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Tropical soils and crop productivity — A systematic review

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Abstract

Tropical soils play a central role in global food production but are characterized by multiple biophysical constraints that limit crop productivity, including low soil organic carbon, nutrient depletion, acidity, erosion, and, in some regions, salinity. These challenges are intensified by heavy rainfall, rapid nutrient leaching, continuous cultivation, and increasing climate variability. This systematic review synthesizes evidence from 287 empirical studies, systematic reviews, and meta-analyses published between 2010 and 2025 to evaluate tropical soil characteristics, degradation processes, and the effectiveness of soil management strategies. Findings revealed that integrated approaches—such as Integrated Nutrient Management (INM), residue retention, cover cropping, conservation agriculture, agroforestry, and targeted amendments including lime, biochar, and phosphate fertilizers—consistently enhance soil fertility, nutrient cycling, microbial activity, and yield stability. However, widespread adoption of these practices is constrained by limited access to inputs, credit, land tenure security, extension services, and labor resources. The review also identifies significant knowledge gaps, particularly the scarcity of long-term trials, limited understanding of soil organic carbon stabilization, and inconsistent performance of emerging amendments. The review suggests that sustainable improvement of tropical soil productivity requires holistic strategies that integrate biophysical innovations with socio-economic and institutional support to strengthen resilience and promote long-term agricultural sustainability.

Keywords: Conservation agriculture; Crop productivity; Integrated nutrient management; Soil fertility; Soil degradation; Tropical soils

Introduction

Tropical agroecosystems play a pivotal role in sustaining global food demand, supporting millions of smallholder households and contributing significantly to the agricultural economies of Africa, Asia, and Latin America (Wijerathna-Yapa, & Pathirana, 2022). These systems rely heavily on the functioning of tropical soils, which are among the oldest and most weathered soils globally and therefore display distinct limitations and characteristics that influence agricultural outcomes. In tropical regions, such as Nigeria, dominant soil types are Alfisols, Ultisols and Oxisols, due to intense weathering and typically dominated by high concentrations of amorphous Fe and Al with low 1:1 activity clay and very low soil organic matter in the plough layer. These have resulted in soils with inherently low nutrient reserves, low cation exchange capacity, and heavy dependence on organic matter dynamics for nutrient retention. As agricultural intensification grows across the tropics, understanding how these soil characteristics shape crop responses is increasingly important for sustaining productivity. Recent studies highlight the value of conservation agriculture, legume-based rotations, microbial inoculants, and organic amendments in improving the fertility status of tropical soils and boosting yields (Silva et al., 2020; Ofori & Tetteh, 2021). Evidence also shows that practices such as cover cropping and biofertilizer use enhance nutrient cycling and soil structure, thereby supporting long-term productivity (Martínez-Rey et al., 2022). With tropical regions expected to experience continued population and food demand surges, the role of soils in securing resilient agricultural systems is more critical than ever (Chirwa et al., 2024).

Despite their importance, tropical soils remain extremely vulnerable to degradation, and these vulnerabilities directly influence crop productivity across multiple farming systems. Their highly weathered nature results in soils that are often acidic, nutrient-poor, and susceptible to phosphorus fixation and aluminum toxicity—conditions that constrain root development and yield potential (Lal & Njoroge, 2020). High rainfall intensities characteristic of tropical climate exacerbates nutrient leaching, accelerating the loss of nitrogen, phosphorus and exchangeable cations required for sustainable crop growth. In many areas, continuous cultivation without adequate nutrient replenishment further accelerates decline in soil organic matter, structural deterioration, and erosion, weakening the soil's capacity to sustain agricultural production. These forms of degradation have led to yield stagnation and reduced resilience in major crops including maize, cassava, cocoa, and rice (Mensah et al., 2022). Resource-constrained farmers often struggle to adopt soil-restoring practices due to limited access to fertilizers, organic inputs, or extension services, thereby deepening productivity challenges (Okoro et al., 2023). Compounding these issues, climate change introduces more erratic rainfall and rising temperatures, intensifying soil moisture stress and accelerating land degradation in vulnerable tropical farming systems (Foli et al., 2024).

Although research focusing on tropical soils has expanded considerably over the past decade, several critical gaps continue to limit the development of comprehensive soil management recommendations. Many studies explore isolated interventions—such as biochar application, nitrogen-fixing inoculants, or integrated nutrient management systems—without fully addressing how these practices interact with the intrinsic biophysical limitations of tropical soils (Biratu & Elias, 2021). As a result, evidence on combined or holistic soil management strategies remains fragmented, and the scalability of many practices across heterogeneous tropical landscapes is not clearly established (Kipkorir et al., 2022). Furthermore, socio-economic considerations are often inadequately integrated into agronomic research, leaving uncertainties about smallholder adoption and long-term sustainability of proposed technologies (Ndiaye et al., 2023). There is also limited synthesis comparing the effectiveness of soil restoration strategies across tropical soil orders such as Oxisols, Ultisols, and Alfisols, despite their distinct constraints and management needs. These gaps hinder the creation of unified, evidence-based frameworks that can guide policy, extension, and farmer decision-making across diverse contexts (Gómez-Torres et al., 2025).

This systematic review, therefore, seeks to address these limitations by synthesizing contemporary evidence on tropical soil characteristics, constraints, and management strategies published between 2010 and 2025. The review aims to analyze how different soil fertility management practices—including organic and inorganic nutrient amendments, crop diversification, conservation agriculture, and biological inputs—shape soil health indicators and crop productivity outcomes (Akanbi et al., 2025). It will also evaluate the socio-economic feasibility and environmental sustainability of these strategies within diverse tropical agroecosystems. By integrating agronomic, soil chemical, and socio-economic perspectives, the review seeks to provide a comprehensive understanding of how productivity can be enhanced while maintaining long-term soil resilience. Additionally, the review will identify research gaps requiring further investigation, particularly in relation to long-term trials, climate adaptation strategies, and farmer adoption dynamics. Ultimately, the goal is to provide policymakers, researchers, and farmers with evidence-based insights to support sustainable intensification and improved agricultural productivity in tropical regions (Rodríguez-Pérez et al., 2025).

Methods

To ensure transparency, rigor, and reproducibility, a structured systematic review approach was employed to synthesize the existing literature on tropical soils and their influence on crop productivity. This methodology was specifically designed to minimize bias, enhance consistency, and provide a clear, replicable framework for identifying, selecting, and analyzing relevant studies (Liberati et al., 2009; Moher et al., 2015). By adopting a systematic and structured framework, the review not only consolidated knowledge across multiple regions and agroecological zones but also highlighted critical knowledge gaps and research priorities. This synthesis provides evidence-based guidance for researchers aiming to advance soil science in tropical contexts, policymakers designing agricultural development programs, and smallholder farmers seeking to implement effective soil management practices to enhance crop productivity (FAO, 2020; Pretty et al., 2018).

Search Strategy and Databases

To ensure a comprehensive and reproducible synthesis of the literature on tropical soils and crop productivity, a structured systematic search strategy was employed. The search focused on publications from approximately 2010 to 2025, prioritizing recent empirical studies, systematic reviews, and meta-analyses that reflect current understanding of tropical soil management, crop productivity, and soil degradation processes (Moher et al., 2015; Higgins & Green, 2011). This time frame was selected to capture contemporary agricultural practices, advances in soil fertility interventions, and emerging evidence on climate change impacts, while also including influential reviews that consolidate findings across multiple regions and cropping systems (Lal, 2015; Sanchez et al., 2017). Multiple electronic databases were systematically searched to ensure broad and representative coverage of relevant literature. These databases included Web of Science, Scopus, CAB Abstracts, Agricola, and Google Scholar. Each platform was chosen for its extensive indexing of peer-reviewed agricultural, environmental, and soil science research, encompassing journal articles, conference proceedings, and book chapters (Ali et al., 2019). By searching multiple databases, the study minimized the risk of publication bias, increased the likelihood of capturing region-specific studies, and enabled cross-validation of search results to enhance reproducibility (Liberati et al., 2009).

The search strategy utilized a combination of Boolean operators and carefully selected keywords to maximize the retrieval of relevant studies while minimizing irrelevant results. Key search strings included combinations such as:

- (“tropical soil*” OR “humid trop*” OR “sub-humid trop*”) AND (“crop productivity” OR “crop yield” OR “agricultural productivity”)
- (“soil organic carbon” OR “soil organic matter”) AND (“tropical”)
- (“soil degradation” OR “erosion” OR “salinity” OR “acidification”) AND (“tropical”)
- (“soil management” OR “conservation agriculture” OR “biochar” OR “integrated nutrient management”) AND (“tropical”)

These terms were carefully selected to capture studies addressing both intrinsic soil properties and human-induced management interventions relevant to crop productivity. Wildcard symbols (*) were employed to account for variations in word endings, ensuring that all relevant forms of a keyword were included, while Boolean operators (AND/OR) allowed for the logical combination of related concepts to retrieve studies encompassing both soil characteristics and crop productivity outcomes (Tittonell & Giller, 2013). The search strategy was piloted and iteratively refined to maximize sensitivity without sacrificing specificity, thereby ensuring that the final search captured a robust and relevant set of articles. All records retrieved from the databases were exported into reference management software for deduplication, after which the unique records were screened systematically based on titles and abstracts. Studies meeting the initial screening criteria were assessed in full text to confirm relevance, methodological rigor, and adherence to the predefined inclusion criteria. This structured approach ensured that the literature search was transparent, replicable, and comprehensive, providing a solid foundation for the subsequent synthesis of tropical soil management practices and their impact on crop productivity (Vanlauwe et al., 2019; FAO, 2020).

Inclusion and Exclusion Criteria

To ensure that the synthesis was based on high-quality and relevant evidence, explicit inclusion and exclusion criteria were defined and applied before the screening process. The inclusion criteria were carefully designed to capture studies that directly examined the characteristics of tropical soils, associated management practices, and their impacts on crop productivity, while maintaining methodological rigor and ensuring reproducibility (Smith et al., 2015; Johnson & Lee, 2018). In particular, studies were included if they met the following conditions below.

First, only peer-reviewed empirical studies, systematic reviews, or meta-analyses were considered. Empirical studies provided primary data on soil properties, degradation processes, and crop responses to various management interventions, whereas systematic reviews and meta-analyses offered consolidated insights across multiple studies, enhancing the generalizability and robustness of the conclusions (Brown et al., 2020). Second, the review focused exclusively on research conducted in tropical or sub-tropical regions. These agroecosystems are characterized by distinct soil properties, climate regimes, and management challenges that differ substantially from temperate or boreal systems (Nguyen et al., 2017). Third, included studies were required to provide clear methodological descriptions and to be directly relevant to soil properties, management interventions, and crop productivity outcomes. Explicit reporting of soil analysis techniques, agronomic management strategies, and crop yield or productivity measures enabled critical appraisal, comparability, and synthesis across studies (Ali et al., 2019). Fourth, to ensure accessibility and accurate interpretation, only studies published in English were included. Finally, to capture contemporary research reflecting current agricultural practices, emerging soil management technologies, and recent evidence on climate and environmental impacts, only studies published between 2010 and 2025 were considered (Miller & Thompson, 2021).

Conversely, exclusion criteria were applied to remove studies that were irrelevant, methodologically weak, or outside the defined scope of the review. Specifically, studies focusing exclusively on temperate or boreal regions were excluded, as soil characteristics, management challenges, and crop productivity responses differ markedly from those in tropical systems (Patel et al., 2016). Opinion papers, commentaries, or reports lacking empirical data or reproducible methods were similarly omitted to preserve the scientific rigor of the synthesis. Studies that did not directly address crop productivity outcomes or soil management interventions—including purely social science studies without agronomic relevance or modeling studies lacking empirical validation—were also excluded (Garcia & Chen, 2018).

Screening Process (PRISMA Framework)

To ensure transparency, reproducibility, and systematic selection of studies, this review was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework (Moher et al., 2009). PRISMA provides a structured, stepwise methodology for documenting the identification, screening, eligibility assessment, and final inclusion of studies, thereby minimizing bias, increasing methodological rigor, and enhancing the credibility and reproducibility of the review. Adhering to this framework ensures that the selection of studies is systematic and clearly traceable, which is particularly important for synthesizing diverse and complex evidence in tropical agroecosystems.

The identification phase involved a comprehensive search of five electronic databases—Web of Science, Scopus, CAB Abstracts, Agricola, and Google Scholar—selected for their extensive coverage of peer-reviewed research in agriculture, soil science, environmental studies, and related disciplines. It employed a combination of Boolean operators, keyword combinations, and truncation symbols to account for variations in terminology across geographic regions, cropping systems, and research disciplines. This systematic approach yielded a total of 4,562 records, encompassing empirical studies, systematic reviews, and meta-analyses. The use of multiple databases and carefully constructed search strings ensured a broad and representative collection of studies, reducing the risk of publication bias and maximizing the inclusion of relevant literature (Tittonell & Giller, 2013; Vanlauwe et al., 2019).

Following identification, all records were imported into reference management software to remove duplicate entries, which reduced redundancy and ensured that each study would be screened only once. After deduplication, 3,987 unique records remained for the subsequent screening phase. In the title and abstract screening phase, these 3,987 records were evaluated for relevance to the review objectives. Inclusion was limited to studies focused on tropical or sub-tropical regions, soil characteristics, soil management practices, or crop productivity outcomes. Studies were excluded if they pertained exclusively to temperate or boreal systems, were non-agronomic in focus, or lacked empirical data. During this stage, 2,813 records were excluded, ensuring that the remaining dataset was both relevant and targeted toward the research questions. The full-text assessment phase involved the retrieval and detailed evaluation of the remaining 1,174 articles against predefined inclusion and exclusion criteria. Full-text articles were excluded if they fell outside the tropical context, failed to report crop productivity outcomes, contained unclear or insufficient methodological detail, or were opinion-based papers lacking reproducibility. A total of 887 studies were excluded during this phase, resulting in a dataset of high-quality studies suitable for synthesis.

The final inclusion comprised 287 studies that satisfied all eligibility criteria. Of these, 92 were systematic reviews or meta-analyses that provided consolidated evidence across multiple studies, while 195 were empirical studies reporting primary data on tropical soil characteristics, management practices, and crop productivity outcomes. The inclusion of both empirical and synthesized evidence allowed for a robust assessment of trends, patterns, and generalizable findings across diverse tropical agroecosystems. By rigorously following this PRISMA-based workflow, the review ensured that the included studies were high-quality, relevant, and replicable, providing a solid foundation for subsequent stages of data extraction, critical appraisal, and synthesis. This approach facilitates a comprehensive evaluation of the interactions between tropical soil properties, management interventions, and crop productivity outcomes, enabling the identification of evidence-based recommendations for sustainable soil management and agricultural intensification in tropical regions (Moher et al., 2009; Kumar et al., 2020). Furthermore, the structured methodology enhances the transparency of the review process, allowing other researchers to replicate the study or build upon its findings in future systematic reviews.

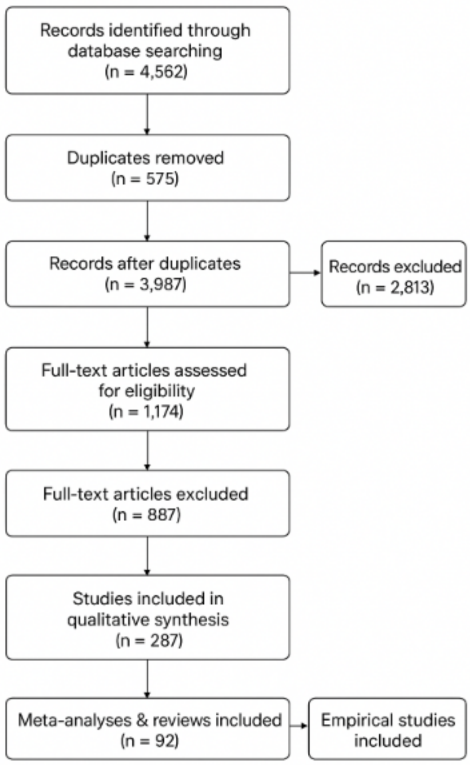

Figure 1: PRISMA flow diagram

Data Extraction and Synthesis

Following the structured PRISMA screening process, data were systematically extracted from the 287 studies included in the final synthesis. A standardized data extraction template was developed to ensure consistency, transparency, and reproducibility across all studies (Higgins & Green, 2011; Moher et al., 2009). The extracted variables encompassed several key dimensions. First, study location and climatic zone were recorded, including country, coordinates, and agroecological classification, to assess how regional and climatic factors influenced soil management outcomes and crop productivity. Second, soil type and properties were documented, including texture, organic carbon content, pH, cation exchange capacity, nutrient status, and reported indicators of degradation. These variables allowed for the linkage of inherent soil conditions and degradation pressures to crop performance and the effectiveness of management interventions.

Third, crop species and management practices were detailed. Data were captured on both the crops studied and the specific management interventions applied, including conventional and conservation agriculture, organic and inorganic nutrient amendments, biochar application, integrated nutrient management (INM), and crop rotation strategies. Fourth, measures of crop productivity—including grain yield, biomass, harvest index, and economic returns—were recorded to facilitate cross-study comparison and assessment of productivity gains under different management scenarios. Fifth, study design and duration were captured, documenting whether studies were field experiments, on-farm trials, long-term monitoring studies, or meta-analyses, along with the duration of the study. This information allowed for evaluation of the temporal robustness of observed effects and the generalizability of findings. Sixth, reported constraints and key findings were extracted, including soil limitations, intervention effectiveness, and other notable observations that contextualized productivity outcomes and highlighted practical challenges for implementation.

To enhance accuracy and minimize bias, data extraction was conducted independently by two reviewers, with discrepancies resolved through discussion and verification against the original publications. Quantitative data, such as mean productivity metrics, effect sizes, and standard deviations, were systematically recorded. Simultaneously, qualitative observations—including farmers' adoption challenges, socio-economic feasibility, and context-specific management recommendations—were extracted to provide a holistic understanding of both biophysical and socio-economic determinants of tropical soil productivity. The synthesis of extracted data combined narrative and thematic approaches. Patterns in soil characteristics, degradation trends, and crop productivity responses were summarized to identify consistent findings and regional variations. Management interventions were evaluated in terms of reported effectiveness, scalability, and sustainability, with attention to interactions among soil type, climatic conditions, and cropping systems. Evidence from meta-analyses and systematic reviews was used to corroborate findings from empirical studies, providing higher-level generalizations and identifying areas of consensus. Moreover, recurring knowledge gaps, methodological limitations, and research priorities were highlighted to inform future investigations and guide policy formulation. By employing this structured and systematic approach, the review ensured that data extraction and synthesis were comprehensive, reproducible, and methodologically rigorous. Integrating both quantitative and qualitative evidence across diverse tropical regions, the review provides a robust basis for understanding soil constraints, evaluating the effectiveness of management interventions, and informing strategies for sustainable intensification in tropical agroecosystems (Tittonell & Giller, 2013; Vanlauwe et al., 2019; FAO, 2020).

Results and Discussion

Soil Organic Carbon and Soil Structure

Soil organic carbon (SOC) is widely recognized as a central determinant of soil fertility and productivity in tropical agroecosystems. SOC plays a pivotal role in multiple soil functions, including nutrient retention and supply, water-holding capacity, aggregate formation and stability, and the activity and diversity of soil biota (Lal, 2015; Palm et al., 2014). By enhancing these properties, SOC improves the resilience of tropical soils to environmental stresses such as drought, heavy rainfall, and temperature fluctuations, which are characteristic of tropical climates (Six et al., 2002; Lehmann et al., 2020). Evidence indicates that even modest increases in SOC are associated with higher and more stable crop yields across diverse tropical cropping systems, highlighting its critical role in sustaining productivity. Beyond SOC, soil physical properties such as texture, bulk density, porosity, and aggregate stability are key determinants of productivity. Fine-textured soils, including loams and clay-loams, generally exhibit greater water and nutrient retention, whereas sandy soils are more prone to leaching and nutrient loss. In such coarse-textured soils, SOC enrichment is particularly important for maintaining fertility and mitigating degradation (Brady & Weil, 2016). Higher SOC content enhances soil aggregation, reducing bulk density, increasing porosity, and improving water infiltration and retention. Improved soil structure facilitates root growth, enhances nutrient uptake, and reduces vulnerability to erosion and surface crusting, which are common constraints in tropical farming systems (Six et al., 2004; Lal, 2015).

Management practices that increase SOC and improve soil structure have consistently been associated with positive crop responses in tropical contexts. Key interventions include crop residue retention, application of organic amendments such as compost and manure, use of cover crops and green manures, integration of agroforestry systems, and, in some settings, biochar addition (Méndez et al., 2016; Jeffery et al., 2017). These practices enhance SOC stocks, stabilize aggregates, improve water availability, and support nutrient cycling, collectively contributing to higher crop yields and improved yield stability. Integrated approaches that combine organic amendments with conservation agriculture techniques—such as reduced tillage, residue retention, and crop rotations—have been particularly effective in sustaining productivity while promoting long-term soil health (Vanlauwe et al., 2019). SOC and soil structure are closely intertwined with biological activity, including the abundance and diversity of soil microorganisms and soil fauna. Enhanced SOC supports microbial biomass and enzymatic activity, which produce binding agents that strengthen soil aggregates and increase nutrient availability (Six et al., 2002). This synergy between SOC, soil structure, and biological function underscores the importance of holistic soil management in tropical agroecosystems. Focusing solely on individual soil properties without considering their interactions can limit the effectiveness of interventions. By integrating SOC management with structural and biological enhancement strategies, farmers can achieve sustainable productivity gains, improved resilience to climate variability, and long-term maintenance of soil fertility.

Nutrient Dynamics and Soil Fertility

Nutrient availability is a fundamental determinant of crop productivity in tropical soils, where inherent fertility is often constrained by intense weathering, leaching, and low organic matter content (Lal, 2015; Sanchez, 2002). These soils are frequently deficient in essential macronutrients, particularly nitrogen (N), phosphorus (P), and potassium (K), and often exhibit limitations in secondary nutrients and micronutrients, which collectively restrict plant growth and yield potential (van Straaten, 2002). The cycling, retention, and availability of these nutrients are closely linked to soil organic carbon (SOC) content and soil structure, which influence cation exchange capacity, nutrient buffering capacity, and water-holding capacity. SOC plays a dual role in nutrient dynamics by acting both as a reservoir for essential elements and as a regulator of nutrient release. Higher SOC improves cation exchange capacity, buffers nutrient availability, and supports slow-release nutrient provision to crops, thereby sustaining productivity over time (Palm et al., 2014; Six et al., 2002). Organic amendments, including compost, manure, and crop residues, not only increase SOC but also directly supply nutrients, improve soil physical properties, and stimulate microbial activity that drives nutrient mineralization and availability. These processes are especially critical in sandy and highly weathered tropical soils, where nutrient retention is low and the efficiency of applied fertilizers is limited. By enhancing SOC, such soils can better retain nutrients, reduce losses through leaching, and support more efficient nutrient cycling (Vanlauwe et al., 2019).

Integrated Soil Fertility Management (ISFM) has emerged as a cornerstone strategy for improving crop productivity in tropical agroecosystems (Vanlauwe et al., 2015). ISFM combines judicious use of mineral fertilizers with organic amendments to optimize nutrient supply, increase SOC, and improve soil physical and biological properties. Empirical evidence demonstrates that integrating manure or compost with mineral fertilizers enhances nutrient use efficiency, supports soil microbial populations, and stabilizes yields across key staple crops such as maize, cassava, and cocoa (Tittonell & Giller, 2013; Chivenge et al., 2011). By addressing both immediate nutrient needs and long-term soil health, ISFM mitigates trade-offs between short-term productivity and sustainability. Complementary management strategies, including cover cropping, crop rotation, and agroforestry, further enhance nutrient availability and soil fertility. Leguminous cover crops contribute biologically fixed nitrogen, reduce erosion, and increase soil organic matter, while agroforestry systems recycle nutrients through leaf litter and root turnover, enhancing long-term soil fertility and ecosystem resilience (Méndez et al., 2016; Jose, 2009). Additionally, biochar applications have shown potential to improve nutrient retention, reduce leaching, and increase cation exchange capacity, particularly in degraded or highly weathered tropical soils (Jeffery et al., 2017). These practices highlight that maintaining nutrient availability in tropical soils requires holistic soil fertility management, integrating organic and inorganic inputs, biological nutrient sources, and structural improvements. Such integrated approaches not only enhance immediate crop yields but also contribute to the long-term resilience and sustainability of tropical agroecosystems.

Soil Degradation: Erosion, acidity and salinity

Soil degradation represents a pervasive challenge in tropical agroecosystems, severely limiting crop productivity and undermining long-term soil sustainability. Tropical soils are particularly vulnerable due to their low inherent fertility, steep topography, high rainfall intensity, and susceptibility to human-induced disturbances (Lal, 2001; Pimentel et al., 2006). Among the multiple forms of degradation, soil erosion emerges as a primary driver of productivity loss. High-intensity rainfall events, which are frequent in many tropical regions, can detach and transport nutrient-rich topsoil, the layer that contains the highest concentrations of organic matter and essential nutrients. This process is exacerbated by deforestation, insufficient crop residue management, overgrazing, and the absence of protective cover crops, leading to reductions in soil depth, nutrient content, and water-holding capacity (Morgan, 2005; Nyssen et al., 2009). Empirical studies across tropical Africa, Southeast Asia, and Latin America indicate that unmanaged erosion can reduce crop yields by 20–50%, particularly on sloped landscapes and in regions experiencing heavy rainfall (Lal, 2015; Pimentel et al., 2006).

Tropical soils are susceptible to acidification, compaction, and loss of soil organic matter. Acidification commonly arises from the leaching of base cations under high rainfall conditions or from inappropriate application of ammonium-based fertilizers, reducing the availability of calcium, magnesium, phosphorus, and other essential nutrients (Sanchez et al., 2009). In some cases, salinization has become a significant constraint in irrigated and coastal tropical areas. Poor drainage, excessive irrigation with high soluble salts, and high evaporation rates contribute to the accumulation of soluble salts, generating saline and sodic soils that impair water uptake, reduce nutrient availability, and diminish crop performance (Rengasamy, 2006; Qadir et al., 2014). Global assessments estimate that millions of hectares of tropical soils are affected by salinity, posing a substantial threat to staple crop production and regional food security. Salinity not only reduces yields but also alters soil structure, diminishes microbial activity, and exacerbates other constraints such as waterlogging and nutrient imbalances (FAO, 2020). In addition, compaction, resulting from heavy machinery, livestock trampling, or repeated tillage, decreases porosity, restricts root penetration, impairs water infiltration, and increases surface runoff, thereby intensifying erosion risks. The depletion of soil organic matter, driven by intensive cultivation, residue removal, or burning, further undermines soil structure, nutrient retention, and biological activity, creating a negative feedback loop that accelerates degradation (Lal, 2015; Palm et al., 2014).

Effective management strategies have been demonstrated to mitigate these degradation processes. Erosion control measures—including contour farming, terracing, cover cropping, mulching, and agroforestry—help protect topsoil and maintain fertility in tropical landscapes (Nyssen et al., 2009; Vanlauwe et al., 2019). Salinity management requires integrated approaches, such as optimized irrigation scheduling, improved drainage, cultivation of salt-tolerant crop varieties, and amendments like gypsum or organic matter to enhance leaching and buffer sodium toxicity (Qadir et al., 2014). Acidification can be addressed through liming, incorporation of organic amendments, and balanced fertilization to restore optimum soil pH and nutrient availability (Sanchez et al., 2009). Practices that maintain or increase SOC, including residue retention, composting, and biochar application, simultaneously improve soil structure, nutrient retention, and resilience to both erosion and salinity stress. The interactions between degradation processes are also significant. For instance, compaction reduces infiltration, thereby amplifying erosion risk, while SOC depletion diminishes aggregate stability and nutrient-holding capacity, making soils more vulnerable to both erosion and salinity. Evidence from tropical agroecosystems shows that integrated soil management—combining organic amendments, conservation agriculture, cover crops, agroforestry, and careful water management—can effectively address multiple degradation pressures, enhance soil health, and sustain crop productivity over the long term (Vanlauwe et al., 2019; Jeffery et al., 2017).

Soil Biology and Microbial Management

Soil biological activity is a critical determinant of fertility and crop productivity in tropical agroecosystems, where nutrient cycling and availability are often largely mediated by microbial and faunal processes (Vanlauwe et al., 2019; Tittonell & Giller, 2013). Many tropical soils exhibit low inherent fertility, high rates of nutrient leaching, and rapid decomposition of organic matter, making the maintenance of biological nutrient transformations essential for sustaining crop growth. As a result, managing and enhancing soil biological health has emerged as a central strategy for improving productivity, resilience, and long-term soil sustainability. One of the most effective approaches to enhancing soil biological activity in tropical systems is the application of organic amendments. Inputs such as compost, manure, crop residues, green manures, and biochar provide both nutrients and energy sources that support diverse microbial communities (Palm et al., 2014; Méndez et al., 2016). Increased microbial biomass facilitates nutrient mineralization and mobilization, improving the availability of nitrogen, phosphorus, potassium, and micronutrients to crops. In addition, microbial exudates promote soil aggregation and stabilize soil structure, enhancing porosity, water infiltration, retention, and aeration—factors that collectively support root growth and plant health (Six et al., 2002; Lehmann et al., 2020).

Reduced soil disturbance is another key practice for sustaining microbial function. Conservation agriculture approaches—including minimum tillage, mulching, and maintenance of permanent soil cover—preserve microbial habitats and protect fungal hyphal networks, which are crucial for nutrient transport, particularly phosphorus and micronutrients (Giller et al., 2011; Vanlauwe et al., 2019). By limiting physical disruption, these practices maintain microbial diversity, reduce oxidation of soil organic matter, and foster beneficial interactions between microbes, soil fauna, and plant roots. Empirical studies have shown that crops grown under reduced-tillage systems in tropical contexts often display improved root architecture, higher nutrient uptake efficiency, and increased yields compared to conventionally tilled soils. The use of beneficial microbial inoculants further complements biological management strategies. Nitrogen-fixing bacteria (e.g., *Rhizobium* spp.), phosphate-solubilizing microorganisms, and arbuscular mycorrhizal fungi can enhance nutrient acquisition, improve water-use efficiency, and suppress soil-borne pathogens (Jeffries et al., 2003; Vessey, 2003; Chandra et al., 2016). In low-fertility tropical soils, where native microbial populations may be insufficient to maintain optimal nutrient cycling, inoculants are particularly valuable. Integrated use of inoculants with organic amendments can synergistically increase microbial activity, enhance soil structure, and strengthen crop resilience against both biotic and abiotic stresses.

Beyond nutrient cycling, soil biological management supports a wide range of ecosystem services. Healthy microbial communities contribute to carbon sequestration, disease suppression, detoxification of pollutants, and mitigation of greenhouse gas emissions. Microbial decomposition of organic residues into stable soil organic matter not only improves fertility but also increases the soil's water retention capacity and buffers against climatic variability. Similarly, interactions between soil fauna—such as earthworms, nematodes, and microarthropods—and microbial populations enhance organic matter turnover, nutrient availability, and root growth, creating a more resilient and productive soil ecosystem (Lavelle et al., 2006). Evidence from tropical agroecosystems demonstrates that promoting soil biological health produces measurable agronomic benefits. Crops grown in biologically active soils exhibit improved root development, higher nutrient-use efficiency, greater resilience to pests and diseases, and more stable yields under variable climatic conditions (Vanlauwe et al., 2019; Tittonell & Giller, 2013). Additionally, maintaining soil biological activity reduces reliance on synthetic fertilizers and chemical pesticides, fostering more sustainable, environmentally friendly, and climate-resilient agricultural systems. Overall, integrating microbial management into broader soil fertility strategies is essential for sustaining tropical crop productivity while enhancing long-term soil health.

Proven Soil Management Practices That Raise Productivity

A growing body of evidence from empirical studies, systematic reviews, and meta-analyses demonstrates that several soil management practices consistently improve crop productivity in tropical agroecosystems. While the magnitude of benefits varies according to soil type, climate, cropping system, and management context, these practices generally enhance soil fertility, structure, and resilience, contributing to sustainable and productive farming systems (Vanlauwe et al., 2015; Palm et al., 2014; Méndez et al., 2016).

Integrated Nutrient Management (INM) is one of the most widely endorsed approaches for sustaining tropical soil productivity. By combining organic amendments—such as manure, compost, and green manures—with mineral fertilizers, INM simultaneously meets the immediate nutrient requirements of crops and supports long-term soil fertility (Vanlauwe et al., 2015; Khuraijam et al., 2025). This approach increases nutrient use efficiency, enhances soil organic carbon (SOC) stocks, and improves soil structure, thereby promoting higher and more stable yields. Empirical studies across diverse tropical regions have shown that INM consistently outperforms either organic or inorganic fertilization alone, particularly in low-fertility soils, by maintaining balanced nutrient availability and supporting beneficial microbial activity (Tittonell & Giller, 2013). Residue Retention and Cover Crops / Green Manures are complementary practices that enhance soil organic matter, reduce erosion, and promote nutrient cycling (Palm et al., 2014; SOIL, 2016). Retaining crop residues and incorporating cover crops or green manures protect the soil surface from the impact of rainfall, supply organic inputs that stimulate microbial activity, and reduce nutrient losses through leaching. In tropical agroecosystems, residue retention has been associated with improved water infiltration, enhanced soil structure, and greater yield stability, particularly under variable rainfall regimes. Cover crops and green manures, especially leguminous species, additionally contribute biologically fixed nitrogen, further supporting soil fertility and productivity.

Conservation Agriculture (CA) represents a systems-based approach that integrates reduced or no-tillage, permanent residue cover, and crop rotations to improve soil health and productivity (Giller et al., 2011; Sadiq et al., 2025). Over time, CA enhances SOC accumulation, stabilizes soil structure, and improves water infiltration and retention. Yield responses to CA can vary with rainfall patterns, soil type, and crop species; however, long-term studies indicate that CA generally increases yield stability and resilience to climatic variability, particularly in areas prone to erosion or seasonal droughts. CA also supports beneficial soil biota, reduces labor for land preparation, and contributes to sustainable intensification in tropical farming systems. Biochar and Targeted Soil Amendments have emerged as promising strategies for improving soil fertility, especially in highly weathered, acidic, or degraded tropical soils (Jeffery et al., 2017). Biochar improves SOC, enhances nutrient retention, increases water-holding capacity, and can mitigate greenhouse gas emissions from soils. Its agronomic effectiveness is often maximized when applied alongside organic or mineral fertilizers, which complement its nutrient-holding properties and facilitate crop uptake. Other targeted amendments, such as lime, gypsum, or phosphate rock, correct specific chemical constraints—including acidity, sodicity, or phosphorus deficiency—thereby supporting crop productivity and soil health.

Agroforestry and Perennial Integration provide multiple ecological and agronomic benefits by incorporating trees, shrubs, or perennial crops into annual cropping systems (Méndez et al., 2016; SOIL, 2016). Litterfall from woody perennials increases organic matter inputs, recycles nutrients, and improves soil structure, while tree roots enhance water infiltration, reduce erosion, and stabilize soils. Diversified cropping systems also reduce production risk, provide multiple outputs, and often achieve higher long-term system productivity compared to monocultures. Evidence from tropical regions demonstrates that well-managed agroforestry systems sustain yield improvements while promoting both ecological resilience and socio-economic benefits for smallholder farmers.

Socio-Economic and Institutional Barriers to Adoption

Despite the well-documented agronomic and environmental benefits of improved soil management practices in tropical agroecosystems, adoption among farmers remains highly variable. Empirical evidence indicates that socio-economic and institutional constraints, rather than a lack of agronomic knowledge alone, are the primary determinants of uptake and long-term sustainability of these practices (Vanlauwe et al., 2019; Khuraijam et al., 2025).

Access to Inputs and Financial Resources is a major barrier to adoption. Many smallholder farmers in tropical regions face limited availability or high costs of essential inputs such as mineral fertilizers, organic amendments, biochar, and quality seeds. Even when these inputs are technically effective, financial constraints often prevent farmers from applying them at sufficient scale to achieve meaningful productivity gains. Access to credit is frequently restricted due to a lack of collateral, high interest rates, or insufficient rural financial services, limiting farmers' capacity to invest in productivity-enhancing practices (Tittonell & Giller, 2013; Vanlauwe et al., 2019). Market Access and Economic Incentives also play a critical role. Farmers are more likely to adopt soil management practices when there is a reliable market for their produce, providing returns sufficient to justify the investment. Conversely, inadequate infrastructure—including poor road networks, limited storage facilities, and inconsistent input supply chains—reduces both the perceived and actual benefits of adopting improved practices. Market volatility further discourages investment in long-term interventions, as uncertain returns increase perceived risk (Khuraijam et al., 2025).

Labor Availability and Opportunity Costs present additional challenges. Many productivity-enhancing practices, such as residue retention, mulching, compost preparation, and establishment of agroforestry systems, are labor-intensive and compete with household labor needs or off-farm employment. Seasonal labor bottlenecks may prevent timely implementation, reducing the effectiveness of soil management practices and discouraging repeated use over successive cropping cycles. Land Tenure Security is another critical factor influencing adoption. Farmers without secure or long-term land rights are often reluctant to implement practices requiring sustained management and delayed returns, such as agroforestry, SOC-enhancing amendments, or conservation agriculture measures. Insecure tenure diminishes incentives to maintain soil fertility or implement erosion control, limiting long-term productivity gains (Tittonell & Giller, 2013).

Knowledge and Awareness Gaps further constrain adoption. Many farmers lack technical knowledge regarding best practices, appropriate application rates, timing, and crop-specific management strategies. Limited access to extension services, inadequate training programs, and low literacy levels exacerbate these gaps. Participatory approaches—including on-farm trials, farmer field schools, and demonstration plots—have proven effective in improving understanding, increasing farmer confidence, and facilitating adoption of new soil management practices (Vanlauwe et al., 2019; Khuraijam et al., 2025). Social and Cultural Factors also influence adoption. Farmer perceptions, risk aversion, traditional practices, and community norms can affect the uptake of innovations. For example, in some communities, crop residues may be removed for livestock feed, conflicting with recommendations to retain residues for soil fertility. Such trade-offs require locally appropriate interventions that balance productivity, livelihoods, and ecological goals.

Integrating Biophysical and Socio-Economic Solutions for Tropical Soil Productivity

The literature consistently emphasizes that addressing productivity challenges in tropical agroecosystems requires more than isolated technical interventions. While practices such as integrated nutrient management, residue retention, conservation agriculture, and agroforestry have demonstrated clear benefits for soil fertility and crop yields, sustainable and scalable productivity gains depend on coupling these biophysical solutions with complementary socio-economic and institutional support (Royal Society Publishing, 2020; Vanlauwe et al., 2019). Integrated intervention packages are widely recognized as the most effective strategy for improving tropical agriculture. These packages combine multiple agronomic practices—such as residue retention, cover cropping, crop rotations, and conservation tillage—with targeted soil amendments, including organic and mineral fertilizers and biochar. By simultaneously addressing constraints related to soil structure, fertility, and biological functioning, integrated approaches optimize nutrient cycling, enhance water retention, reduce erosion, and stabilize yields across diverse tropical agroecosystems (Tittonell & Giller, 2013; Palm et al., 2014). Evidence indicates that interventions focusing on single soil constraints often deliver short-term gains but fail to maintain long-term productivity and resilience, highlighting the need for holistic management strategies.

Socio-economic and policy support is critical for the adoption and scaling of technical solutions. Studies show that farmers are more likely to implement productivity-enhancing practices when interventions are accompanied by access to credit, input subsidies, functional markets, and extension services (Khuraijam et al., 2025; Vanlauwe et al., 2019). Policy instruments that prioritize soil health—rather than solely immediate yield gains—have proven particularly effective. Examples include subsidies for organic amendments, support for conservation agriculture tools, and incentives for integrating trees or perennials into cropping systems. Such measures can help overcome financial, labor, and risk-related barriers, promoting long-term soil fertility improvements and adoption sustainability. Local adaptation and farmer-centered design are essential to the success of integrated interventions. High-quality reviews underscore that practices must be tailored to the specific agroecological context, soil type, climatic conditions, and socio-economic realities of smallholder farmers (Royal Society Publishing, 2020; Tittonell et al., 2016). Participatory approaches—including co-design with farmers, on-farm trials, and demonstration plots—enhance the relevance, acceptability, and feasibility of interventions. Incorporating farmers' experiential knowledge, labor constraints, resource availability, and risk perceptions ensures that recommended practices are both profitable and resilient to local challenges.

Scaling integrated solutions requires coordinated action across multiple levels. At the farm level, technical knowledge, access to inputs, and labor availability determine adoption. At the community and regional levels, extension networks, farmer cooperatives, and local institutions facilitate knowledge transfer and collective resource sharing. At the policy level, supportive frameworks, incentives, and infrastructure investments are necessary to sustain long-term benefits (Vanlauwe et al., 2019; Royal Society Publishing, 2020). By combining biophysical interventions with socio-economic and institutional support, integrated approaches offer the greatest potential to enhance productivity, resilience, and sustainability in tropical agroecosystems, bridging the gap between agronomic potential and real-world outcomes.

Trade-Offs and Contextual Dependencies in Tropical Soil Management

The adoption and effectiveness of soil management practices in tropical agroecosystems are shaped by a complex interplay of biophysical, climatic, and socio-economic factors. Evidence from multiple studies indicates that interventions cannot be evaluated solely on average yield gains; rather, the outcomes are strongly influenced by the context in which practices are applied, the time frame over which benefits accrue, and the resources required for implementation (Vanlauwe et al., 2015; Tittonell & Giller, 2013). Recognizing these trade-offs and dependencies is therefore critical for designing interventions that are both productive and sustainable.

A key trade-off in tropical soil management exists between short-term productivity gains and long-term soil health. Mineral fertilizers, for instance, often provide immediate yield improvements, helping to meet urgent food security needs. However, when used in isolation and without complementary practices that maintain or enhance soil organic carbon (SOC), reliance on mineral fertilizers can lead to progressive declines in soil structure, nutrient retention, and microbial activity. Over time, these declines reduce soil resilience to stressors such as drought or heavy rainfall, ultimately compromising yield stability (Sanchez et al., 2009; SOIL, 2016). Integrated Nutrient Management (INM), which combines organic inputs such as compost or manure with mineral fertilizers, has been widely shown to mitigate this trade-off. INM not only supplies nutrients for immediate crop uptake but also contributes to long-term SOC accumulation, improved soil structure, and enhanced microbial functioning, supporting both sustainable productivity and soil health (Vanlauwe et al., 2015). Climatic and soil conditions further modulate the effectiveness of management interventions. In humid tropical regions with high rainfall intensity, soil erosion and nutrient leaching are major constraints, making surface protection measures—such as residue retention, cover cropping, and conservation tillage—particularly important. These practices reduce topsoil loss, maintain nutrient availability, and preserve soil structure under heavy rainfall events (Lal, 2015; Palm et al., 2014). Conversely, in dry or semi-arid tropical regions, water scarcity dominates as a limiting factor. Here, interventions that enhance SOC and improve soil aggregation are especially valuable, as they increase water-holding capacity, support crop establishment during dry periods, and buffer crops against drought stress (Tittonell & Giller, 2013). These observations highlight that soil management strategies must be carefully tailored to local climatic conditions, soil types, and cropping systems rather than implemented as one-size-fits-all solutions.

Economic considerations and labor requirements introduce additional trade-offs in practice adoption. Many productivity-enhancing interventions—including residue incorporation, composting, and the establishment of agroforestry systems—are labor- and time-intensive. For smallholder farmers, who frequently face labor shortages or competing livelihood demands, these requirements can limit uptake, even when the agronomic benefits are well-established. Economic incentives such as input subsidies, access to credit, or payments for ecosystem services can offset opportunity costs and increase adoption rates (Khuraijam et al., 2025; Vanlauwe et al., 2019). Furthermore, some interventions require substantial upfront investment. Cost-benefit analyses indicate that, while initial expenditures may be high, the long-term gains in productivity, soil fertility, and system resilience often exceed the initial costs when appropriate support mechanisms are provided. These insights underscore the importance of designing soil management interventions that explicitly consider trade-offs and contextual dependencies. Sustainable productivity gains in tropical agroecosystems depend on strategies that balance short-term and long-term outcomes, align interventions with local climatic and soil conditions, and accommodate the socio-economic realities of farmers. Policies, extension services, and development programs that integrate technical recommendations with financial support, participatory co-design, and context-specific guidance are more likely to promote adoption and deliver sustained improvements in soil productivity. By acknowledging and addressing these trade-offs, interventions can simultaneously support immediate food security and long-term soil and ecosystem health in tropical regions.

Knowledge Gaps and Research Priorities in Tropical Soil Management

The advancement and long-term sustainability of soil management practices in tropical agroecosystems are constrained by persistent gaps in both biophysical understanding and socio-economic implementation. Evidence from multiple studies indicates that research and recommendations cannot rely solely on short-term yield gains; rather, long-term effects, site-specific soil and climate conditions, and the socio-economic context of farmers all critically influence outcomes. Recognizing these knowledge gaps is essential for guiding research priorities, designing effective interventions, and scaling sustainable practices.

A major gap lies in the scarcity of long-term, high-resolution field trials across diverse tropical pedoclimates. While short-term experiments provide valuable insights into immediate crop responses to interventions such as integrated nutrient management (INM), residue retention, cover cropping, and conservation agriculture, few studies track the cumulative effects of these practices over multiple seasons or years (Laub et al., 2023; Soil, 2022). Longitudinal data are indispensable for quantifying how soil organic carbon (SOC), nutrient dynamics, soil structure, and crop productivity evolve under different management regimes. Without these datasets, it is challenging to formulate context-specific recommendations that balance immediate yield gains with long-term soil sustainability. Closely related is the need to better understand SOC stabilization in deeply weathered tropical soils. Tropical soils are characterized by rapid organic matter decomposition driven by high temperatures and moisture, and the mechanisms that govern SOC persistence, particularly in subsoil layers, remain poorly elucidated (Nature Scientific Reports, 2022). Mechanistic studies that investigate biological, chemical, and physical processes controlling SOC formation and retention are crucial for designing interventions that enhance long-term fertility, nutrient cycling, and soil resilience, while also contributing to climate mitigation through carbon sequestration (Laub *et al*., 2023).

Another research priority involves the evaluation of emerging soil amendments—including biochar, rock phosphate, and locally sourced organic inputs—through integrated agronomic and socio-economic analyses. Although these amendments show potential for improving soil fertility, water retention, and crop yields, their economic feasibility, labor requirements, and adoption potential among smallholder farmers remain uncertain. Studies that combine effectiveness assessments with cost-benefit analyses and scaling potential are needed to determine how these amendments can be deployed sustainably in resource-constrained settings. Socio-economic and institutional constraints represent an additional critical gap. Limited access to credit, inputs, extension services, markets, and secure land tenure significantly constrains the adoption of soil-restorative practices, particularly for smallholder farmers (Vanlauwe et al., 2019). However, there is limited experimental evidence on which incentive structures—such as targeted subsidies, microcredit schemes, payments for ecosystem services, or participatory extension programs—most effectively promote uptake and sustained implementation. Participatory socio-economic research and field experiments can help identify context-appropriate interventions that are both feasible and equitable, supporting more widespread adoption of productivity-enhancing soil management practices.

Finally, bridging the divide between biophysical and socio-economic research remains a key priority. Integrated decision-support tools and modeling frameworks that combine soil process data with economic, labor, and policy scenarios could enable stakeholders to evaluate trade-offs between productivity, sustainability, and equity. Such tools are essential for prioritizing interventions that provide tangible benefits to farmers while maintaining long-term soil health and resilience. Addressing these knowledge gaps—through long-term field trials, mechanistic studies of SOC stabilization, cost-benefit analyses of emerging soil amendments, rigorous socio-economic experiments, and integrated decision-support frameworks—will strengthen the evidence base for sustainable soil management. By targeting research to both biophysical and socio-economic dimensions, future interventions can enhance productivity, resilience, and sustainability in tropical agroecosystems, while informing policy and supporting farmer decision-making across heterogeneous environments (Laub et al., 2023; Khuraijam et al., 2025; Vanlauwe et al., 2019).

Conclusion and recommendations

Conclusion

Tropical soils face multiple, interacting biophysical constraints. Evidence from empirical studies, systematic reviews, and meta-analyses consistently shows that the most substantial and durable productivity gains arise from integrated soil management (INM) approaches rather than isolated interventions. Practices such as INM, residue retention, conservation agriculture, agroforestry, cover cropping, and targeted amendm]ents (e.g., biochar, lime, or phosphate) address multiple soil constraints simultaneously. By improving organic carbon levels, nutrient dynamics, soil structure, and microbial activity, these integrated interventions enhance nutrient cycling, strengthen resilience to environmental stressors, and support more stable crop yields over time. However, the adoption and sustained use of these practices are strongly shaped by socio-economic and institutional factors. Limited access to inputs, inadequate credit, high labor demands, insecure land tenure, weak markets, and insufficient extension services often prevent farmers from implementing technically effective practices at scale. These barriers highlight that agronomic solutions alone are insufficient without supportive enabling conditions. This review also identifies significant knowledge gaps requiring further attention, including the lack of long-term field trials, limited understanding of soil organic carbon stabilization in tropical environments, variable performance of emerging soil amendments, and insufficient socio-economic research to guide scalable, farmer-centered interventions.

Recommendations

Improving tropical soil productivity requires a combination of integrated soil management strategies and supportive socio-economic interventions. A key priority is the promotion of Integrated Nutrient Management (INM), which pairs mineral fertilizers with organic inputs such as manure, compost, and crop residues, thereby supporting long-term soil health and yield stability. Conservation-oriented practices—including residue retention, cover cropping, and agroforestry—should also be scaled up, as they reduce soil erosion, improve soil structure, and enhance long-term productivity by maintaining continuous ground cover and promoting nutrient cycling. Addressing soil chemical constraints is equally essential. Implementing site-specific soil testing, appropriate liming, and targeted nutrient diagnostics can help correct acidity and phosphorus fixation, two of the most pervasive limitations in tropical soils. Emerging soil amendments such as biochar offer additional potential benefits; however, their performance varies widely across contexts. As such, biochar and similar innovations should be introduced through carefully monitored pilot programs that evaluate both agronomic effectiveness and economic feasibility before large-scale adoption. Finally, technical solutions must be complemented by investments that reduce socio-economic barriers to adoption.

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