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Assessing the Health of Tropical Soils in Sub-Saharan Africa: Indicators, Challenges and Future Directions

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Abstract

Soils are facing critical and overlapping challenges that threaten food security. Assessing soil health is critical for providing scientific evidence-based, appropriate, site-specific and sustainable solutions to support the resilience of our agrifood systems. This systematic review analyzes 48 publications published between 2015 and 2025 on soil health assessment of tropical soils in Sub-Saharan Africa. The objective was to identify the indicators used, the analytical methods, the technologies used and the associated management strategies, in order to characterize the dominant scientific orientations and the persistent gaps, and future directions. 48 relevant papers out of 220 downloaded were examined. The results highlight that soil health assessment studies were concentrated in East and West Africa, primarily Ethiopia, Ghana, and Kenya while it remains very rare in Central and Southern Africa. Key findings include a dominance of physicochemical indicators, with organic carbon as a focus in 75% of studies, pH at 31%, total nitrogen at 24% and CEC at 22%; whereas biological indicators remain less frequent. Analytical methods included regression and ANOVA, with emerging techniques like digital soil mapping. Conventional laboratory analyses are used in more than 80% of studies. However, soil health assessment using observational and indigenous knowledge indicators remains very rare in Sub-Saharan Africa. Recommendations emphasize methodological harmonization and incorporating observational and local knowledge for a comprehensive soil health assessment.

Keywords

Soil Health, Assessment Indicators, Challenges, Sub-Saharan Africa, Sustainable Management, Future Directions

1. Introduction

Soil is the majority of the world's agricultural production reservoir. The sustainability of tropical agricultural systems in Sub-Saharan Africa (SSA) relies on an often invisible but crucial capital for food security, livelihood stability, and climate resilience [1] [2]. In this region characterized by rapid population growth, intensification of land uses and high hydroclimatic variability, the ability of soils to maintain their biological, chemical and physical functions is a major strategic issue [3] [4]. Increasing agricultural production, restoring degraded land and mitigating the effects of climate change require the availability of reliable tools to assess soil health and monitor changes over time [5] [6].

The notion of soil health today goes beyond the simple measurement of fertility and refers to the soil's ability to support plant productivity, regulate water and nutrient flows, store carbon, host functional biodiversity and provide essential ecosystem services [1] [6]. In tropical environments, these functions are subject to specific constraints such as pronounced mineral weathering, low nutrient reserves, rapid organic matter dynamics, and high susceptibility to erosion and compaction [7]. Agricultural practices, whether extensive or intensified, interact with these constraints and can accelerate both soil degradation and regeneration [8] [9]. Faced with this complexity, scientific research has developed a variety of indicators to quantify this multidimensional concept [10] [11]. Classical physicochemical parameters such as pH, total soil organic carbon (SOC), total nitrogen, cation exchange capacity (CEC) and bulk density are widely mobilized [12] [13]. However, they are now complemented by biological indicators reflecting the living activity of the soil: microbial biomass, respiration, enzymatic activities, functional diversity and macrofauna, highlighting the central role of organisms in the productivity and resilience of agroecosystems [7] [14].

Despite this progress, several challenges remain. Studies use variable sets of indicators, heterogeneous analytical methods, and scoring systems that are difficult to compare across regions [3] [4]. The critical thresholds differ according to the pedoclimatic contexts, making any attempt at generalization difficult. Logistical and financial constraints often limit the integration of expensive biology analysis, while access to laboratories remains uneven [2] [11]. In addition, there is the need to articulate scientific measures and local knowledge, which provide valuable information on the degradation or regeneration dynamics observed by producers

[8] [12].

At the same time, the emergence of new technologies is transforming soil health assessment. Infrared spectroscopy (IRS), digital soil mapping (DSM), machine learning (ML), and open data platforms (ODP) enable rapid, less costly, and spatially explicit acquisition of edaphic properties [13]-[15]. These tools offer major potential for large-scale monitoring, but raise questions about calibration, validation, and data governance. Their relevance depends on the ability to integrate these technologies into operational devices that can be used by agricultural services and local communities [3] [7].

In this context, it is essential to establish a critical reading of the indicators mobilized over the last decade. Identifying the most used indicators, the methods applied and the sub-regions of SSA concerned makes it possible to highlight convergences, gaps and future priorities. Such analysis also promotes the harmonization of approaches, which is essential for comparing results, guiding public policies, and targeting investments towards effective restoration strategies [6] [10]. This systematic review aims to clarify the state of knowledge, highlight structural challenges and identify credible avenues for improving the assessment of the health of tropical soils in SSA.

Tropical soils in SSA provide the biophysical foundation for food security, ecological stability, and the livelihoods of millions of rural households. However, these soils are under increasing pressures resulting from agricultural expansion, reduced fallow periods, deforestation, erosion and increased climate variability [16] [17]. Land degradation in SSA already affects a significant proportion of cropland, compromising agricultural productivity and accentuating socioeconomic vulnerability [18] [19]. In this context, the notion of soil health emerges as an integrative conceptual framework for assessing the capacity of soil to simultaneously fulfil its productive, ecological and regulatory functions.

Unlike soil fertility, which has historically focused on nutrient availability, soil health encompasses interconnected physical, chemical, and biological dimensions [4] [6] [20]. It includes soil structure, organic matter, microbial activity, edaphic biodiversity, and resilience to disturbances [1] [7]. However, while the concept is now widely accepted in international frameworks, its operational implementation in Sub-Saharan Africa remains fragmented and heterogeneous [21].

During the period 2015-2025, research conducted in West Africa by [11] and [22] in East Africa by [8] and [23], in Central Africa by [24], and in Southern Africa by [25] and [26] used a variety of indicators to characterize the health of tropical soils. The most frequently used physicochemical indicators include pH, soil organic carbon (SOC), total nitrogen, assimilable phosphorus, cation exchange capacity (CEC) and bulk density [15] [27]. At the same time, there is a growing interest in biological indicators such as microbial biomass, enzymatic activities, soil respiration and microbial diversity [7] [28].

However, the selection of indicators varies considerably from one study to another, reflecting the lack of regional methodological consensus. Some studies favour composite soil quality indices (SQI) based on principal component analysis [21] [23]. Others adopt weighted multi-criteria approaches or participatory frameworks that integrate farmers' perceptions [29] [30]. This methodological diversity complicates inter-study comparison and limits the identification of robust indicators at the subregional scale.

The pedoclimatic heterogeneity of Sub-Saharan Africa reinforces this complexity. Acidic ferrallitic soils in Central Africa, tropical ferruginous soils in West Africa, Andosols and Nitisols in the highlands of East Africa, and semi-arid sandy soils in southern Africa have distinct biogeochemical dynamics [13] [31]. Therefore, the relevance of an indicator depends strongly on the agroecological context. However, few studies have carried out a systematic comparison of the indicators used according to the tropical subregions, leaving a major analytical gap.

Recent technological advances offer new perspectives for soil health assessment. Digital Soil Mapping combined with Machine Learning can now predict soil properties at high spatial resolution [13] [32]. Near-infrared spectroscopy techniques used by [3] and [14] reduce analytical costs and facilitate the analysis of large sample sets. Similarly, the integration of geospatial tools and satellite data improves the understanding of spatial dynamics [33]. However, the accessibility of these technologies remains uneven, and their validation in heterogeneous tropical environments remains incomplete.

In parallel, several studies have analyzed the effect of sustainable agricultural practices on soil health indicators. Conservation agriculture, agroforestry, organic amendments, or integrated fertility management show varying impacts depending on the duration of application and local conditions [15] [28]. However, the results sometimes remain contradictory, particularly regarding the evolution of organic carbon and biological parameters in tropical climates [34]. A regional quantitative synthesis is therefore necessary to clarify these discrepancies.

Structural challenges are also noteworthy. Lack of analytical infrastructure, insufficient long time series, scarcity of harmonized data, and weak institutional monitoring frameworks are major obstacles [16] [34]. In addition, the weak integration of local knowledge in the definition of indicators limits the ownership of results by rural communities [29].

Thus, despite the increase in scientific work since 2015, knowledge remains dispersed, fragmented and rarely compared across the four tropical Sub-Regions of Sub-Saharan Africa. No recent systematic review has simultaneously incorporated:

1) the inventory of physico-chemical and biological indicators;

2) a sub-regional benchmarking;

3) the examination of the methodologies and technologies used;

4) an assessment of associated sustainable practices

5) the identification of structural challenges and opportunities for improvement.

The central issue can therefore be formulated as follows: What soil health indicators have been mobilized in Sub-Saharan Africa between 2015 and 2025, how do they vary across tropical Sub-Regions, what methodologies and technologies support their assessment, and to what extent do these approaches effectively guide sustainable soil management strategies?

Answering these questions requires a rigorous systematic review, including a comparative meta-analysis by sub-region, in order to identify the most robust indicators, the most relevant methodologies and the persistent scientific gaps. Such an approach will contribute to the harmonization of assessment frameworks, the improvement of interregional comparability and the formulation of recommendations adapted to the specificities of tropical soils in SSA.

2. Methodology

2.1. Type of Study and Conceptual Framework

This study adopts a systematic review with quantitative meta-analysis, aiming to rigorously synthesize the scientific knowledge published between January 2015 and March 2025 on the assessment of tropical soil health in Sub-Saharan Africa (SSA). The methodological approach is guided by the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) recommendations [35]. Indeed, the review is based on a conceptual framework integrating three main dimensions of soil health: 1) physico-chemical indicators, 2) biological indicators, and 3) assessment tools and methodologies. These dimensions are analyzed in relation to sustainable management practices and agroecological specificities of the four Sub-Regions of Sub-Saharan Africa: West Africa, East Africa, Central Africa and Southern Africa.

2.2. Search Strategy

A systematic search was conducted in the main international scientific databases: Web of Science, Scopus, ScienceDirect, SpringerLink, Wiley Online Library, MDPI, PLOS, Frontiers, as well as Google Scholar to complete the identification of relevant publications. The institutional bases (FAO, ISRIC, CGIAR, Soils4Africa) were consulted to integrate major technical reports when scientifically justified. The search equations combined keywords related to soil health and the target geographical area, using Boolean operators: ("soil health" OR "soil quality" OR "soil indicators" OR "soil biological indicators"), AND ("Sub-Saharan Africa" OR "West Africa" OR "East Africa" OR "Central Africa" OR "Southern Africa"), AND ("assessment" OR "evaluation" OR "soil quality index" OR "digital soil mapping"), AND (2015–2025). Additional research has specifically targeted biological indicators (e.g., "microbial biomass", "soil respiration", "enzyme activity").

2.3. Inclusion and Exclusion Criteria

The selection criteria have been defined a priori in order to ensure scientific consistency. These criteria are presented in **Table 1**.

Table 1. Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
Publication between 2015 and 2026	Studies outside Sub-Saharan Africa
Peer Review	Opinion pieces without empirical data
Empirical data on soil health	Studies focused solely on fertilization without health indicators
Clear methodological description	Methodology insufficiently described
At least one physical, chemical, or biological indicator	Lay Reports

Only studies that met all inclusion criteria were retained for the final analysis.

2.4. Study Selection Process

The selection process took place in four stages:

1) Identification of references in databases;

2) Removal of duplicates;

3) reading of titles and summaries for a first sorting;

4) Complete read in full text for final validation according to the established criteria.

The application of the collection strategy leads to a pre-corpus of 220 documents. From the 200 references initially identified, including 150 from databases and 50 from complementary sources, 95 duplicates were eliminated, leaving 105 articles for initial screening. After a rigorous screening phase, 23 articles were excluded for non-compliance with the inclusion criteria, leading to 82 articles evaluated in full text. Of these, 34 were excluded for methodological or relevance reasons, allowing 29 studies to be retained for qualitative analysis and 19 studies for quantitative meta-analysis. Thus, a corpus of 48 documents (*i.e.* 21.81% of the pre-corpus). This methodical approach ensures transparency and reproducibility of the literature selection, while ensuring that qualitative and quantitative syntheses are based on robust and comparable data, thus providing a solid basis for the integrated assessment of soil health indicators.

2.5. Data Extraction and Structuring

A standardized extraction grid was developed using a spreadsheet to ensure the homogeneity of the information collection (**Table 2**).

The soil health indicators identified have been structured into three broad functional categories, in line with international conceptual frameworks for integrated soil assessment that recognize the physical, chemical and biological dimensions as complementary pillars of soil ecological functioning [1] [2] [5] [6].

Physical indicators, such as bulk density and porosity, provide information mainly on the structural condition of the soil, its capacity for water infiltration, aeration and storage, which are essential elements for productivity and water

Table 2. Variables extracted from selected studies.

Category	Variables collected
General information	Author, year, country, sub-region, type of ecosystem
Physical indicators	Bulk density, structural stability, texture
Chemical Indicators	pH, SOC, Total N, Available P, CEC
Biological indicators	Microbial biomass, respiration, enzymes, diversity
Methodology	Sampling type, depth, statistical analysis
Composite Index	SQI weighting method
Technologies	NIR/MIR, GIS, DSM, ML
Agricultural Practices	Agroforestry, conservation, organic amendments

regulation. Chemical indicators, including soil organic carbon (SOC), total nitrogen (N), available phosphorus (P), pH and cation exchange capacity (CEC), reflect fertility potential, biogeochemical cycle function and nutrient availability for crops. Finally, biological indicators, such as microbial biomass and enzymatic activities, reflect the intensity of biological activity, the dynamics of organic matter decomposition and the ecological resilience of tropical agroecosystems. In order to identify regional trends, a frequency analysis was conducted to determine the indicators most used in the studies of each Sub-Region of Sub-Saharan Africa, thus highlighting methodological convergences, contextual specificities and possible imbalances in the representation of the physical, chemical and biological dimensions of soil health.

2.6. Quantitative Meta-Analysis

For studies reporting comparable quantitative data, including means, standard deviations and sample sizes, a quantitative meta-analysis was performed to estimate the effect of sustainable management practices on key soil health indicators, with a particular focus on soil organic carbon (SOC), which is recognized as a key marker of tropical soil fertility and resilience [36] [37]. Effect sizes were standardized using Hedges' g to allow comparison of results from different methodological contexts, and a random-effects model was adopted to account for inter-study heterogeneity [38]. Statistical heterogeneity was assessed using the I^2 index and the Cochran Q test, consistent with the recommendations of methodological reviews in ecology and soil science [39]. Subgroup analyses were conducted to compare effects by sub-region: West Africa, East Africa, Central Africa and Southern Africa, to identify specific regional trends and understand the influence of agroecological context and local practices [4].

2.7. Thematic Qualitative Analysis

In parallel, a thematic qualitative analysis was conducted to complement the quantitative approach and provide a contextualized interpretation of the results [40].

This analysis identified recurrent methodological challenges, such as variability in sampling protocols, lack of standardization of indicators, and analytical capacity constraints in Sub-Saharan Africa [6] [41]. Analytical limitations, including the sensitivity of the methods to seasonal variations and soil types, were examined to identify areas for improvement. Emerging technologies such as MIR/NIR spectroscopy and DSM have been codified and ranked by relevance for integrated soil monitoring [13] [14]. Finally, the themes were coded inductively, allowing for the emergence of common trends and opportunities for improvement, including the need to integrate local knowledge with analytical tools, to optimize composite indicators (SQI) and to strengthen the adoption of sustainable practices adapted to regional constraints [4] [10] [26].

This methodology combines systematic rigor, regional comparability and robust quantitative analysis. It identifies the dominant soil health indicators in Sub-Saharan Africa between 2015 and 2025, assesses their contextual relevance and proposes scientific guidance for the future improvement of assessment frameworks.

3. Results

3.1. Geographical and Temporal Distribution of Documents

Analysis of the geographical distribution (**Figure 1(b)**) of soil health literature in Sub-Saharan Africa reveals a notable concentration in some regions, particularly in East and West Africa. Ethiopia stands out with 6 publications, followed by Ghana (3) and Kenya (2), while countries such as Mozambique, Benin, Côte d'Ivoire, Rwanda, Tanzania, Cameroon and Botswana appear with a more limited number of publications (1 to 2). This distribution (**Figure 1(a)**) reflects both the focus of research projects, the availability of scientific infrastructure, and the implementation of soil monitoring programs. The map highlights a spatial gradient of knowledge, with a strong representation of areas of intensive agriculture and historical research basins, while some regions remain under documented.

In terms of time, the annual evolution of publications between 2015 and 2025 shows a growing dynamic. Between 2015 and 2019, the number of publications remains limited (0 to 3 articles per year), reflecting an emerging interest in tropical soil health and the associated methodological challenges. From 2020 onwards, a clear increase is observed, peaking at 13 publications in 2025. This significant increase can be explained by several factors: the rise of research initiatives on food security, the increasing integration of sustainable agricultural practices and the active involvement of international funding programs. It also reflects the consideration of the Sustainable Development Goals (SDGs), which underline the importance of restoring and maintaining soil health to ensure the resilience of agricultural systems and the sustainability of ecosystems.

By combining spatial and temporal dimensions, this analysis provides a clear diagnosis of current scientific coverage and highlights areas and periods of high research activity. It highlights the importance of strengthening the harmonization

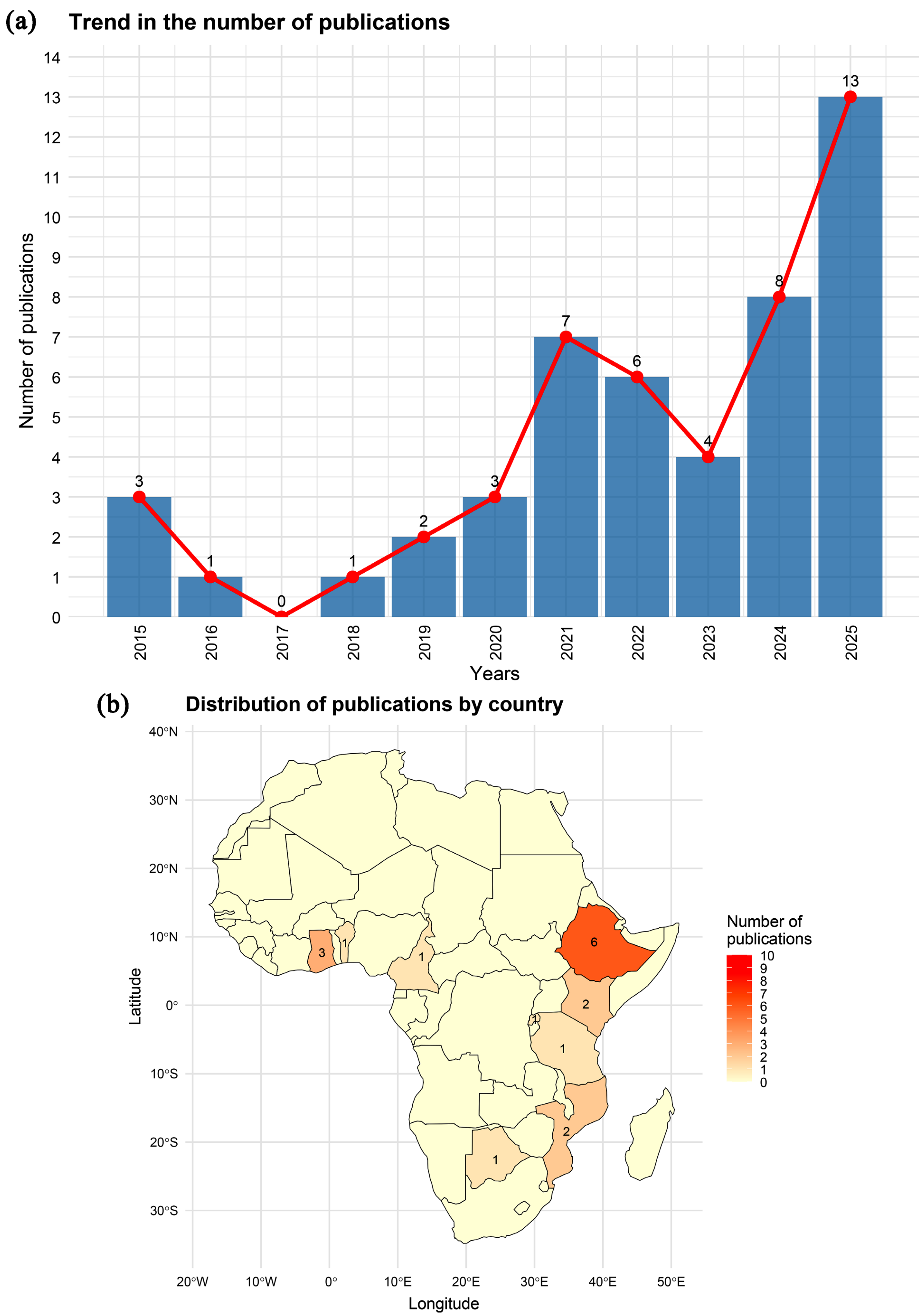

Figure 1. Temporal (a) and Geographic (b) distribution of publications between 2015-2025.

of methods and indicators, to enable cross-site comparison and support evidence-based policymaking. In addition, the increase in publications over the past five years illustrates a growing alignment of soil health research with global sustainable development priorities, reinforcing the relevance of studies to guide sustainable agricultural interventions and territorial planning.

3.2. Thematic Structure of the Corpus Units

The keyword cloud of the documents (**Figure 2**) highlights a clear structuring of the scientific corpus around a few dominant poles that reflect the methodological and operational priorities of research on soil health in Sub-Saharan Africa.

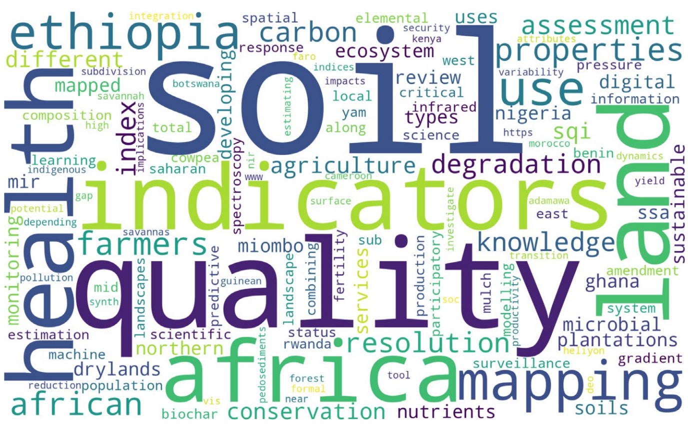

Figure 2. Clouds of Kays words from the documents in the corpus.

The visual pre-eminence of soil, quality, indicators, properties and assessment confirms that the literature is primarily oriented towards the quantification and standardization of diagnostics. The high frequency of the terms Africa, mapping, resolution and digital simultaneously reveals the rise of digital mapping and spatial modelling approaches, which have become central to extrapolating results and supporting territorial planning. The words land use, agriculture and farmers indicate that these assessments are mostly in productive contexts, where agronomic performance and sustainability guide the interpretation of the indicators. The sustained visibility of carbon, nutrients and fertility shows that biogeochemical regulation, in particular organic matter, is a pivot linking food security and climate issues. On the other hand, the smaller size of microbial suggests that, despite increasing recognition, biological dimensions remain less integrated than physico-chemical parameters. Finally, the strong presence of certain countries, notably Ethiopia, reflects a geographical concentration of research efforts, revealing inequalities in infrastructure and funding at the regional level.

3.3. Soil Health Indicators

The quantitative analysis of the corpus (48 studies) highlights a clear dominance of physico-chemical indicators in the assessment of soil health in Sub-Saharan Africa (**Table 3**).

Table 3. Classification of soil health indicators.

Category	Indicator	Main function	Number of documents	Level of use
Physico-chemical	Organic Carbon (SOC)	Fertility, structure, climate	36	Dominant
	pH	Nutrient availability	31	Very common
	Total Nitrogen	Productive potential	24	High
	CEC	Cation retention	22	High
	Bulk density	Compaction, porosity	18	Medium
	Available Phosphorus	Plant Nutrition	17	Medium
Biological	Microbial biomass	Biological activity	9	Low
	Soil respiration	Mineralization	7	Low
	Enzyme activities	Nutrient cycling	6	Low
	Macrofauna	Structure, biological engineering	5	Low
Functional/Index	SQI composite	Global diagnosis	26	Very common
	ACP/weighted scoring	Variable aggregation	19	Medium
Participatory	Visual farmer indicators	Local appreciation	8	Low
	Crop performance	Functional validation	10	Low to medium

Organic carbon is mobilized in about 36 publications, *i.e.* nearly 75% of the work, confirming its central role in simultaneously interpreting fertility, structure and sequestration potential. pH appears in 31 studies, total nitrogen in 24 and cation exchange capacity in 22, reflecting a strong reliance on standardized, comparable parameters compatible with regional mapping exercises. Physical variables such as bulk density (18) and available phosphorus (17) occupy an intermediate position. On the other hand, the biological dimensions remain marginal: microbial biomass is considered in only 9 studies, respiration in 7, enzymes in 6 and macrofauna in 5, *i.e.* less than a quarter of the corpus. At the same time, integrated approaches are progressing, with 26 publications offering composite indices and 19 using statistical weighting methods. These figures describe a field still dominated by soil chemistry, while the functional integration of living organisms remains in transition.

Indeed, the indicators identified can be grouped into three broad categories: physical, chemical and biological, in accordance with the international conceptual frameworks for integrated soil assessment. Physical indicators include bulk density, porosity, and texture, which reflect the structure of the soil and its infiltration capacity. Chemical indicators include soil organic carbon (SOC), total nitrogen, available phosphorus, pH, and cation exchange capacity (CEC), which are essential for fertility and biogeochemical cycles. Biological indicators, such as microbial biomass and enzyme activity, are crucial for the resilience and maintenance of soil biological function. Frequency analysis showed that SOC is the most widely used chemical indicator, while microbial biomass dominates in biological indicators. The distribution by subregion reveals a predominance of studies in West Africa (n = 22), followed by East Africa (n = 15), Central Africa (n = 13), and Southern Africa (n = 14).

3.4. Typology of Methods for Soil Health Assessment

The methodologies used vary from the classic field (systematic sampling, physico-chemical analyses) to numerical and spectroscopic approaches, including remote sensing and MIR/NIR spectroscopy [14] [18]. Composite indices (SQIs) have been widely adopted to synthesize soil quality from multiple parameters, facilitating cross-site and inter-sub-regional comparison. Table 4 presents the methods identified.

An examination of the 48 studies shows a clear methodological hierarchy dominated by statistical tools and the aggregation of indicators. Principal component analysis is used in about 19 publications, mainly to reduce the redundancy of matrices including chemical, physical and sometimes biological variables, and to isolate the factors explaining the variability. The construction of synthetic soil quality indices is the most frequent approach (26 studies), reflecting the search for a directly interpretable result for decision-making; However, these indices remain sensitive to normalization and weighting rules. Scoring methods accompany this logic in ≈17 studies. Statistical comparisons between uses or practices, via ANOVA and associated tests, appear in 21 studies, while regressions and correlations aimed at establishing functional relationships are present in 23. Spatialization is progressing with digital soil mapping (14) and machine learning

Table 4. Methods used for soil health assessment.

Methodological category	Method/Approach	Analytical objective	Number Of documents	Level of adoption
Multivariate statistics	Principal Component Analysis (PCA/BCP)	Dimensional reduction, selection of indicators	19	High
Index construction	Soil Quality Index (SQI)	Single-score aggregation	26	Very high
Index construction	Linear/Non-Linear scoring methods	Variable Normalization	17	High
Spatial Modeling	Digital Soil Mapping (DSM)	Continuous spatial prediction	14	Medium to High
Modeling	Machine learning (RF, etc.)	Improved prediction	12	Medium
Spectroscopy	MIR/NIR	Quick property valuation	8	Emerging
Group Comparison	ANOVA/statistical tests	Land use effects	21	Very common
Correlation/Regression	Indicator relationships	Process Understanding	23	Very common
Participatory approach	Farmer evaluation	Field validation	8	Low
Qualitative methods	Interviews/perceptions	Socio-ecological supplement	5	Marginal
Meta-analysis	Quantitative synthesis	Effect Size	2	Rare

(12), allowing regional extrapolation but highly dependent on the quality of training data. MIR/NIR spectroscopy remains emerging (8). Finally, participatory approaches remain limited (8) (5 of which are qualitative), indicating that local knowledge is still peripheral in quantitative frameworks.

3.5. Tools and Technologies Used for Soil Health Assessment

Of the 48 methodologically usable studies, the dominant analytical infrastructure remains the conventional laboratory, which is used in about 40 publications (>80%). This work is mainly based on standardized physicochemical protocols (soil organic carbon, pH, total nitrogen, cation exchange capacity), guaranteeing inter-site comparability and metrological robustness. This predominance is explained by the international standardization of analytical methods and their integration into recognized evaluation frameworks, although these devices imply high operational costs and a low temporal density of observations.

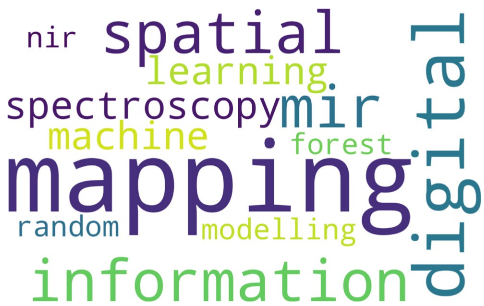

Figure 3. Word cloud related to soil health assessment tools and technologies.

The lexical cloud presented in **Figure 3** highlights the preponderance of geospatial and digital vocabulary in the corpus analyzed. The terms mapping, spatial and information occupy the largest visual area, which corroborates the methodological results showing that nearly a third of the studies use geographic information systems or predictive digital mapping approaches. The assessment of soil health thus appears to be closely linked to the ability to transform punctual observations from laboratory protocols (SOC, pH, nitrogen, CEC), dominant in more than 80% of publications, into continuous representations of the territory. This articulation between standardized measurement and spatialization reflects a shift in research towards decision-making frameworks at the landscape level.

The high frequency of the terms machine, learning, random and modelling confirms the rise of algorithmic approaches, consistent with the presence of about 12 studies integrating supervised learning models. This evolution signals a transition to a computational science where predictive performance depends on both the robustness of datasets and the sophistication of statistical architectures. In addition, the visibility of spectroscopy, MIR and NIR reflects the progressive development of rapid diagnostic technologies (≈8 studies), still in the minority but strategic to increase observational density at a reduced cost, subject to calibration libraries adapted to tropical soils. Finally, the presence of terms associated with production systems, such as forest, indicates that these tools are mainly applied to anthropogenic landscapes. Overall, the lexical hierarchy confirms a field oriented towards predictive spatialization, supported by AI and gradually enriched by spectral innovation, while remaining structurally dependent on robust analytical repositories.

3.6. Strategies and Technologies Used for Soil Health Improvement

The distribution of strategies and technologies /practices shows a clear dominance of conservation agriculture, cited in about 26% of the corpus (Figure 4).

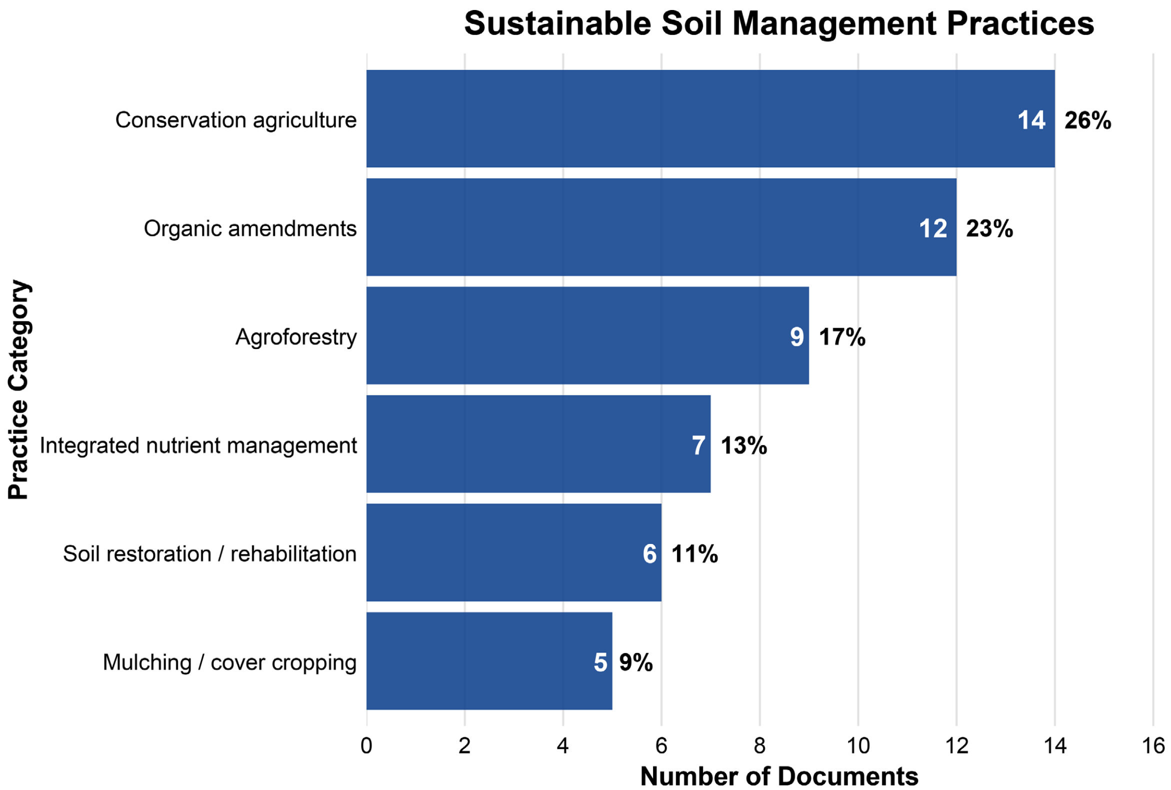

Figure 4. Frequencies of sustainable soil management strategies and practices.

This pre-eminence reflects the strength of international programs promoting reduced tillage, permanent cover and rotations as rapid levers for improving carbon and structural stability. Organic amendments follow (23%), confirming the attention paid to the restoration of organic matter in highly depleted contexts. Agroforestry appears in nearly 17% of the studies, often associated with the maintenance of the SOC and microclimatic regulation. On the other hand, large-scale restoration approaches or integrated nutrient management remain less represented. This hierarchy reveals research that is more focused on the experimental plot than on the systemic transformation of agricultural landscapes. It also suggests a preference for short-term, measurable practices that are consistent with existing evaluation frameworks.

3.7. Challenges in Assessing Soil Health

The main obstacle identified concerns the lack of methodological harmonization, mentioned in 44% of the studies (**Figure 5**). The studies use variable sets of indicators, different standardization procedures and rarely comparable thresholds, which limits regional syntheses. The cost of analyses represents the second major obstacle (33%), particularly for biological parameters. Data deficits and low density of observations appear in about a third of the corpus, constraining the robustness of spatial extrapolations. The limited transferability of the models confirms that many tools remain dependent on specific local conditions. Finally, the low place given to peasant knowledge indicates that evaluation remains predominantly technocentric. Together, these constraints draw a science that is analytically efficient but still fragile in its capacity for generalization and appropriation.

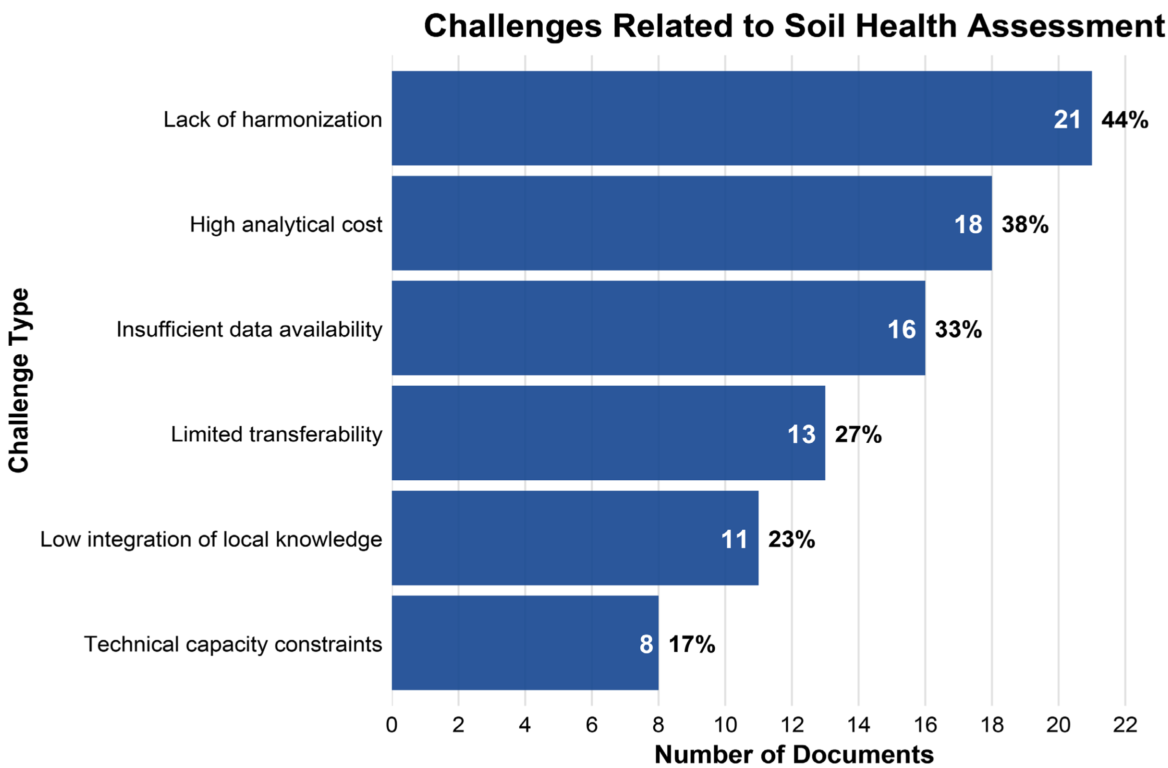

Figure 5. Constraints in assessing soil health.

3.8. Prospects for Improving Soil Health Assessment Indicators

The analysis of the corpus highlights a discipline engaged in a major methodological transition phase. Nearly 35% of the studies explicitly call for strengthening the integration of biological dimensions in order to overcome historical dependence on classical chemical variables. Work conducted in East Africa and highland areas highlights that microbial biomass, enzyme activity and functional indicators improve diagnostic sensitivity to land use change. This evolution responds to the need to better link soil quality and ecosystem services, already identified in previous conceptual frameworks.

At the same time, about 30% of publications insist on the rise of digital approaches. High-resolution predictive mapping and machine learning are transforming fragmented datasets into operational information at the regional scale. However, several authors point out that these performances are based on the availability of reliable analytical references. Without robust calibration, algorithmic sophistication risks amplifying uncertainties rather than reducing them.

The question of harmonization is another central axis, mentioned in nearly a third of the corpus. The development of standardized indices would facilitate inter-site comparability and strengthen the political usefulness of the assessments. Nevertheless, excessive standardization could ignore the pedoclimatic and socio-agronomic diversity of territories.

Spectroscopic technologies appear to be a promising intermediate solution. Several studies demonstrate their ability to simultaneously estimate many parameters with a substantial reduction in costs and processing time. However, their widespread use depends on sustainable investments in data infrastructures. In addition, nearly 20% of studies argue for a hybridization between formal science and peasant knowledge. The integration of perceptual indicators improves the local relevance of diagnoses and promotes the adoption of recommendations. Thus, the perspectives converge towards a more integrated evaluation, combining biology, digital technology and participation. The challenge is no longer just to measure better, but to produce indicators that are transferable, economically viable and socially legitimate.

4. Discussion

The analysis of the forty-eight publications selected highlights a rapid but uneven consolidation of the field of soil health assessment in Sub-Saharan Africa. The results simultaneously reveal a rise in methodological sophistication, a diversification of analytical tools and an extension of the objectives assigned to soil diagnosis, which are now located at the crossroads of agricultural productivity, climate adaptation and ecosystem restoration. However, behind this dynamic, are persistent imbalances in terms of the geographical distribution of knowledge, the choice of indicators and the ability to integrate scientific knowledge and local realities.

The spatial distribution of the corpus illustrates first of all a marked polarization around a few countries. Ethiopia clearly dominates production, driven by work on degradation, land use differentiation and the construction of composite indices [8] [27] [42]. This concentration reflects the existence of structured academic networks and the age of conservation programs in the highlands. Kenya is following a similar trajectory, with particular attention paid to biological dimensions and agroecological gradients [7] [21] [43] [44]. In West Africa, Ghana and Nigeria appear to be prime fields for analyzing the interactions between land use change, fertility and carbon storage [45] [46]. Conversely, Central Africa remains poorly represented; contributions from Cameroon remain ad hoc in view of the strategic importance of these territories [24]. This asymmetry suggests that the scientific mapping of the continent is also a mapping of institutional capacities and funding priorities.

Temporal dynamics reinforce this interpretation. The low production between 2015 and 2019 corresponds to a period of conceptual structuring, marked by the gradual appropriation of the soil health framework promoted internationally [2]. The rapid increase in publications after 2020 reflects a change in scale: soil health is becoming a central instrument to simultaneously respond to food security and climate challenges. In particular, the studies of [46] have contributed to positioning soil as a provider of ecosystem services, paving the way for an increase in projects linking fertility, carbon sequestration and resilience.

Despite this expansion, the analysis of the indicators shows a remarkable stability in the choices made by researchers. Organic carbon dominates by a large margin, present in nearly three-quarters of the studies. This consensus is explained by its ability to link productivity, soil structure and climate mitigation. Continental mapping initiatives have reinforced this centrality by making SOC a key variable for spatial modelling [13] [47]. pH, nitrogen and CEC complete this core of indicators, providing a robust and comparable analytical basis.

However, several authors highlight the limits of this approach. The work of [13] shows that microbiological variables detect the effects of management changes earlier. [7] emphasize that biological dynamics condition the functional stability of soils in constrained environments. However, these indicators remain in the minority. The reasons given relate to the cost of analyses, the scarcity of equipped laboratories and the difficulty of integrating these data into large-scale monitoring frameworks. Thus, the scientific recognition of the role of living things is progressing faster than its implementation.

The generalization of composite indices is another major characteristic of the corpus. By aggregating several parameters into a single score, these tools meet the demand for operationality of decision-makers. Nevertheless, comparisons show that the results depend strongly on normalization and weighting choices [8]. This methodological sensitivity fuels a fundamental debate: should we favor global comparability or local adaptation?

The digital shift accentuates these tensions. The use of machine learning and digital soil mapping has significantly improved spatial prediction ability [11]. However, several studies point out that the quality of maps depends closely on the density and representativeness of the field data. Regions with a small sample size are thus likely to be described on the basis of imported models, reproducing inequalities in knowledge.

Spectroscopic technologies offer the prospect of a breakthrough. [14] demonstrated its effectiveness in simultaneously estimating multiple properties. [48] confirm this potential in Mediterranean and North African contexts. However, their dissemination remains hampered by the lack of shared calibration libraries and equipment requirements.

The management strategies studied also reflect the influence of international agendas. Conservation agriculture largely dominates, supported by evidence of improved carbon and structure. Organic amendments and biochar appear to be relevant supplements for restoring fertility [9] [15]. Agroforestry helps stabilize microclimates and protect against erosion, but requires longer time horizons to produce measurable benefits [49] [50]. One observation runs through the entire corpus: the still marginal place given to peasant knowledge. However, [23] show that farmers have rapid diagnoses that are consistent with scientific measurements. Their low integration suggests a persistent difficulty in articulating academic expertise and local experience [51]-[53].

Ultimately, the results describe a dynamic, technologically innovative discipline, but confronted with major structural challenges: spatial inequalities in knowledge production, dependence on analytical infrastructures, heterogeneity of methodological frameworks and still limited integration of actors. The future consolidation of the field will depend on the ability to overcome these divisions to build evaluation systems that are rigorous, comparable and anchored in territorial realities.

5. Conclusions

The integrated analysis of the corpus highlights a scientific dynamic that is clearly accelerating, with a marked increase in publications after 2020, ranging from 3 publications in 2020 to 13 in 2025. This quantitative increase reflects a growing recognition of the strategic role of soils in climate, food and environmental policies, in line with the Sustainable Development Goals, especially SDGs 2, 13 and 15. However, it is accompanied by a significant geographical concentration. East Africa dominates scientific production, while Central Africa remains under-documented, which calls into question the continental representativeness of diagnoses. Methodologically, the discipline has reached an advanced level of analytical sophistication. The generalization of multivariate analyses, the increasing use of composite indices and the rise of digital soil mapping now make it possible to spatialize edaphic properties with unprecedented resolution and precision. Digital approaches, including machine learning, enhance predictive capacity and decision support. However, this rise in technical power reveals three major weaknesses. Firstly, the lack of methodological harmonization remains a central barrier. Differences in minimum sets of indicators, weights and interpretation thresholds limit comparability across studies. Some analyses show that different methodological choices can significantly modify site rankings, compromising regional comparisons. The construction of common reference frameworks, combining international standardization and local contextualization, is therefore a strategic priority. Secondly, an imbalance persists between physico-chemical and biological indicators. Despite scientific recognition of the role of microbial communities and soil biodiversity in resilience and productivity, biological indicators remain in the minority due to high analytical costs (mentioned in 38% of the studies reviewed) and technical constraints. The development of simplified protocols, the rise of MIR/NIR spectroscopy and high-throughput approaches nevertheless offer concrete prospects for a more systematic integration of living organisms into diagnostics. Thirdly, the question of territorial anchoring appears to be decisive. While predictive models improve spatial coverage, their robustness depends on the density of field data—insufficient in 33% of the cases identified—and the capacity for local ownership. The low level of integration of farmers' knowledge (17% of studies) highlights a participatory deficit that can limit the legitimacy and effectiveness of evaluation mechanisms. Ultimately, soil health assessment is entering a phase of technical maturity but remains in conceptual transition. The challenge in the coming years will no longer be just to increase the accuracy of measurements, but to build comparable, interoperable and socially legitimate frameworks. The future methodological trajectory will be based on a structuring triptych:

- Harmonization of standards, to ensure interregional comparability;
- Controlled technological innovation, to democratize access to advanced diagnostics;
- Co-construction of knowledge, to ensure the territorial anchoring and sustainability of evaluation systems.

It is at the intersection of these three dimensions that a soil science that is robust, inclusive and strategically aligned with global sustainability objectives can emerge.

Authors' Contribution

Anani Ogou: Designed the study, performed the methodology, conducted the review, wrote the original draft of the manuscript, reviewed and finalized the manuscript. Christopher Mubeteneh Tankou: Designed the study, performed the methodology, conducted the review, and edited the manuscript. Honoré Beyegue-Djonko: Performed the methodology, Conducted the review, wrote the manuscript. Asafor Henry Chotangui: Performed the methodology, wrote the manuscript, and edited the manuscript. Georges Martial Ndzana: Performed the methodology, and edited the manuscript. Etienne Mboua: Performed the methodology, and edited the manuscript. Eric Bertrand Kouam: Performed the methodology, and edited the manuscript. Komi Agboka: Performed the methodology, and edited the manuscript. Komi Kouma Mokpokpo Fiaboe: Supervised, and edited the manuscript. Peter Läderach: Supervised, performed the methodology, and edited the manuscript. All the authors checked and approved the final manuscript for the final publication.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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