observable indicators, was also associated with soil property measures such as soil organic carbon.

The review indicates the importance of indigenous knowledge systems as an augmentation to scientifically based soil analysis and the need for integrated, co-produced approaches in adaptation to climate change. Despite this convergence, indigenous and scientific knowledge systems are still often characterized to be distinct or hierarchical in agricultural policy and practice. Standardisation and empirical foundation for scientific knowledge tend to be prioritised, while indigenous knowledge is excluded from formal extension processes (Mapfumo et al., 2013; Pretty, 2011). Such disconnect hampers the effectiveness, uptake and sustainability of climate adaptation policies, especially in resource-poor smallholder areas (Nazir et al., 2023).

Consequently, a critical gap remains in climate adaptation research and practice. Although both indigenous and scientific knowledge systems contribute valuable insights into soil management. There remains guidance on how these knowledge systems can be systematically integrated to support climate-resilient agriculture. Existing adaptation frameworks tend to support climate or indigenous approaches, with few providing structured mechanisms for knowledge coproduction, joint decision making and integrated soil management.

Moreover, the failure to integrate soil into farm production as an essential resource may lead to land degradation and poor agricultural yields, in which not only scientific advice but also local knowledge is underappreciated or poorly integrated (Hualpa et al., 2025). Scientific methods offer precision and are generally scalable, but they are constrained by access, including cost, limited extension services, and a lack of contextualisation. Conversely, indigenous knowledge systems might be locally embedded and readily available but may not be codified within formal agricultural planning processes.

The constraints of scientific approaches to soil management in semi-arid areas highlight the necessity for an integration framework. This research addresses these limitations by presenting a three-part framework integrating indicators, practices, and scales. The suggested framework aspires to transcend the isolated application of indicators and methods, enabling their symbiotic use and better adaptation to climate change. Prior research has acknowledged the importance of indigenous knowledge in agriculture alongside the role of scientific methods in soil management; however, it often lacks a cohesive strategy for merging these viewpoints.

This study intends to address this gap by developing a comprehensive framework that fuses traditional agricultural knowledge with contemporary scientific techniques. The objective of this research is to establish a more comprehensive and effective soil management methodology that serves both farmers and the environment. Central to this framework is the recognition of land as pivotal to climate change adaptation, proposing the integration of indicators, practices, and scaling as means to connect knowledge systems, enhance soil management, and bolster resilience within smallholder farming systems.

While the advantages of integrating indigenous and scientific knowledge systems are well recognised, implementation remains limited. Policy and practice areas that lack integration of local soil indicators, such as local soil biota and context categorisations into the formal soil assessment framework and climate adaptation strategy, exist (Hualpa et al., 2025; Kuria et al., 2019). This highlights a significant gap in current adaptation strategies. Within this context, the present study proposes a framework to integrate indigenous and scientific soil knowledge systems to advance climate adaptation. The research aims to improve soil management, enhance agricultural resilience to climate risks, and strengthen livelihoods in climate-vulnerable smallholder farming systems through a co-produced, participatory approach. Objectives are given below:

1. To examine the role of indigenous soil knowledge and scientific approaches in supporting climate adaptation and sustainable management within smallholder agricultural systems.
2. To identify areas of convergence and divergence between indigenous soil indicators and scientific soil assessment.

3. To examine the key barriers and opportunities influencing the integration of indigenous and scientific soil knowledge.
4. To develop a coproduced Soil Systems Adaptation Framework (SSAF) that integrates indigenous and scientific knowledge systems.

2. Soil Indicators

2.1. Scientific Soil Indicators and Climate Adaptation

Scientific soil approaches to agriculture are a critical element of climate change adaptation, as they offer systematic, quantifiable, and standardised methods to study soil processes and to apply management strategies to soil resource management, considering changes resulting from climate change (Yang et al., 2024). Such approaches are rooted in empirical assessment of physical, chemical and biological properties of soil, and, as such, are used to identify the main constraints (e.g., nutrient deficiencies, soil acidity, salinity, and structural deterioration) that impact plant productivity and resilience (Lal, 2015).

The importance of soil health as a central vehicle for climate-resilient and productive farming systems, as a matter of soil characteristics that can be quantified, is gaining more importance in the scientific literature for directly addressing crop performance in the presence of climate stress (Kabato et al., 2025; Maqbool et al., 2025; Shafiq & Zafar, 2023). Increasing literature evidence indicates a relationship between poor soil traits, crop yield, and climate resilience. Elevated Soil Organic Carbon (SOC) and higher soil quality have been reported to be protective for crop yield loss and variability under climate warming and environmental variability, as well as enhancing average cereal and maize yields and maintaining the stability of crop yield in different agroecological contexts (Chen et al., 2024; Deng et al., 2023; Qiao et al., 2022). SOC is significant for soil structure improvement, water-holding capacity, nutrient cycling, and microbial activity, which, under climate change, contribute to more stable and productive agriculture (Maqbool et al., 2025; Rashmi et al., 2024).

Review evidence from Climate-Smart Agriculture (CSA) systems, however, suggests that practices such as zero tillage, residue retention, and crop diversification yield much larger increases in SOC stocks and biological activity than conventional systems (Jat et al., 2019). Soil physical properties, such as texture, field capacity, bulk density, aggregate stability, porosity, and pore structure, are also important in controlling crop responses to climatic extremes, along with chemical characteristics. Good soil structure enables infiltration, reduces erosion, and improves water-holding capacity, thereby buffering crops from drought and extreme (high-intensity) rainfall (Francaviglia et al., 2023; Qiao et al., 2022; Rashmi et al., 2024; Veettil et al., 2024).

These physical improvements will be needed to remain productive amid increased climate variability. Yet climate change is also accelerating soil degradation, which restricts agricultural productivity. These are organic matter depletion, soil erosion, nutrient deficiency, acidification and salinisation, among other factors that decrease soil function and resistance (Jat et al., 2019; Kabato et al., 2025; Maqbool et al., 2025; Rashmi et al., 2024; Xing et al., 2025). These challenges are especially pronounced in arid and semi-arid systems, where low SOC, poor soil structure, salinity, and wind erosion threaten nutrient availability and long-term productivity.

To better address these limitations, specific soil management methods, including residue management, soil amendments, and water management (irrigation and drainage optimisation), may be used (Kabato et al., 2025). It is therefore important that scientific soil management practices identify conservation and climate-smart agriculture as one of the main adaptation strategies. The methods comprise reduced or zero tillage, cover cropping, residue retention, varied crop rotation, biochar application, and agroforestry that rehabilitate soil function, improve carbon sequestration, and strengthen resilience to climate stress (Francaviglia et al., 2023; Maqbool et al., 2025; Rashmi et al., 2024).

Collectively, these practices aim to promote better soil physical, chemical, and biological properties to better support sustainable agricultural cultivation under changing climatic conditions (Bhatti & Shafiq, 2025). Soil science has also improved diagnostics and measurements of soil limitations by leveraging analytical and technological methods. Because of the increased use of Remote Sensing (RS), proximal soil sensors, bioinformatics, molecular methods, deep learning and other kinds of techniques, assessing soil features, detecting salinity, tracking nutrient availability and tracking trends in soil degradation to multiple scales is becoming essential (Li et al., 2025; Sahbeni et al., 2023; Xing et al., 2025).

Such tools provide a quick, scalable means to evaluate and manage soils in an evidence-based manner for climate adaptation. Yet these technologies and scientific methodologies, however accurate and statistically sound, have many limitations; these are mainly specific to the smallholder farming system. Access to soil testing, advanced technologies, and extension services is often limited by financial, infrastructural, and institutional constraints (Otieno & Adamtey, 2021; Vanlauwe et al., 2014). Moreover, there are costs and issues related to data quality and the integration of technical outputs into the decision-making support system, which limit the widespread adoption of these tools, particularly at scale in vulnerable areas (Li et al., 2025; Sahbeni et al., 2023).

In addition, scientific soil principles often rely on top-down frameworks that are poorly adapted to the microscale variability of soil and control the naturalness of local management practices, while technological transformation can provide new pathways for improving environmental sustainability (Yang et al., 2025). The current approach, based on available data, is not sufficiently effective to be meaningful in practice; it is limited by the need for improved digital resources for sustainability measures, monitoring, and quality assurance (Sahbeni et al., 2023; Vanlauwe et al., 2014). Standardised classifications and coarse-scale data are used to compare the same inputs, but this can overlook micro-variations that are important for farm-wide decision-making (Snapp, 2022).

Therefore, although scientific approaches have important diagnostic precision and scalability, their ability to facilitate climate adaptation is typically constrained by accessibility, contextual relevance, and adoption. Hence, the evidence supports an effective and meaningful connection between scientifically assessed soil health and climate adaptability, as documented in the literature. These methods that promote soil organic carbon and physical and biological characteristics increase resilience to climate variability. These methods would still have to be adapted to local soils, climatic conditions, and farmers' capabilities to be effective (Francaviglia et al., 2023; Kabato et al., 2025; Rashmi et al., 2024). Scientific approaches, coupled with contextualised management models, policy actions, and farmer training, can translate diagnostic precision into climate-resilient and inclusive agricultural systems.

2.2. Limitations of Scientific Soil Management

When indigenous knowledge is not integrated with scientific soil management practices, the uniform application of these practices across various soil types can prove ineffective. This often results in poor agricultural yields and, in some cases, the abandonment of cultivated fields, which may contribute to soil degradation. Semi-arid soils, in particular, are highly sensitive and cannot be effectively managed with a one-size-fits-all approach. Therefore, it is essential to combine scientific soil management with indigenous soil knowledge to enhance soil health.

Semi-arid systems pose significant biophysical and agroecological challenges to the effective implementation of soil management practices. Many soil-enhancing methods depend on adequate plant growth to provide residues, root biomass, and organic inputs; however, in these systems, biomass production is frequently insufficient at scale (Ghimire et al., 2022). Reduced net primary production, attributed to limited water availability, results in lower carbon inputs into the soil, complicating efforts to maintain increased soil organic carbon levels. Even with additional residue inputs, long-term carbon retention remains constrained, as these environments often lack the physical mechanisms needed to safeguard stored carbon (Ghimire et al., 2022).

In semi-arid regions, the combination of low and unpredictable rainfall significantly undermines the effectiveness of nutrient-based soil management. This often results in negative plant-nutrient balances, reduced nutrient use efficiency, and inconsistent crop responses to fertilizers, especially in contexts where the quantity, timing, and distribution of rainfall are frequently inadequate (Bhagwan et al., 2025). Additionally, chemical constraints on crop growth are just as critical as physical limitations; semi-arid soils are commonly shallow, nutrient-deficient, mechanically unstable, and prone to degradation from intense rainfall events, which cause excessive runoff and erosion due to poor soil structure and insufficient ground cover, leaving the soils exposed. This persistent issue of water scarcity, combined with episodic physical disturbances, necessitates that effective scientific soil management address both challenges, thereby potentially compromising the long-term efficacy of traditional agronomic interventions (Bhagwan et al., 2025).

In semi-arid regions, scientific soil management faces methodological problems, as many practices recommended on the basis of scientific soil indicators are ineffective when applied in isolation. For example, in semi-arid systems, no-till practices alone usually yield only modest improvements in soil quality, unless combined with appropriate crop rotation and residue management (Kangela et al., 2025).

In semi-arid regions, scientific soil management strategies are hampered by socio-economic and institutional barriers, such as high economic risk, which discourage farmers from implementing even beneficial soil management practices when yields are uncertain, as well as factors that make it difficult to predict investment outcomes (Kuria et al., 2019). Investments in soil management often involve a high economic risk for farmers, as yields are uncertain and practices which theoretically improve soil may not be economically viable unless the gains are sufficient to offset the costs. Mechanic protection structures such as terraces and related activities may reduce erosion, but often require considerable labour, time, land, inspections and materials. Moreover, many recommendations are formulated in too abstract terms and many farmers will be reluctant to take soil fertility and soil protection measures if the guidelines are not provided in terms of context or if the extension services promote a uniform approach (Mutio et al., 2025).

2.3. Indigenous Soil Knowledge and Local Indicators

Indigenous soil knowledge is vital in smallholder farming systems in a range of agroecological landscapes. Farmers rely on accumulated, experience-based understanding to assess soil quality, inform land-use decisions, and adapt to environmental changes. This understanding evolved through prolonged environmental contact and is transmitted across generations, adapting to changing climatic, ecological, and socio-economic contexts. Indigenous knowledge is accumulated and experiential, while scientific knowledge is based on systematic observation, experimentation, and empirical validation (Hualpa et al., 2025).

Farmers assess the quality of soil based on a wide spectrum of visible physical indicators, including but not limited to soil colour, texture, structure, depth, stoniness, workability, moisture status, slope position, and visible evidence of erosion (Jiménez et al., 2022; Kuria et al., 2019; Rankoana, 2023a; Yageta et al., 2019). In addition, they utilise these indicators consistently to discriminate between fertile and degraded soils and to guide agricultural decisions, including crop selection, input allocation, and land-use practices, as demonstrated by studies from Ecuador, Rwanda, Kenya, India, Bhutan, Ethiopia, Nepal, and South Africa (Jiménez et al., 2022; Lal et al., 2024; Yageta et al., 2019). Farmers often equate dark or black soils with more fertility and greater crop yields. This perception tends to be linked with higher soil organic carbon and nutrient availability as substantiated by laboratory studies (Jiménez et al., 2022; Lal et al., 2024; Yageta et al., 2019).

In contrast, pale, yellowish, or sandy soils are commonly identified as degraded, nutrient-poor, and less suitable for crop production (Jiménez et al., 2022; Yageta et al., 2019). Soil texture and related physical characteristics are particularly important in shaping farmer decision-making. Farmers use texture (e.g., fine versus coarse soils) and associated properties such as moisture retention, cracking, ponding, and ease of tillage to infer water-holding capacity, workability, and crop suitability (Jiménez et al., 2022; Lal et al., 2024; Yageta et al., 2019).

These assessments form the basis of farmer-developed soil quality indices and strongly influence the spatial placement of crops and inputs within fields. Because such evaluations are conducted at field and sub-field scales, they enable farmers to capture fine-scale soil heterogeneity that is often overlooked by standardised scientific classifications and coarse-resolution soil maps (Nuwategeka & Nyeko, 2019). Comparative studies further indicate that, while there is generally strong agreement between indigenous and scientific soil evaluation systems, farmer-based approaches often provide greater sensitivity to micro-variations directly relevant to management decisions (Nuwategeka & Nyeko, 2019; Wawire et al., 2021; Yageta et al., 2019).

Taken together, these studies illustrate that indigenous soil assessment are not simply descriptive categorizations, but represent complex, site-specific soil assessment methodologies, with farmers across different agroecological regions using similar physical indicators to evaluate fertility, productivity, and land suitability, and that indigenous assessments are more effective at capturing fine scale spatial variability that is often missed by broader scientific classifications, thus supplying information that is directly applicable to the farm scale.

Indigenous soil knowledge systems are rooted in biological and ecological indicators at a deeper level than physical properties. Thus, for farmers, the signals of soil fertility and degradation, such as vegetation patterns, indicator plants, weeds, crop vigour, and yield performance, are perceived through an important lens (Kuria et al., 2019). In Rwanda, for instance, farmers use indicator plants, crop vigour, and crop residues to provide immediate feedback on soil fertility and land productivity that they can use to inform real-time assessment of the extent of degradation (Kuria et al., 2019). Vegetation performance and crop yield are among the most frequently used indicators of soil health across the African Highlands and greatly influence land management decisions (Eze et al., 2021).

Review evidence from Ecuador and Ghana further shows that farmers use crops, weeds, and yield outcomes as primary indicators of soil condition, with certain weed species associated with degraded or low-fertility soils (Álvarez et al., 2021; Ansong Omari et al., 2018). In Niger, farmers identify multiple indicator species, using the presence or absence of specific non-woody plants to classify soils by fertility status (Manssour et al., 2021). Soil fauna, particularly earthworms and other macrofauna, are also widely recognised as indicators of biologically active and fertile soils (Rankoana, 2023b). There is ample empirical evidence that farmers have comprehensive knowledge of soil organisms and their relationships to soil quality. For example, farmers in Rwanda identified more than 20 soil macrofaunal species and used their presence or absence as a key indicator of soil fertility, with bare soils lacking fauna interpreted as highly degraded (Kuria et al., 2019). Indeed, in Honduras, they can differentiate several macrofauna taxa, including earthworms and beetle larvae, with specific indicators about soil fertility and crop performance (Pauli et al., 2016).

The broader literature supports the idea that farmers in several places have in-depth local soil taxonomies of soil biota and regularly use soil biological activities as a primary indicator of soil health (Ansong Omari et al., 2018; Manssour et al., 2021; Pauli et al., 2016). Amid these studies, the biological indicators are intimately related to important functions such as nutrient supply, organic matter situation and water movement of the soil, showing how locally-based soil knowledge and concepts are essentially biophysical: combining the ecological, as well as the physical aspects of a soil system (Kuria et al., 2019; Zapico et al., 2024).

One pattern that becomes apparent during the literature review is that soil knowledge is not just about physically knowing, but biological and ecological information. Although the nature of indicator species differs from region to region, agriculture producers invariably relate vegetation performance, biological activity, and soil fauna with soil fertility and ecosystem function. This seems to suggest that indigenous soil evaluation may be holistic and the measurement of factors that influence soil health, beyond the soil quality, needs to be viewed from multiple perspectives including ecological context. This unified understanding enables farmers to construct context dependent soil classification systems e.g. "black soils", "red soils" and "salty soils" being more readily connected to fertility, salinity and crop appropriateness (Jiménez et al., 2022; Rankoana, 2023a).

Consequently, Indigenous soil knowledge is not only descriptive but also functional, informing many land management practices such as composting, manuring, residue management, fallowing, agroforestry, and contour farming (Huynh et al., 2022). Practising these core principles of climate adaptation within smallholder systems, where farmers apply this information to crop types and cultivation for soil types, soil moisture retention, and conservation measures that reduce the influence of irregular rainfall and soil degradation (Kuria et al., 2019; Rankoana, 2023b; Zapico et al., 2024). Such practices are generally low-cost, locally replicable, and highly adaptable in settings characterised by constrained resources.

The literature shows that indigenous and scientific soil knowledge systems converge in significant ways. Farmer assessments of soil properties (especially texture, colour and overall fertility) and laboratory-based measurements of soil organic carbon, nutrient content, bulk density and salinity consistently produce similar results (Buthelezi & Modi, 2013; Hualpa et al., 2025; Jiménez et al., 2022; Kuria et al., 2019). But this convergence is not universal. Divergence is most commonly observed in complex chemical characteristics, and farmers' perceptions may be insufficient to capture underlying soil processes (Ansong Omari et al., 2018; Buthelezi & Modi, 2013; Jiménez et al., 2022).

Yet the literature also notes areas of divergence. As indigenous indicators focus on the visible and functional aspects of soil quality, they are less effective at detecting nuanced chemical dynamics, such as micronutrient deficiencies, salinity levels, and subtle pH variations. These contradictions suggest diverse but complementary strengths within indigenous and scientific knowledge systems, reinforcing the argument in integration rather than substitution. Indigenous soil knowledge, however, faces an increased threat despite its essential role. Globalisation, input-intensive agricultural practices, and socio-economic changes, such as limited land availability and youth disengagement from agriculture, are weakening intergenerational knowledge transfer (Melash et al., 2023; Mishra et al., 2025).

In addition, Western-centric agricultural models often overshadow indigenous knowledge systems, preventing their incorporation into formal policy and extension frameworks (Matsapa & Thelma, 2025). This context-specific knowledge is relevant, adaptable, and accessible, and there is growing awareness of the need to combine indigenous soil knowledge with scientific methods. Such integration supports the co-production of systems of knowledge, where local experiences are interdependent with scientific knowledge, resulting in more viable, site-specific, and widely available climate adaptation approaches (Hualpa et al., 2025; Kuria et al., 2019).

2.4. Limitations and Complementarity of Indigenous Soil Knowledge

A proper assessment of ISK, when used, is necessary to highlight its limitations, even though it is an excellent basis for climate change adaptation and sustainable land management. Indigenous knowledge is context-dependent, having been developed through long-term interactions by communities and their local environments (Hualpa et al., 2025; Rankoana, 2023b). While this contextual framing enhances the relevance of the indicators to local decision-making, it may constrain how these indicators and the management approach can be transferred to other agroecological and socio-cultural settings. As a result, extremely effective knowledge systems in one location may need to be modified and verified before transfer to other locations.

Moreover, native soil assessments are dominated by such physical measurements as colour, texture, plant diversity, crop performance and biological activity in soil (Hualpa et al., 2025; Rankoana, 2023a). Although these measures often map closely to soil quality indicators developed by science, they suffer from the partial nature of subjective interpretation, rendering them inadequate to detect intricate soil processes such as micronutrient deficiencies as well as salinisation, toxicity, and slight alterations to soil chemistry that need laboratory testing (Ansong Omari et al., 2018; Jiménez et al., 2022). Also, indigenous knowledge systems are increasingly threatened by urbanisation, modified livelihood practices, decreased youth participation in agriculture, and the expansion of input-intensive farming systems, which reduce intergenerational knowledge transmission (Melash et al., 2023; Mishra et al., 2025).

The knowledge base of indigenous peoples, though largely oral and dynamic, also constrains documentation, standardisation, and incorporation into formal agricultural extension and policy (Mapfumo et al., 2013). These limitations do not undercut indigenous soil knowledge, though it is important to note. Instead, they validate the importance of integration with scientific knowledge systems. Indigenous knowledge yields fine-grained, contextual information and on-the-spot environmental observations and scientific approaches offer diagnostic accuracy, standardisation and broader relevance. Accordingly, the Soil Systems Adaptation Framework (SSAF) promotes complementarity rather than substitution, and focuses on co-production of knowledge that leverages the strengths of the two systems to drive climate adaptation, sustainable land management practices, and resilient smallholder agricultural systems.

3. Methodology

3.1. Research Design

This conceptual research design aims to develop a model for integrating indigenous and scientific soil knowledge systems for climate-resilient environmental management in the context of smallholder production systems. Conceptual articles are important tools for theory-building and development, particularly when they integrate existing knowledge and are based on a purposeful study design rather than new empirical evidence (Jaakkola, 2020). This study followed a model-type conceptual research design, which integrates and structures previous research into a novel framework (Jaakkola, 2020). The study was inspired by the growing awareness that climate adaptation for smallholder systems requires context-specific strategies that incorporate both indigenous and scientific knowledge rather than relying on either alone (Apraku et al., 2021; Jaakkola, 2020).

3.2. Sampling

The framework was developed from a thorough review of the literature, including peer-reviewed articles, reports, and policy-relevant studies on indigenous soil knowledge, scientific soil assessment, climate adaptation, soil health, sustainable land management, and smallholder agriculture. Critical entry points were reviews and empirically-based studies of indigenous knowledge and adaptation to climate change in African smallholder systems (Mapfumo et al., 2015). To allow for gathering input from varying agroecological and socio-cultural settings, studies on sites or regions within Africa and other areas where smallholders are highly dependent on local indicators and practices were deliberately selected (Apraku et al., 2021). In particular, emphasis was placed on indigenous soil indicators and farmer classifications, scientific soil health metrics, climate-smart agriculture, and knowledge co-production or integration (Chamasula & Rabumbulu, 2024).

3.3. Thematic Synthesis and Concept Development

The literature was then organised and interpreted utilising a thematic synthesis approach. Thematic synthesis involves the process of coding, development of descriptive themes, and formation of analytical themes that serve to "go beyond" primary studies while generating novel concepts and explanations (Thomas & Harden, 2008). The synthesis was guided by three different analytical foci. Initially, studies were analysed to isolate indigenous indicators commonly used by farmers to assess soil quality and environmental change (e.g., soil colour, structure, and biological indicators) (Chamasula & Rabumbulu, 2024). Second, scientific approaches to soil assessment and climate adaptation were examined for their strengths and limitations (Sohad & Mafrolla, 2025). Third, a literature review of the integration of both Indigenous and scientific knowledge was conducted in light of the challenges and opportunities of co-production (Chamasula & Rabumbulu, 2024). These categories were distilled into three main domains of integration through iterative comparison: Indicator Integration, Practice Integration, and Scale Integration.

This aligns with the analytical themes that generate new conceptual constructs from qualitative syntheses (McMahon et al., 2022). Indicator Integration encompasses applications that combine farmer-used soil indicators with laboratory and instrumental measures; Practice Integration examines ways to align indigenous management practices with climate-smart interventions; and Scale Integration interconnects local observations with GIS, remote sensing, and climate information systems (Chamasula & Rabumbulu, 2024; Partelow, 2018).

3.4. Framework Development

The Soil Systems Adaptation Framework (SSAF) was developed by integrative synthesis, with existing theories and empirical findings serving as a basis for a new conceptual model. This is similar to model-type conceptual papers, which connect and structure existing work into a coherent framework that aims at explanatory clarity (Lindgreen et al., 2021). In the SSAF, soil plays a paramount role in the intermixed interactions of environmental processes, agricultural practices, and knowledge systems, similar to that found in general social ecological frameworks that place biophysical subsystems at the centre of human–environment interactions (Partelow, 2018; Wang et al., 2025). The framework also explicitly acknowledges farmers, researchers, extension services, and policy institutions as co-producers of knowledge, in accordance with relevant scholarship on integration of multiple knowledge systems for adaptation (Apraku et al., 2021; Sohad & Mafrolla, 2025). The framework addresses this noted gap: although there are numerous social-ecological and knowledge-integration frameworks, there is a lack of operational guidance on how to systematically integrate indigenous and scientific knowledge across indicators, practices, and decision-making scales in smallholder climate adaptation (Chamasula & Rabumbulu, 2024; Partelow, 2018).

3.5. Framework Contribution

The SSAF provides a theoretical framework to guide future empirical research, policy development, and climate adaptation planning in smallholder systems, echoing the role to be played by strong conceptual frameworks in social and applied research (Lindgreen et al., 2021; van der Waldt, 2020). Integrating indigenous and scientific knowledge, this article seeks to contribute to sustainable land management and greater resilience in smallholder agriculture, consistent with the call for hybrid or syncretic agronomic knowledge enabling climate adaptation (Apraku et al., 2021; Mapfumo et al., 2015).

4. Discussion

4.1. Integration of Indigenous and Scientific Soil Knowledge Systems

This section covers the Framework's implementation, particularly looking at its application in the context of the Framework's strategies in relation to existing systems. It also explores and scrutinises the potential contributions and policy implications of the Framework from a policy-making perspective, as well as crucial policy areas for aligning the policy goals with the Framework for successful implementation. In addition, this chapter focuses on potential barriers to the use of the Framework, e.g., resource constraints, stakeholder willingness, and institutional unwillingness. It is important to identify these issues to propose effective solutions for greater uptake. The role of agricultural extension services is considered, specifically how they promote farmers' and stakeholders’ understanding and application of the Framework. Support services of the extension service, as support services bridge the gap between research and implementation and are the only means by which the benefits of the

Framework are realised at a local level. The purpose of this study is to identify lessons for better implementing the Framework across different settings.

4.1.1. Re-imagining Integration: From Parallel Systems to Co-Production

Soil knowledge systems within Indigenous and scientific communities have traditionally been seen as parallel or hierarchical, with scientific knowledge often prioritised for incorporation into agricultural policy and extension practices. With systems operating in smallholder communities where local context and variability determine many climate adaptation efforts, this maintains the separation of the two approaches and thus limits their effectiveness. It is hoped that we can shift to co-produced knowledge systems that combine Indigenous and scientific knowledge through collaboration among farmers, researchers, and institutions (Hualpa et al., 2025; Kuria et al., 2019). Co-production is more than the inclusion of Indigenous knowledge; it involves mutual validation, shared problem-solving skills, and solutions tailored to the local context. This method considers farmers as a necessary source of knowledge, and it places scientific tools not as the dominant but complementary tool.

4.1.2. Complementarity of Soil Indicators: A Biophysical Integration Approach

Indigenous and scientific soil indicators should be integrated for their complementary nature. These measures emphasise visible physical and biological features we can observe, such as the colour of the soil itself and the distribution of plant and animal life in that soil (indigenous measurements). In contrast with other empirical methods, scientific approaches rely on measurements based on laboratory results, such as soil organic carbon, nutrient status, and physical structure. This study uses a biophysical integration perspective and integrates these indicators form an integrated approach to assessment. Observable indicators provide fast, cost-effective, and geographically detailed information, whereas scientific measurements enable accuracy and quantification. The integrated approach provides a broader, more practical view of the soil system, accounting for both ecological processes and quantifiable aspects (Hualpa et al., 2025; Jiménez et al., 2022; Kuria et al., 2019).

4.1.3. Soil Management Practices for Climate Adaptation

Integration is evident in the blending of indigenous management methods with climate-smart, science-based methods. Composting, manuring, agroforestry, residue retention, and crop diversification are widespread practices among farmers. This accords with both conservation approaches and climate-smart tactics to increase organic carbon accumulation. Integration should not supplant indigenous practices; they should be supported and maximised through scientific understanding: soil testing, nutrient management, and carbon monitoring, for sure. This presents a hybrid model that is locally based and science-based.

4.1.4. Integration at Multi-Scale: Connecting the Fine-Scale and Scientific Mapping

However, there are many challenges in the existing soil management approaches the most relevant being the inconsistencies between the analysis scales. Scientific soil analysis generally takes place at much broader geographic scales, using standardised classifications and remote sensing techniques, while regional knowledge accounts for smaller-scale differences at the field and sub-field scales. A new integrated model of multi-scale analysis is then proposed, which integrates scientific methods of GIS, remote sensing and soil testing along with farmer-level assessment. This integration of the two aims to increase spatial validity and decision-making utility. It allows pinpointing micro-variation in soil properties and thus targeted management, which is important, particularly where smallholder systems are heterogeneous (Nuwategeka & Nyeko, 2019; Snapp, 2022).

It would increase integration through the combination of knowledge and practices to bridge the gap between silos. Institutional biases have a way of privileging scientific knowledge to other knowledge systems which often means that there is a heavy neglect of indigenous ways of knowing. This discrepancy is complicated by the absence of comprehensive documentation and the lack of formal recognition of valuable local knowledge. In addition, mechanisms for participation in agricultural extension and research systems are often lacking, placing an inadequate burden on the local communities towards decision-making structures (Mapfumo et al., 2013; Melash et al., 2023). While scientific tools and technologies have made great strides, large numbers of smallholder farmers still find these tools out of reach, due to the expense involved, technical complexities, and lack of extension assistance. The aforementioned barriers highlight the critical and pressing need for systematic approaches to better integrate varied knowledge systems that will not exist merely for superficial inclusion, but in ways that ensure all voices are given due and value in agricultural development.

4.2. Proposed Conceptual Framework: A Co-Produced Soil Adaptation Model

Drawing on the analysis presented, the study proposes a co-produced soil-adaptation framework that integrates indigenous knowledge with scientific insights to enhance climate-resilient smallholder agriculture. The framework acknowledges that successful soil management in relation to climate change necessitates an integration of local, experiential knowledge with scientifically proven, quantifiable data. It is organised around three interconnected dimensions: indicator integration, practice integration, and scale integration, which collectively offer a comprehensive and actionable approach to soil assessment and management.

4.2.1. Indicator Integration: Linking Local Indicators with Scientific Measurement

Indicator integration is a common approach for aligning visible indigenous soil indicators (e.g., soil colour, vegetation patterns, soil fauna, and crop performance) with scientifically accepted indicators such as soil organic carbon (SOC), nutrient concentrations, and physical soil properties. At least at the smallholder level, farmers identify local indicators that best align with their experience of soil conditions in the fields where they have lived. These indicators are then validated against scientific parameters through basic soil testing, and some scientific data are collected to convert observable characteristics into measurable soil properties. Using this approach, simplified and locally adapted soil assessment tools are developed, such as field-based scorecards or classification guides, so that farmers can monitor conditions in real time. Extension services further support farmers in interpreting these integrated indicators through capacity-building and knowledge exchange. To this end, indicator integration yields a low-cost, scientifically robust hybrid assessment system that supports informed decision-making under climate variability.

4.2.2. Aligning Indigenous Management with Climate-Smart Strategies

Integrating practice reinforces indigenous soil management by aligning it with scientifically backed climate-smart agriculture strategies. In essence, smallholder farmers already implement practices such as composting, manuring, residue retention, agroforestry, and crop diversification, all of which enhance soil fertility and build resilience. Within this framework, these practices are first recognised and documented in their local context, and then refined with scientific insights through nutrient management, soil testing, and agronomic optimisation.

Participation-based integration, involving collaboration between farmers and researchers and on-farm experimentation, allows these practices to be tested and tailored to local environmental conditions, thereby operationalising the integration process. Feedback from farmers plays a vital role in these initiatives, helping continually improve management strategies to ensure they remain effective, relevant, and suitable to the context. Consequently, incorporating practices improves the efficiency of current systems while retaining local knowledge, ultimately enhancing soil health, productivity, and resilience to climate change.

4.2.3. Integrating Fine-Scale Knowledge with Spatial Tools

Scale integration addresses the gap between the small-scale spatial nature of indigenous knowledge and the large-scale spatial nature of common scientific soil assessment tools by integrating farmer-mediated soil classification with common spatial tools (e.g., Geographic Information Systems, GIS, remote sensing, and community-based mapping) and combining it with more complete spatial datasets to inform site-specific management decisions. This allows us to divide management units into separate zones for intervention on soil features. With less technical capability, simplified mapping tools, and community knowledge, one may yield similar results. Soil management is spatially accurate and locally relevant through multi-scale integration.

4.2.4. Toward Co-Produced and Climate-Resilient Systems

This framework offers a concept of co-production that brings together farmers, researchers, and extension systems across all three dimensions. Through a participatory approach, knowledge is co-constructed, checked, and practised, ensuring that soil management solutions are scientifically based and contextually aligned. This method of knowing builds capacity and facilitates the sharing and integration of indigenous knowledge with formal farming practices. Soil is therefore the key to connecting environmental processes and agricultural and knowledge systems in the framework. Focusing on indicators, practices, and scales in a co-produced framework, this framework represents a pragmatic, contextually relevant pathway to enhance soil management, build climate resilience, and promote wider, inclusive agricultural development in smallholder farming settings.

4.3. Soil as a Central System in Climate Adaptation

The study shows that soil acts as a central system in climate adaptation, bridging environmental processes and agricultural productivity with farmer choice through both indigenous and scientific knowledge systems. The importance of soil stems from its regulation of key processes, such as water retention, nutrient cycling, and carbon storage, which directly affect crop resilience to climate variability (Yang et al., 2026). We have abundant scientific data that show soil organic carbon, structure, and moisture retention are all key in buffering the effects of climate extremes (Qiao et al., 2022; Rashmi et al., 2024), while these processes are evident in indigenous knowledge systems through indicators of visible soil colour, vegetation patterns, and soil fauna (Hualpa et al., 2025; Kuria et al., 2019). This finding corroborates both Indigenous Soil Knowledge and Scientific Soil Approaches, showing that both systems understand soil as foundational, albeit through different lenses. Placing soil at the centre of adaptation shifts the focus of climate strategy to resilience through an internal systems lens, especially in low-resourced smallholder farming settings characterised by extreme soil quality degradation as a critical driver of climate stress.

4.4. Complementarity of Indigenous and Scientific Knowledge Systems

Indigenous and scientific soil knowledge systems complement one another, particularly in assessing soil fertility, structure, and functionality (Gillani et al., 2026). Indigenous knowledge captures fine-scale, real-time, and context-specific soil conditions, whereas scientific approaches offer measurable, standardised, and scalable assessments. The convergence of these indicators reflects shared underlying biophysical processes. Empirical studies demonstrate alignment between farmer-based indicators, such as soil texture and colour, and scientific measurements, including soil organic carbon and nutrient status (Hualpa et al., 2025; Jiménez et al., 2022; Kuria et al., 2019). However, divergence persists in more complex chemical assessments (Ansong Omari et al., 2018; Buthelezi & Modi, 2013). This directly supports the integration framework, particularly the concept of indicator integration. Recognising complementarity allows for the development of hybrid knowledge systems, improving both the accessibility and accuracy of soil assessment and enabling more effective climate adaptation strategies.

4.5. Implications for Smallholder Farming Systems

The presented framework shows that incorporating knowledge systems into soil management would significantly improve soil management in smallholder farming systems. Smallholder farmers already use adaptive (climate-smart) practices, often poorly tuned on these farms, due to constraints imposed by science-based approaches. Studies have found that composting, agroforestry, and residue management are established as key practices for increasing soil resilience according to indigenous and scientific literature (Kuria et al., 2019; Maqbool et al., 2025; Rashmi et al., 2024). This also aligns with the work on practice integration and illustrates that local practices can be built upon by science, and that integrating science into practice can reinforce them. This enables low-cost scalability and local adaptation of solutions, which are essential to fostering resilience in the hard-working land and in resource-constrained farming systems such as those in the Eastern Cape.

4.6. Institutional and Policy Gaps in Knowledge Integration

The research highlights major institutional and policy constraints to the incorporation of indigenous and scientific knowledge systems. These barriers arise from the predominance of top-down, science-driven approaches that marginalise indigenous knowledge and fail to incorporate local variability into extension systems. As in other studies, extension service delivery results in standardised recommendations that lead to low adoption rates, according to the literature review (Mapfumo et al., 2013; Nazir et al., 2026; Snapp, 2022). Indigenous knowledge is also under-documented and increasingly at risk of erosion (Melash et al., 2023; Mishra et al., 2025). This enhances the argument for co-production, specifically in the proposed framework, and emphasises that addressing these needs requires policy reform, participatory extension systems, and institutional recognition of indigenous knowledge that informs inclusive and effective climate adaptation. Further details are presented in Table 1 and Figure 1.

Table 1
Advancing a Co-Produced Soil Adaptation Framework

Indigenous indicator	Farmer interpretation	Scientific equivalent	Method of validation	Climate adaptation relevance
Dark soil colour	Fertile soil with good crop performance	Higher soil organic matter and carbon stocks, often linked to better fertility (Ansong Omari et al., 2018; Hualpa et al., 2025)	Laboratory analysis of SOC and key nutrients (e.g) (Wiesmeier et al., 2019)	Higher SOC improves water retention, structure, and nutrient buffering, supporting drought resilience and nutrient management (Wiesm eier et al., 2019)
Earthworms and soil fauna	Living, fertile soils with good tilth	Soil biological activity, soil macrofauna and associated ecosystem functions (Ansong Omari et al., 2018; Kuria et al., 2019)	Macrofauna counts, microbial and respiration assays, and biological soil health indicators	
Indicator plants and weeds	Presence or absence signals fertility, degradation or salinity	Vegetation-based indicators of nutrient status, pH, salinity and soil condition (Ansong Omari et al., 2018; Hualpa et al., 2025)	Vegetation surveys combined with soil chemical analysis (pH, EC, nutrients) (Kangel a et al., 2025)	Enables low-cost, real-time detection of degradation or salinity to guide adaptive soil management (Kangel a et al., 2025)
Fine-textured soils	Hold moisture better and are seen as more productive	Higher clay content and field capacity, greater water-holding capacity	Differentiation according to management and texture	Particle-size (texture) analysis and soil moisture/retention measurements (Wies meier et al., 2019)

Crop vigour and colour	Strong growth and greenness indicate good soil fertility	Plant nutrient status and chlorophyll content (e.g. N supply) (Ansong Omari et al., 2018; Hermans et al., 2021)	Leaf/tissue nutrient analysis and optical measurements (e.g. chlorophyll meters, NDVI/SPAD-type approaches) (Zay ani et al., 2023)	Enables site-specific, adaptive nutrient management in response to climate-driven stress
Visible erosion signs	Indicate soil degradation, fertility loss and reduced yields	Soil loss rates, erosion risk and land degradation status (Gambo et al., 2025; Hermans et al., 2021)	Field assessments, erosion modelling and GIS-based land degradation mapping (Gambo et al., 2025)	Identifies priority areas for conservation measures and restoration under more intense rainfall regimes

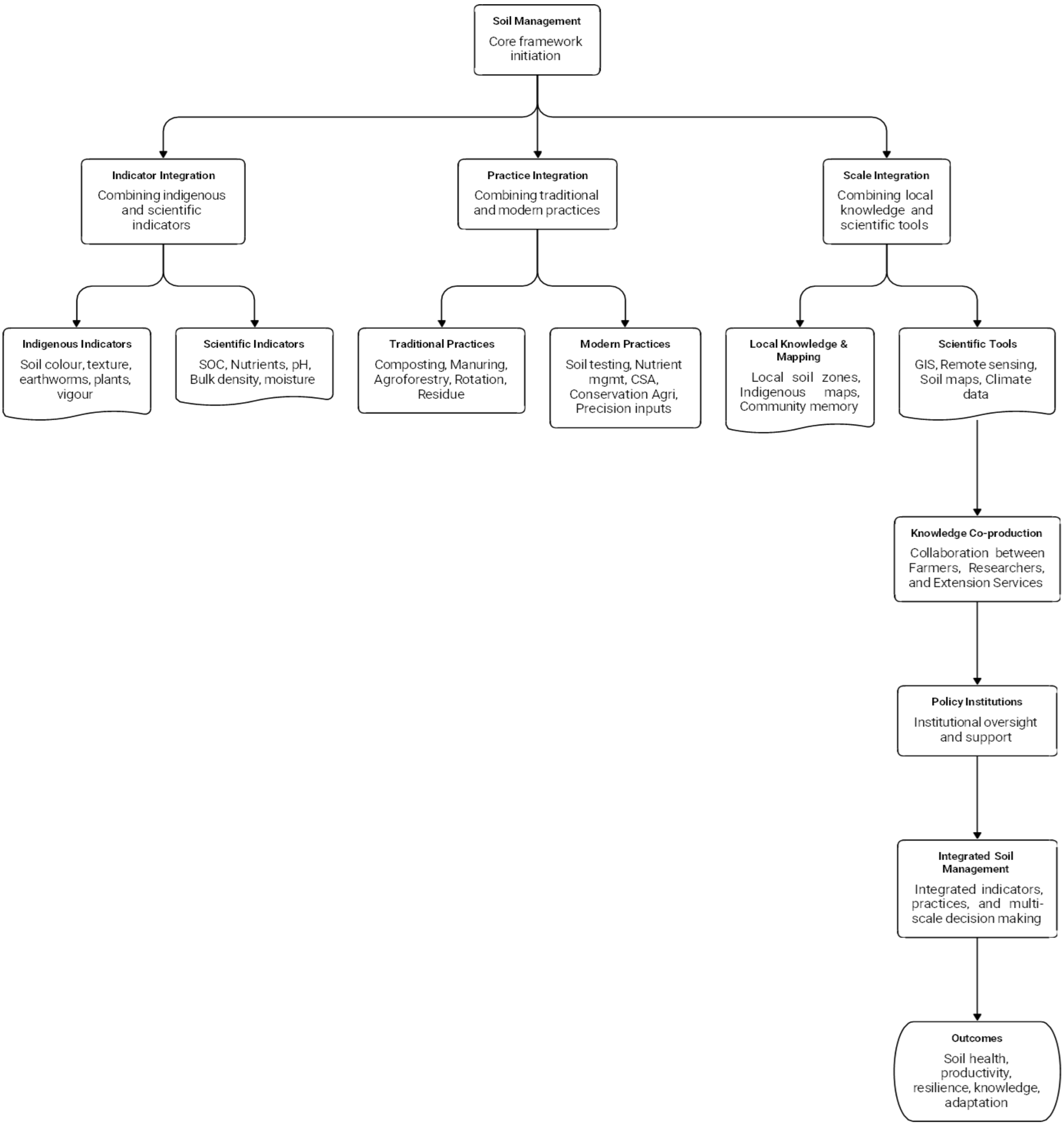

Figure 1: Soil Systems Adaptation Framework

The study offers a coherent model that complements indigenous and scientific knowledge systems regarding indicators, practices, and scales. Although it addresses the shortcomings of siloed techniques based on observation, analysis, and spatial dimensions in soil management, its model offers an integrated approach that accounts for multidimensionality. Co-production and integration are supported by the previous literature; however, no implementation model to guide such efforts has been developed (Hualpa et al., 2025; Kuria et al., 2019). This corresponds directly to the proposed Framework and is the core contribution of the present study. The framework contributes to the field by presenting a pragmatic, working model suitable for translating theoretical knowledge into practical application in smallholder farming systems.

5. Conclusion

Smallholder farmers, therefore, are particularly vulnerable to the changing climate, requiring a transition to a co-produced framework that can meet the increasingly severe conditions of future food production. This structure is critical because it embeds the principles of productivity, adaptation, soil health, and livelihoods within the realities of local agriculture. Climate change exerts considerable pressure on food production systems, disproportionately impacting smallholder farmers and others who rely on rain-fed agriculture, have limited access to finance and technology, and are at the highest risk during climate shocks. Without successful adaptation approaches, rural livelihoods and food security will be affected, as will food security overall.

Consequently, there is greater emphasis on climate-resilient agricultural strategies that aim to increase productivity and incomes, provide resilience to climate change, and build adaptive capacity, while also reducing emissions and increasing the ability and resilience of agriculture. This model is vital for smallholders, who underpin a significant share of farms in developing countries and are responsible for a great deal of food supply to this region. Smallholders, at the same time, have limited capacity for adaptation and are vulnerable to extreme weather events.

Climate-resilient smallholder agriculture extends its remit beyond yield maintenance to preserving important natural resources, especially soil and water, as well as supporting livelihoods and local food systems. New studies show that the strategies adopted for sustainable farming practices, including good soil conservation, help improve food systems, mitigate the vulnerability of communities, and secure food supply, especially when these approaches are attuned to local conditions. The evidence supports the conclusion that some agricultural strategies would produce many other benefits, including adaptation, profitability, and mitigation.

The co-produced framework comprises three domains: indicator integration, practice integration, and scale integration. Effective outcomes are determined by ensuring that these fields are seamlessly integrated. Indigenous knowledge, particularly that of smallholder farmers, is critical in understanding and adjusting to local environmental conditions. Traditional soil indicator systems, such as soil colour and nutrient measurement, make up this skill set.

The specific colours of the soil give farmers an indication of both fertility levels and soil health. In addition, synthesising indigenous knowledge with contemporary scientific soil-testing techniques (e.g., laboratory analyses that quantitatively assess soil fertility) has synergistic effects in strengthening climate adaptation measures. An integrated research system to optimise soil condition assessment, including data collection, classification, analysis, and monitoring, is thus a more accurate tool for climate adaptation. An essential aspect of such a framework is the role of extension officers. Such experts serve as a transitional connection between scientific research and practical application. Their role is to develop new domains and translate complex scientific and conventional indicators into solutions suited to the diverse local circumstances of farming communities. In so doing, they ensure farmers have the best information on which to base action and adaptation in their agricultural practices to address climate change, building resilience among farmers.

6. Recommendations For Policy, Practice, and Future Implementation

The proposed Soil Systems Adaptation Framework (SSAF) provides a theoretical basis for integrating soil-based and scientific knowledge for climate change adaptation. Several recommendations are proposed to assist in implementing this policy. First, agricultural extension systems can be structured to go beyond top-down methods and adopt participatory approaches that actively integrate soil-based indigenous knowledge into consultancy services. Extension officers should be trained to use local soil indicators in addition to soil analysis and scientific soil sampling tools, thereby strengthening their knowledge, cooperation and making recommendations more meaningful for smallholder farmers. Secondly, adaptation planning at the local and regional levels should address soil directly as a central route for adaptation. Integrated land-use management strategies (integrated with land areas) that address soil health, water retention, nutrient management, and ecosystem resilience are key elements of climate change adaptation and should be integrated into urban and rural development plans.

Thirdly, access to low-cost soil testing programmes in rural areas should be expanded. This fieldwork should be led and carried out by a community-based soil research initiative supported by universities, agricultural departments, and extension services, enabling farmers to link their soil observations to scientific metrics and conduct soil assessments to make better soil management decisions. Fourthly, farmer-based schools need to be strengthened as vehicles for experiential learning and knowledge sharing. Such programmes would allow for joint evaluation of local indicators, climate-smart farming practices, and soil management innovations, and would also promote mutual learning and adaptation to local conditions. Fifth, participatory mapping activities should be integrated into land-use planning. Integrating soil categories and soil and local environmental knowledge from farmers with geographic information systems (GIS) and remote sensing can also improve the detection of soil variability, degradation hotspots and priority areas for intervention.

Finally, environmental and agricultural policy institutions need to legally recognise soil heritage as an active part of climate change adaptation and sustainable soil management. The policy framework should also promote the recording, preservation, and integration of indigenous knowledge systems into agricultural development, spatial planning, and climate change adaptation programmes. There is a need to test the proposed framework in a specific agro-ecological context to determine its effectiveness in improving soil health, agricultural productivity and climate resilience in smallholder farming systems.

Authors Contribution

Siyanda Nkwenkwe: conceptualization, writing – original draft, writing – review & editing.
Lwanda Matiso: conceptualization, writing – original draft, writing – review & editing.

Conflict of Interests/Disclosures

The authors declared no potential conflicts of interest w.r.t the research, authorship and/or publication of this article.

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