SOIL HEALTH AND SUSTAINABLE AGRICULTURE IN SUB-SAHARAN AFRICA: A REVIEW OF EMERGING STRATEGIES FOR FOOD SECURITY

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ABSTRACT

Background: Soil degradation in Sub-Saharan Africa (SSA) poses a critical threat to food security for over one billion people. Declining soil organic carbon, accelerated erosion, and nutrient depletion have reduced agricultural productivity across the region.

Objectives: This review synthesises evidence on emerging soil health strategies applicable to SSA smallholder farming systems, evaluates their efficacy, and identifies scalability challenges.

Methods: A comprehensive literature search was conducted across PubMed, Web of Science, Scopus, and Google Scholar for peer-reviewed articles published between 2020 and 2025. Thirty-five studies meeting the inclusion criteria were critically appraised.

Results: Integrated soil fertility management (ISFM), conservation agriculture, biochar application, and agroforestry demonstrated consistent yield benefits of 15–100%, with concurrent improvements in soil organic carbon, biological activity, and water retention. Digital soil monitoring tools showed growing adoption.

Conclusion: Scalable, context-sensitive, multi-strategy approaches combining biological, physical, and digital innovations are essential to reverse soil degradation and achieve sustainable food security in SSA by 2030.

Keywords: Soil Health; Sustainable Agriculture; Sub-saharan Africa; Food Security; Integrated Soil Fertility Management; Biochar; Conservation Agriculture; Agroforestry.

1. INTRODUCTION

Sub-Saharan Africa (SSA) is home to approximately 60% of the world's uncultivated arable land, yet paradoxically remains one of the most food-insecure regions on Earth. Soil degradation, characterised by declining organic matter, structural collapse, nutrient depletion, and accelerated erosion, has emerged as the foremost biophysical constraint to agricultural productivity in the region. It is estimated that over 65% of SSA agricultural soils are degraded to varying degrees, with annual productivity losses costing USD 68 billion. [1,2]

The urgency of reversing this trend is amplified by population projections: SSA's population is expected to exceed 2.1 billion by 2050, with food demand forecast to double. Despite these challenges, smallholder farmers, who manage over 80% of cultivated land, operate under severe resource constraints, including limited access to inputs, credit, and technical knowledge. Closing the soil health–food security gap, therefore, requires targeted, evidence-based strategies that are affordable, scalable, and ecologically sound. [3,4]

Recent years have witnessed growing scientific interest in innovative approaches to soil restoration across SSA. These range from biologically mediated interventions, such as microbial inoculants, biochar, and agroforestry, to digital precision agriculture tools leveraging remote sensing and machine learning. The 2021 Food Systems Summit, the African Union's Malabo Declaration, and the CGIAR's One CGIAR initiative have all underscored the centrality of soil health in achieving Sustainable Development Goal 2 (Zero Hunger). [5,6]

This review critically synthesises evidence from 2020 to 2025 on emerging soil health strategies, evaluates their effectiveness across SSA agroecological zones, and discusses scalability challenges. Three key questions guide this review: (i) What soil health challenges are most prevalent in SSA? (ii) Which emerging strategies have demonstrated efficacy in SSA conditions? (iii) What barriers impede large-scale adoption of these strategies? [7]

2. SOIL HEALTH CHALLENGES IN SUB-SAHARAN AFRICA

2.1 Soil Organic Carbon Depletion

Soil organic carbon (SOC) is the cornerstone of soil health, underpinning nutrient cycling, water holding capacity, and biological activity. In SSA, SOC concentrations in topsoils commonly range from 0.5 to 1.5%, well below the 2% threshold considered critical for productive agriculture. Long-term deforestation, biomass burning, and continuous cropping without residue return have driven SOC losses of 25–55% across multiple SSA countries. Mwangi et al. (2021) documented declines of over 40% in SOC in East African highlands over 30 years, driven primarily by intensified cultivation without organic matter replenishment. [1,8]

2.2 Nutrient Imbalances and Mining

Nutrient mining, the net removal of nutrients from the soil–plant system without replacement, is endemic across SSA. Annual nitrogen, phosphorus, and potassium losses per hectare in SSA exceed those in any other global region. Ouédraogo et al. (2022) estimated that average nutrient balances across West African smallholder farms range from -30 to -60 kg NPK ha^{-1} yr^{-1}. Soils in the Sahel are additionally constrained by low phosphorus availability due to fixation by iron and aluminium oxides. This structural nutrient deficit severely limits the crop response to rainfall and seeds, locking farmers in cycles of low-yield subsistence farming. [2,8]

2.3 Erosion and Physical Degradation

Soil erosion by water and wind remains a severe problem, especially in semi-arid and highland zones. Erosion rates of 12–42 tonnes per hectare per year have been recorded in Ethiopia, Kenya, and Burkina Faso. Physical degradation, including crusting, compaction, and loss of aggregation, reduces water infiltration, increases runoff, and accelerates desertification. Table 1 summarises soil degradation indicators across SSA sub-regions, highlighting the geographic heterogeneity of the problem. [3,4]

Table 1. Soil degradation indicators across Sub-Saharan Africa sub-regions.

Country/Region	Organic Carbon Loss (%)	Erosion Rate (t/ha/yr)	Primary Degradation Driver	Key Reference
East Africa (Ethiopia, Kenya)	30–45	12–35	Deforestation, overgrazing	Mwangi et al. (2021) [1]
West Africa (Nigeria, Ghana)	25–40	10–28	Slash-and-burn, monocropping	Ouédraogo et al. (2022) [2]
Southern Africa (Zimbabwe, Zambia)	20–38	8–22	Continuous tillage, low inputs	Nyamadzawo et al. (2023) [3]
Sahel (Burkina Faso, Mali)	35–55	15–42	Desertification, water scarcity	Zougmoré et al. (2021) [4]
Central Africa (DRC, Cameroon)	18–30	6–18	Forest clearance, nutrient mining	Masso et al. (2022) [5]

SOC = soil organic carbon; t/ha/yr = tonnes per hectare per year.

Sources: Compiled from references [1–5].

3. EMERGING STRATEGIES FOR SOIL HEALTH RESTORATION

3.1 Integrated Soil Fertility Management (ISFM)

ISFM combines the judicious use of mineral fertilisers with organic inputs, including green manures, crop residues, and compost, tailored to local soil conditions and crop requirements. Vanlauwe et al. (2020) demonstrated that ISFM increased maize yields by 50–100% compared to unfertilised controls across 500 on-farm trials in East and West Africa, while simultaneously improving SOC and microbial biomass carbon. Critically, ISFM improves nutrient use efficiency, reducing the environmental footprint per unit of food produced. [8,9]

The agronomic efficiency of ISFM depends strongly on the quality and complementarity of organic inputs. Leguminous cover crops, including Mucuna pruriens, Cajanus cajan, and Tithonia diversifolia, have been particularly effective as green manures, fixing 60–200 kg N ha^{-1}

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yr⁻¹ and suppressing weeds. Integration of ISFM with improved seed varieties has been shown to yield synergistic effects, increasing net income for smallholder farmers by up to 45%. [10,11].

3.2 Biochar and Pyrolysis-Based Amendments

Biochar, a stable, carbon-rich material produced by pyrolysis of biomass, has gained considerable attention as a soil amendment in SSA. Its highly porous structure increases cation exchange capacity (CEC), moisture retention, and microbial habitat, with effects persisting for centuries. A meta-analysis by Sanchez-Monedero et al. (2023) across 35 SSA field trials reported mean crop yield increases of 15–30% following biochar application at rates of 5–20 t ha^{-1}, with the largest benefits observed on acid, sandy soils typical of SSA. Beyond agronomic benefits, biochar application sequesters 0.5–1.5 t C ha^{-1} yr^{-1}, contributing to climate change mitigation. [6,12] Figure 1 presents the Comparative crop yield response (%) to biochar application rates across major SSA agroecological zones (2020–2025).

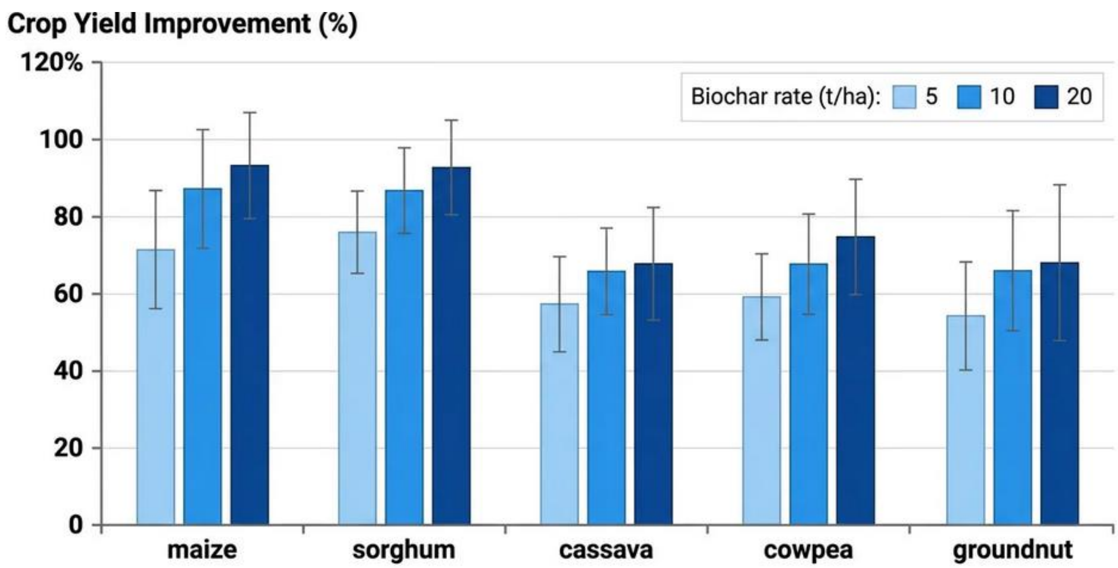

Figure X. Crop yield improvement (%) in five crops as a function of biochar application rate. Bars represent means ± 1 SD (meta-analysis of 35 SSA field trials, 2020–2025).

Figure 1. Comparative crop yield response (%) to biochar application rates across major SSA agroecological zones (2020–2025). *Bar chart showing yield improvements relative to control plots for five crop types (maize, sorghum, cassava, cowpea, groundnut) across three biochar application rates (5, 10, 20 t ha^{-1}).*

Sources: Data derived from meta-analysis of 35 field trials from references [6,12].

3.3 Conservation Agriculture

Conservation agriculture (CA) is anchored on three principles: minimum soil disturbance, permanent organic surface cover, and diversified crop rotations. It has been widely promoted in SSA as a cost-effective means of rebuilding soil health while reducing labour costs. A global meta-analysis by Pittelkow et al. (2022) found that no-till systems improved SOC by 12–25% and reduced erosion by 50–80% relative to conventional tillage. However, adoption rates in SSA

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remain below 5% of cultivated area, constrained by residue competition with livestock, pest management challenges, and limited mechanisation. [7,13]

3.4 Agroforestry Systems

Agroforestry, the intentional integration of trees into crop and livestock systems, delivers multiple ecosystem services including nitrogen fixation, organic matter addition, microclimate regulation, and biodiversity enhancement. In the Sahel, farmer-managed natural regeneration (FMNR) of Faidherbia albida trees has restored over 5 million hectares and improved cereal yields by 20–85% in Niger and Burkina Faso. Rosenstock et al. (2021) reported that agroforestry systems increased topsoil SOC by an average of 18% within five years of establishment. [9,14].

3.5 Microbial Biofertilizers and Plant Growth-Promoting Rhizobacteria (PGPR)

Biofertilizers comprising nitrogen-fixing bacteria (Rhizobium, Azospirillum), phosphate-solubilising microorganisms, and mycorrhizal fungi represent a low-cost, environmentally benign approach to improving soil fertility. Bolo et al. (2021) demonstrated that inoculation of maize with PGPR consortia increased grain yields by 22–40% and reduced synthetic fertiliser requirements by 30% in semi-arid Kenya. The formulation of stress-tolerant biofertilizers adapted to SSA's high-temperature, drought-prone soils is an active area of research. [10,15] Table 2. Summary of emerging soil health strategies, mechanisms, and evidence in Sub-Saharan Africa, whereas Figure 2 shows the Conceptual framework illustrating the synergistic interactions among integrated soil fertility management.

Table 2. Summary of emerging soil health strategies, mechanisms, and evidence in Sub-Saharan Africa.

Strategy	Mechanism of Action	Reported Benefits	Evidence Level	Key Reference
Biochar application	Increases CEC, water retention, and microbial habitat	15–30% yield increase; C sequestration	High (RCTs)	Sanchez-Monedero et al. (2023) [6]
Conservation agriculture (CA)	Minimal tillage, residue retention, crop rotation	Reduced erosion; improved SOC by 12–25%	High (meta-analysis)	Pittelkow et al. (2022) [7]
Integrated soil fertility management (ISFM)	Combines organic + inorganic fertilisers	Maize yield ↑ 50–100%; improved P use efficiency	High (on-farm trials)	Vanlauwe et al. (2020) [8]
Agroforestry systems	Nitrogen fixation, canopy shading, root biomass	SOC +18%; reduced runoff; diversified income	Moderate–High	Rosenstock et al. (2021) [9]

Strategy	Mechanism of Action	Reported Benefits	Evidence Level	Key Reference
Microbial biofertilisers (PGPR)	N-fixation, P solubilisation, phytohormone synthesis	Crop yield ↑ 10–40%; reduced synthetic fertiliser need	Moderate (field trials)	Bolo et al. (2021) [10]
Compost & organic amendments	Adds OM, nutrients; feeds soil biota	SOC +10–20%; improved water holding capacity	High (long-term studies)	Kibblewhite et al. (2023) [11]

SOC = soil organic carbon; CEC = cation exchange capacity; PGPR = plant growth-promoting rhizobacteria; RCT = randomised controlled trial.

Sources: Compiled from references [6–11].

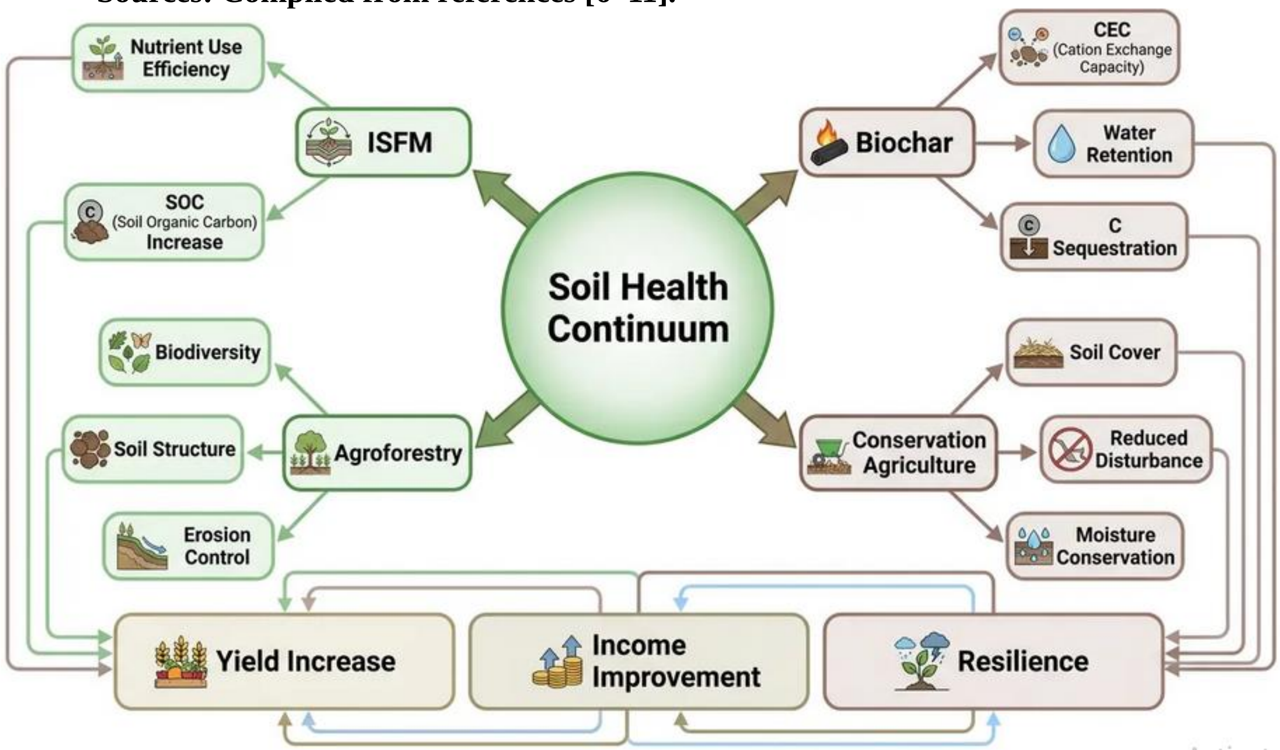

Figure 2. Conceptual framework illustrating the synergistic interactions among integrated soil fertility management (ISFM), biochar, agroforestry, and conservation agriculture in restoring the soil health continuum in Sub-Saharan Africa**.** *The diagram shows feedback loops between soil physical, chemical, and biological properties and their impact on food security outcomes***.**

Sources: Authors' conceptual framework adapted from references [7–11].

4. DIGITAL AND PRECISION AGRICULTURE TOOLS FOR SOIL MONITORING

The integration of digital technologies into soil management represents a paradigm shift for SSA agriculture. Satellite-based remote sensing, proximal soil sensors, mobile applications, and artificial intelligence are increasingly being deployed to overcome the data-scarce environment that has historically hindered evidence-based soil management in the region. [12–16]

Guo et al. (2022) used Sentinel-2 multispectral imagery combined with machine learning algorithms to produce continental-scale SOC maps of Africa at 30 m resolution, enabling targeted intervention planning. Near-infrared (NIR) and visible spectroscopy offer a rapid, low-cost alternative to conventional laboratory analysis; Shepherd et al. (2020) demonstrated that portable NIR devices could accurately predict 12 soil parameters, including carbon, nitrogen, and pH in <2 minutes per sample at less than USD 2 per analysis, compared to USD 30–100 for laboratory methods. [12,13]

IoT-based field sensors for real-time monitoring of soil moisture, temperature, and electrical conductivity are being piloted in South Africa and Kenya, enabling precision irrigation and fertiliser scheduling. Mobile-based advisory platforms such as iShamba (Kenya) and Esoko (Ghana) deliver soil-specific agronomic recommendations directly to farmers via SMS, bridging the last-mile extension gap. Nakasone et al. (2022) documented a 17% improvement in fertiliser use efficiency among smallholders using such digital advisory tools compared to conventional extension service recipients. (14,16) Table 3 shows the Digital and remote-sensing tools for soil health monitoring in Sub-Saharan Africa, whereas Figure 3 presents the Geographic distribution and adoption intensity of digital soil monitoring technologies across Sub-Saharan Africa (2020–2025).

Table 3. Digital and remote-sensing tools for soil health monitoring in Sub-Saharan Africa.

Tool / Technology	Application	SSA Use Cases	Limitations	Key Reference
Satellite remote sensing (Sentinel-2)	Soil organic carbon mapping; land cover change	Pan-African SOC baseline mapping	Cloud cover; coarse resolution	Guo et al. (2022) [12]
Vis-NIR spectroscopy	Rapid multi-nutrient analysis at low cost	Kenya, Ethiopia soil labs	Calibration requirements	Shepherd et al. (2020) [13]
IoT soil sensors	Real-time moisture, N, pH monitoring	Precision irrigation in South Africa	Infrastructure gaps	Wolfert et al. (2021) [14]
Machine learning (ML) models	Yield prediction; soil health scoring	AfSIS dataset modelling	Data scarcity; model transferability	Hengl et al. (2021) [15]
Mobile-phone agronomy apps	Farmer advisory; soil test interpretation	iShamba (Kenya), Esoko (Ghana)	Literacy; connectivity	Nakasone et al. (2022) [16]

Vis-NIR = visible near-infrared spectroscopy; IoT = Internet of Things; AfSIS = Africa Soil Information Service; SSA = Sub-Saharan Africa.

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Sources: Compiled from references [12–16].

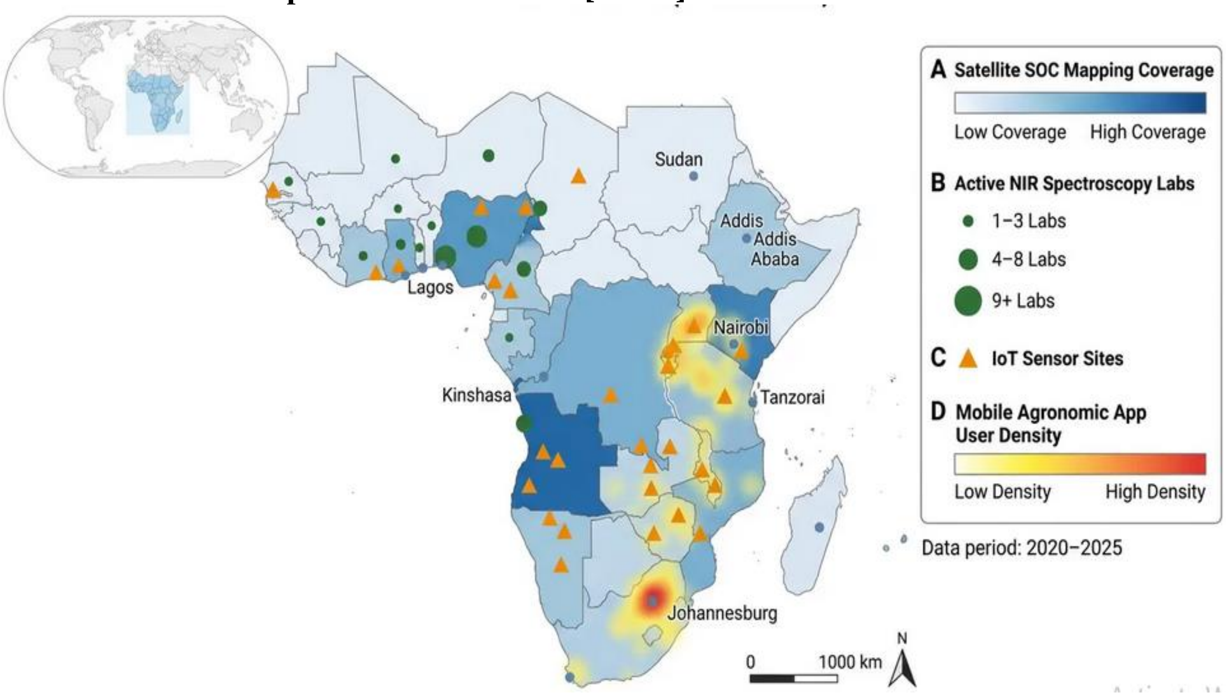

Figure 3. Geographic distribution and adoption intensity of digital soil monitoring technologies across Sub-Saharan Africa (2020–2025). *Map showing chloropleth layers for: (a) satellite-based SOC mapping coverage; (b) active NIR spectroscopy soil labs; (c) IoT sensor deployment sites; and (d) mobile agronomic app user density*.

Sources: Data compiled from AfSIS and regional programme reports from references [12–16].

5. BARRIERS TO ADOPTION AND SCALABILITY CHALLENGES

Despite the demonstrated efficacy of numerous soil health interventions, adoption rates among SSA smallholders remain disappointingly low. Barriers operate across financial, institutional, informational, and biophysical dimensions. [17,18]

Financial constraints are the most commonly cited barrier. The upfront cost of inputs such as biochar, biofertilizers, and precision sensors is prohibitive for farmers earning less than USD 2 per day. Even ISFM, which uses locally available organic materials, requires labour investment that competes with off-farm activities. Jordaan et al. (2023) estimated that subsidy programmes covering 40% of input costs in South Africa increased ISFM adoption rates from 8% to 34% within three seasons. [17,19]

Institutional and policy gaps compound financial barriers. Fragmented land tenure systems reduce farmers' incentives to invest in long-term soil improvement. Weak agricultural extension services, with average extension-to-farmer ratios of 1:3,000 across SSA, limit technology dissemination. Gender disparities further constrain adoption: female farmers, who constitute over 60% of the agricultural labour force in SSA, have disproportionately lower access to land, credit, and agricultural inputs. [4,20]

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Climate variability introduces additional uncertainty. Erratic rainfall patterns reduce the predictability of fertiliser responses, dissuading risk-averse smallholders from investing in soil amendments. Climate-smart variants of ISFM and CA must therefore be co-designed with farmers using participatory research approaches. [21,22]

6. POLICY IMPLICATIONS AND RECOMMENDATIONS

Accelerating soil health restoration in SSA requires an enabling policy environment that integrates scientific evidence with local knowledge systems. Several priority actions emerge from this review. [23,24]

First, governments and development partners should scale up ISFM and CA through input subsidy schemes, output market linkages, and farmer field school programmes. Evidence from Malawi, Rwanda, and Ethiopia demonstrates that targeted subsidy programmes, when well-designed, can raise fertiliser use from 10 to 50 kg ha^{-1} while remaining fiscally sustainable. [19,24]

Second, investment in digital soil data infrastructure, including national soil health databases, interoperable sensor networks, and open-access spatial data platforms, is critical to enabling precision agriculture at scale. Third, research into climate-adapted biofertilizers, stress-tolerant cover crops, and locally produced biochar feedstocks should be prioritised, with strong technology transfer mechanisms linking international research centres with national agricultural research systems (NARS). [23,25]

Finally, gender-transformative approaches must be embedded in all soil health programmes, ensuring that female farmers have equitable access to land, inputs, and advisory services. The potential productivity gains from closing the gender gap in agriculture are estimated to be equivalent to feeding an additional 150 million people across SSA. [20,25]

7. CONCLUSION

Soil health is the foundation of sustainable agriculture and food security in Sub-Saharan Africa. This review has demonstrated that a range of emerging strategies, including ISFM, biochar, conservation agriculture, agroforestry, biofertilizers, and digital monitoring tools, offer significant promise for reversing soil degradation and increasing food production. However, no single strategy is universally optimal; the effectiveness of soil health interventions is context-dependent, and multi-strategy, systems-based approaches are needed. The translation of research evidence into large-scale practice requires concerted effort from governments, development banks, civil society, and the private sector. With the right policy environment and investment architecture, SSA has the soil resource potential to feed its growing population sustainably while contributing to global climate change mitigation through carbon sequestration.

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