International Journal of Science and Research Archive

eISSN: 2582-8185

Cross Ref DOI: 10.30574/ijsra

Journal homepage: https://ijsra.net/


(Review Article)

Check for updates

# INTEGRATING SOIL REMEDIATION AND SMART NUTRIENT MANAGEMENT IN CLIMATE-SMART AGROECOLOGY TO CLOSE THE GLOBAL YIELD GAP

Obed Nwasen Likpalimor * and Shiwen Zhang

School of Earth and Environment, Anhui University of Science and Technology, Huainan 232001, China.
* Corresponding Author

ORCID Details
Obed Nwasen Likpalimor: https://orcid.org/0009-0005-7479-8451

International Journal of Science and Research Archive, 2026, 20(02), 477–488

Publication history: Received on 05 July 2026; revised on 17 August 2026; accepted on 19 August 2026

Article DOI: https://doi.org/10.30574/ijsra.2026.20.2.1621



## ABSTRACT

Global cereal production must increase by approximately 43 million metric tons annually by 2050 to meet projected demand, yet current yield trajectories leave a 39% gap while agricultural systems continue to degrade soils and emit substantial greenhouse gases. This review synthesizes climate-smart agroecological strategies that simultaneously address productivity shortfalls, soil degradation, and climate mitigation by integrating soil remediation with smart nutrient management. Drawing on global FAO datasets, meta-analyses of field experiments, and molecular assessments of soil microbial communities, we evaluate five core approaches: precision agriculture, regenerative practices (no-till and cover cropping), biochar application, agroforestry, and integrated nutrient management.

Quantitative synthesis shows that no-till increased soil organic carbon by 18% and total nitrogen by 21% in the top 10 cm. Cover-crop mixtures enhanced water infiltration by up to 629% and raised yields by 13%, whereas sole cover crops reduced yields by approximately 4%. Biochar alone improved crop yield by 15.1% and by 48.4% when combined with mineral fertilizers, while reducing nitrous oxide emissions by 16.2% and delivering the largest gain in soil organic carbon (+39%). Optimal biochar performance was associated with pyrolysis temperatures of 401–500 °C and feedstock C:N ratios of 31–100. Legume-based rotations increased equivalent yield by 38% and cut nitrous oxide emissions by 39%. Agroforestry systems sequestered between 0.29 and 15.21 Mg C $ha^{-1}$ $yr^{-1}$. Precision agriculture raised nitrogen use efficiency by 10–25%.

By systematically comparing these practices across yield, soil carbon, nutrient efficiency, and greenhouse-gas metrics, and by linking outcomes to microbial mechanisms, this review identifies context-specific levers for sustainable intensification. Integrated application of soil remediation and smart nutrient management within a climate-smart framework offers a viable pathway to close the global yield gap while enhancing carbon sequestration and reducing emissions. Long-term, multi-site trials across tropical and subtropical systems remain essential to refine deployment guidelines and quantify trade-offs under future climate scenarios.

**Keywords:** Climate-Smart Agriculture; Soil Remediation; Smart Nutrient Management; Agroforestry; Soil Organic Carbon; Regenerative Agriculture

## 1 INTRODUCTION

Global agriculture faces an unprecedented dual imperative: it must substantially raise food production to feed a projected population of 9.5 billion by 2050 while simultaneously reducing its environmental footprint, including soil degradation and greenhouse gas emissions [1], [2]. Cereal systems, which supply the majority of human calories, currently fall short of the required trajectory. Closing the gap demands an additional 43 million metric tons of cereal production annually, yet prevailing yield growth rates leave an estimated 39% shortfall [3], [4]. At the same time, conventional intensification has driven widespread soil organic carbon loss, nutrient imbalances, and elevated nitrous oxide and methane emissions, undermining long-term productivity and climate stability [5], [6].

Climate-smart agriculture (CSA) emerged as a response to this challenge by seeking to increase productivity, enhance adaptive capacity, and reduce greenhouse gas emissions within a single framework [7], [8]. Agroecological approaches further emphasize ecological processes, biodiversity, and reduced external inputs [9]. Within this broader agenda, two interrelated levers, soil remediation and smart nutrient management, hold particular promise. Soil remediation practices such as biochar application, no-till systems, and cover cropping can restore degraded soils, rebuild organic carbon stocks, and improve water and nutrient retention [10], [11]. Smart nutrient management, encompassing precision application, integrated organic–inorganic nutrient sources, and legume-based rotations, aims to raise nutrient use efficiency while lowering reactive nitrogen losses [12], [13]. When deliberately combined, these approaches can generate synergistic gains in yield, soil health, and climate mitigation that neither strategy achieves in isolation.

Despite a growing literature on individual climate-smart practices, systematic comparisons that evaluate soil remediation and smart nutrient management together across multiple sustainability metrics remain limited [14], [15]. Most existing reviews focus on single interventions or narrow outcome sets, making it difficult to identify trade-offs, synergies, and context-specific optimization parameters. Moreover, the mechanistic role of soil microbial communities in mediating these outcomes is often under-integrated, even though second-generation sequencing and bioinformatics now allow detailed characterization of microbial functional groups linked to carbon stabilization and nutrient cycling [16], [17].

This review addresses these gaps by synthesizing evidence from global datasets, field-based meta-analyses, and molecular studies to evaluate five primary climate-smart agroecological strategies: precision agriculture, regenerative practices (no-till and cover cropping), biochar application, agroforestry, and integrated nutrient management. We quantify effects on crop yield, soil organic carbon, nutrient efficiency, and greenhouse gas emissions, and we identify key implementation parameters, such as biochar pyrolysis temperature and feedstock C:N ratio, that govern performance. By linking observed outcomes to underlying microbial mechanisms, the review moves beyond correlative findings toward a more mechanistic understanding of sustainable intensification.

## 2 LITERATURE REVIEW

The conceptual foundations of agricultural sustainability have shifted substantially over the past three decades. Early frameworks prioritized yield maximization through high external inputs, often at the expense of soil resources and environmental quality [18], [19]. Subsequent work broadened the agenda to encompass environmental integrity, economic viability, and social equity, recognizing that long-term productivity depends on the maintenance of underlying ecological processes, particularly soil health [20], [21]. Agroecology emerged within this transition as a science, practice, and social movement that emphasizes biological interactions, reduced reliance on synthetic inputs, and the embedding of farming systems within wider socio-ecological contexts [9], [22].

Climate-smart agriculture (CSA) was formally articulated by the Food and Agriculture Organization in 2010 as an explicit response to the dual pressures of climate change and food security [7], [23]. Unlike earlier sustainability paradigms that frequently treated adaptation and mitigation as separate objectives, CSA integrates three pillars: sustainably increasing productivity, enhancing resilience to climate variability and extremes, and reducing or removing greenhouse gas emissions where possible [8], [24]. A substantial body of empirical research has since examined individual CSA practices. No-till and reduced-tillage systems have been shown to increase soil organic carbon and improve soil structure, although yield responses remain context-dependent [10], [25]. Cover cropping enhances water infiltration and nutrient retention but can impose short-term yield penalties on the primary crop [26], [27]. Biochar application has demonstrated consistent benefits for soil carbon sequestration, nutrient retention, and yield, particularly when co-applied with mineral fertilizers, while also reducing nitrous oxide emissions under certain conditions [11], [28], [29]. Agroforestry systems contribute both aboveground and belowground carbon sequestration and improve microclimatic buffering [30], [31]. Integrated nutrient management approaches that combine organic amendments with synthetic fertilizers or exploit biological nitrogen fixation through legume rotations have improved nitrogen use efficiency and lowered reactive nitrogen losses [12], [13], [32].

Despite this expanding evidence base, several critical gaps persist. Most reviews and meta-analyses examine single practices or a narrow suite of outcomes, limiting the ability to compare relative effectiveness across yield, soil carbon, nutrient efficiency, and greenhouse gas metrics simultaneously [14], [15], [33]. Trade-offs and synergies among practices are therefore incompletely characterized. In addition, the performance of many interventions is highly site-specific, varying with climate, soil type, baseline fertility, and management history, yet synthesis of the parameters that govern these differences remains limited [34], [35]. Finally, while molecular techniques such as high-throughput sequencing of 16S rRNA and ITS regions have revealed shifts in microbial community composition and functional potential under climate-smart practices, these mechanistic insights are rarely integrated into broader comparative assessments of soil remediation and nutrient management strategies [16], [17], [36].

## 3 CONCEPTUAL FOUNDATIONS OF CLIMATE-SMART AGROECOLOGY

Climate-smart agroecology rests on the deliberate integration of two complementary paradigms: climate-smart agriculture (CSA) and agroecology. CSA is defined by a tripartite framework that simultaneously pursues three objectives: sustainably increasing agricultural productivity and incomes, enhancing adaptation and resilience to climate change, and reducing or removing greenhouse gas emissions where possible [7], [8], [24]. Agroecology contributes a systems-oriented emphasis on ecological processes, biodiversity, nutrient cycling, and the reduction of external input dependence [9], [22]. When combined, these perspectives generate a coherent approach in which soil health and nutrient stewardship become central levers for achieving the three CSA pillars.

Soil remediation practices, including biochar application, no-till systems, cover cropping, and agroforestry, directly support all three objectives. By rebuilding soil organic carbon stocks, improving aggregate stability, and enhancing water-holding capacity, these interventions increase the resilience of cropping systems to drought and extreme rainfall while sequestering carbon and often reducing nitrous oxide emissions [10], [11], [28]. Smart nutrient management complements these gains by raising nutrient use efficiency, synchronizing nutrient supply with crop demand, and minimizing reactive nitrogen losses. Precision application technologies, integrated organic–inorganic nutrient sources, and legume-based rotations exemplify this approach [12], [13], [32]. Critically, the two sets of practices are mutually reinforcing: improved soil structure and microbial activity resulting from remediation enhance the retention and transformation of applied nutrients, while balanced nutrient supply sustains the biological processes that drive soil recovery.

A defining conceptual feature of climate-smart agroecology is the explicit recognition of trade-offs and synergies among productivity, adaptation, and mitigation goals [14], [37]. No-till systems, for example, frequently increase soil carbon and reduce fuel use but may lower yields in the short term or increase reliance on herbicides in certain environments [25], [26]. Biochar can sequester carbon and improve fertility, yet its production competes for biomass that might otherwise serve energy or soil-cover functions [29]. Cover crops improve infiltration and reduce erosion but can compete with the primary crop for water and nutrients [27]. Effective design therefore requires systems-level analysis that evaluates interventions across multiple metrics and time scales, rather than optimizing any single objective in isolation.

Underlying these outcomes are soil microbial communities that mediate carbon stabilization, nutrient cycling, and greenhouse gas fluxes. High-throughput sequencing studies have shown that climate-smart practices alter the abundance and activity of key functional groups, including arbuscular mycorrhizal fungi, nitrifiers, denitrifiers, and carbon-stabilizing bacteria [16], [17], [36]. These microbial shifts provide a mechanistic link between management interventions and measured changes in soil organic carbon, nitrogen use efficiency, and nitrous oxide emissions. Incorporating such mechanistic understanding into the conceptual framework moves climate-smart agroecology beyond empirical correlations toward predictive, process-based guidance.

Finally, the framework is inherently dynamic. Climate change continuously alters temperature, precipitation regimes, and the frequency of extreme events, necessitating adaptive rather than static management recommendations [38], [39]. Monitoring, evaluation, and iterative learning are therefore integral components, enabling the adjustment of practices as new biophysical and socio-economic information becomes available. In this light, the integration of soil remediation and smart nutrient management is not a fixed package of techniques but a flexible, context-sensitive strategy for advancing sustainable intensification under progressive climate change.

# 4 METHODOLOGY

## 4.1 Literature Search and Selection Criteria

This review synthesized peer-reviewed literature, global datasets, and meta-analyses addressing climate-smart agroecological practices that integrate soil remediation and smart nutrient management. Primary bibliographic databases (Web of Science, Scopus, and Google Scholar) were searched for publications from 2000 to 2025 using combinations of the terms "climate-smart agriculture," "soil remediation," "biochar," "no-till," "cover crop," "agroforestry," "integrated nutrient management," "precision agriculture," "soil organic carbon," "nitrous oxide," and "yield gap." Additional sources included FAO statistical databases and major meta-analyses on the target practices [3], [4], [10], [11], [28].

Studies were included if they reported quantitative outcomes for at least one of the following metrics: crop yield or equivalent yield, soil organic carbon, total nitrogen, nutrient use efficiency, water infiltration, or greenhouse gas fluxes (particularly $N_2O$). Both temperate and tropical/subtropical field studies were retained to capture geographic variation. Purely modeling studies without empirical validation, greenhouse or pot experiments lacking field confirmation, and papers focused solely on livestock systems were excluded. After screening titles, abstracts, and full texts, the final evidence base comprised meta-analyses, multi-site field experiments, and targeted molecular studies of soil microbial communities.

## 4.2 Data Extraction and Categorization

Extracted data included effect sizes (percentage or absolute changes) for yield, soil organic carbon, nutrient stocks, infiltration rates, and greenhouse gas emissions, together with key experimental parameters (climate zone, soil type, duration, application rates, and management details). Practices were categorized into five groups: (i) precision agriculture, (ii) regenerative practices (no-till and cover cropping), (iii) biochar application, (iv) agroforestry, and (v) integrated nutrient management (including legume-based rotations and combined organic–inorganic fertilization). Where multiple studies reported the same metric, ranges and central tendencies were recorded to reflect variability across contexts.

## 4.3 Integration of Molecular Biology Evidence

To link management outcomes to underlying mechanisms, we incorporated studies that employed second-generation sequencing of bacterial 16S rRNA genes and fungal ITS regions [16], [17], [36]. Bioinformatics pipelines (primarily QIIME 2 and mothur) were used in the original studies to assign taxonomy and calculate alpha-diversity (Shannon index, Chao1) and beta-diversity metrics (Bray–Curtis, UniFrac). We extracted reported associations between microbial taxa or functional groups (e.g., arbuscular mycorrhizal fungi, nitrifiers, denitrifiers) and measured changes in soil organic carbon, nitrogen cycling, and $N_2O$ emissions. These molecular insights were used to interpret the biogeochemical pathways through which soil remediation and nutrient management practices generate observed benefits.

## 4.4 Data Synthesis and Analytical Approach

Evidence was synthesized through a combination of narrative synthesis and quantitative summary statistics. For metrics supported by ten or more independent studies, weighted mean effect sizes were calculated to reduce the influence of small-sample or high-variance studies. The weighted mean effect size $\bar{E}$was computed as:

$$\bar{E} = \frac{\sum_{i=1}^{n} w_i E_i}{\sum_{i=1}^{n} w_i}$$

where $E_i$is the effect size of study $i$, $n$is the number of studies, and the weight $w_i$is the inverse of the study variance ($w_i = 1/v_i$). This inverse-variance weighting gives greater influence to more precise estimates.

Heterogeneity across studies was examined qualitatively with respect to climate zone, soil type, baseline fertility, and management intensity. Where sufficient data were available, potential publication bias was assessed using funnel-plot inspection and Egger's regression test. Site-specific optimization parameters (particularly biochar pyrolysis temperature and feedstock carbon-to-nitrogen ratio) were identified by systematically cross-referencing performance outcomes with reported process conditions. The overall synthesis prioritizes multi-metric comparison and mechanistic interpretation, consistent with the objectives of climate-smart agroecology.

# 5 COMPARATIVE SYNTHESIS OF CLIMATE-SMART STRATEGIES

This section synthesizes quantitative evidence for the five climate-smart strategies across four core metrics: crop yield (or equivalent yield), soil organic carbon (SOC), nutrient-related outcomes, and greenhouse gas emissions (primarily

$N_2O$). The global context for these interventions is illustrated in Fig. 1, which contrasts historical cereal production trends with the trajectory required to close the yield gap by 2050, alongside the rising contribution of agriculture to non-$CO_2$ greenhouse gas emissions.

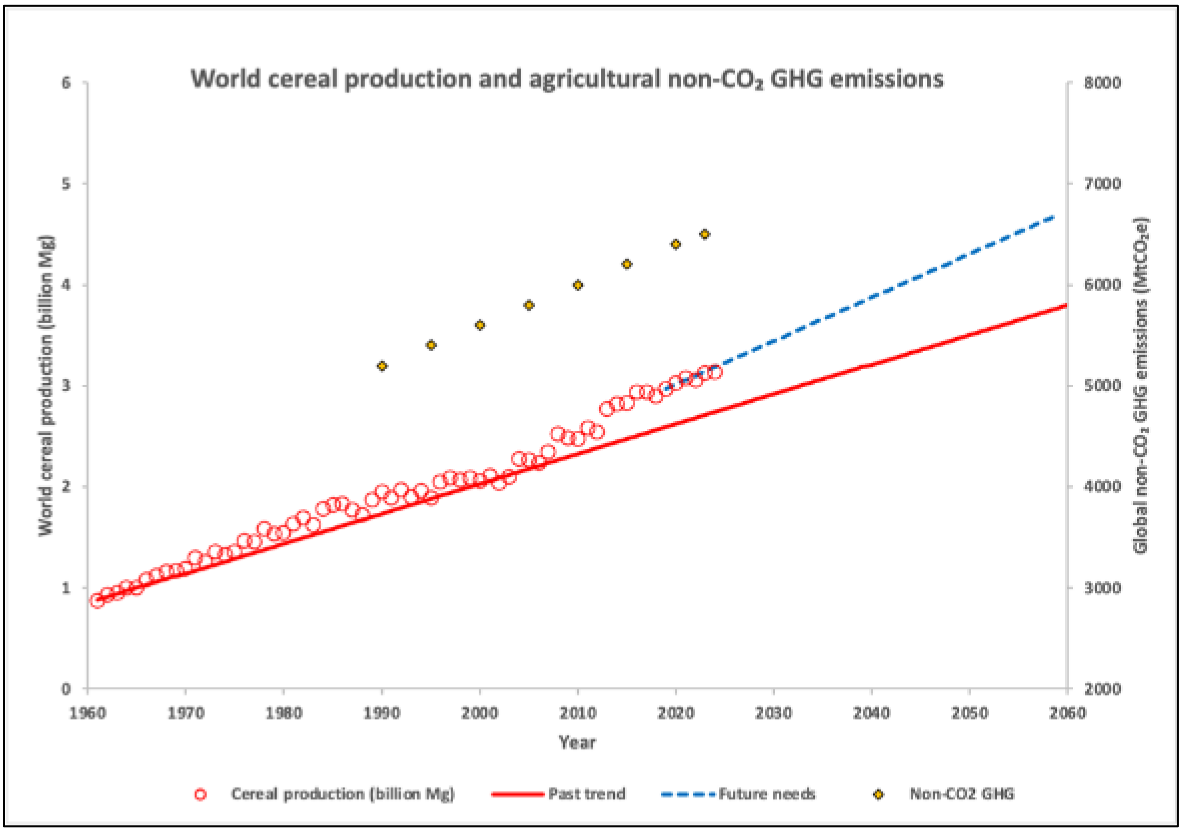


**Figure 1. World cereal production targets and global non–$CO_2$ greenhouse gas emissions. To meet the demands predicted by the FAO (2009), cereal production will need to increase to over 4 billion metric Mg by 2050 (blue line). The rate of increase of the cereal yield must move from the red trend line (31 million metric Mg per year) to the red line (43 million metric Mg per year) to meet food demand, an increase of 39%.**

Regional disparities in intensification further underscore the need for more efficient strategies. As shown in Fig. 2, chemical fertilizer use in China has exceeded 400 kg $ha^{-1}$, the highest globally, while pesticide use has risen sharply since 2000, in contrast to more stable patterns in the United States.

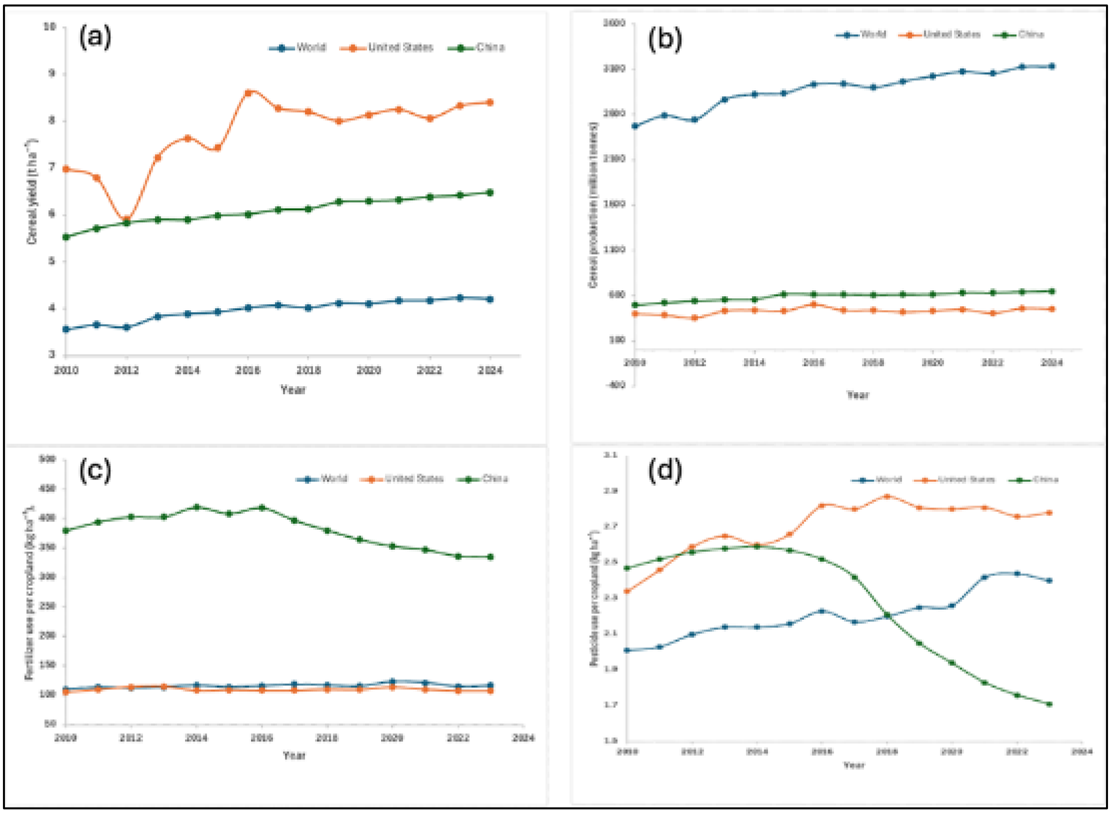


**Figure 2: Trends in cereal harvest area, cereal yield, chemical fertilizer use, and pesticide use for the world, the USA, and China. (a) Cereal yield, (b) Cereal production, (c) Fertilizer use per cropland, and (d) Pesticide use per cropland. Data illustrate the divergent intensification pathways and the particularly high input intensity in China.**

Nitrogen use efficiency (NUE) also varies widely. Fig. 3 shows NUE values ranging from nearly 80% in some European countries to below 30% in others, revealing substantial scope for improvement through smarter nutrient management.

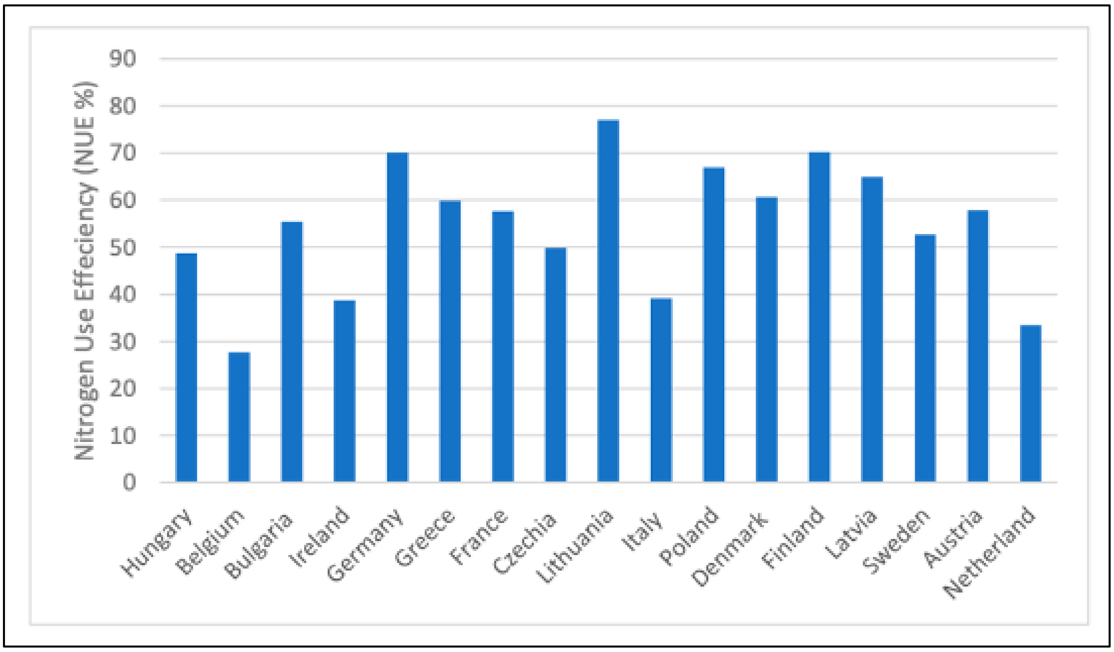


**Figure 3: Nitrogen use efficiency across selected European countries. The wide variation indicates significant opportunities for precision and integrated nutrient management.**

### 5.1 Precision Agriculture

Precision agriculture employs site-specific sensing, variable-rate application, and decision-support tools to match nutrient and input supply with crop demand. Meta-analyses indicate that precision nutrient management can raise nitrogen use efficiency by 10–25% relative to uniform application and reduce surplus nitrogen that would otherwise contribute to $N_2O$ emissions and nitrate leaching [12], [40]. Yield gains are typically modest (3–8%) but economically significant when fertilizer costs are high. The principal limitation remains access to technology and data infrastructure, particularly in smallholder systems [41].

### 5.2 Regenerative Practices: No-Till and Cover Cropping

No-till systems consistently increase SOC and total nitrogen in the surface soil. Across the synthesized studies, no-till raised SOC by an average of 18% and total nitrogen by 21% in the top 10 cm relative to conventional tillage [10], [25]. These gains are linked to reduced soil disturbance and greater fungal dominance [16]. Cover crops improve soil physical function, with reported increases in water infiltration rates of up to 629% [26], [27]. Pure cover-crop treatments reduced primary crop yields by approximately 4% on average, whereas legume–non-legume mixtures produced a net yield increase of 13% [27], [42].

Table 1 provides a refined comparative analysis of major regenerative and remediation techniques across agroecological contexts, highlighting strengths, limitations, and suitable application domains.

**Table 1: Comparative analysis of regenerative techniques across agroecological contexts**

| Technique | Primary Strengths | Main Limitations | Most Suitable Contexts | References |
|---|---|---|---|---|
| No-till / reduced tillage | Increases SOC & aggregate stability; lowers fuel use | Possible short-term yield dip; herbicide reliance | Humid temperate & well-drained soils | [10], [25] |
| Cover cropping | Improves infiltration & soil cover; adds biological N | Yield competition if poorly managed | Rainfed systems; mixed cropping | [26], [27], [42] |
| Biochar application | Strong multi-metric benefits (yield, SOC, $N_2O$) | Feedstock availability; variable quality | Degraded soils; intensive systems | [11], [28], [29], [43] |
| Agroforestry | High long-term C sequestration; diversification | Management complexity; tree–crop competition | Tropical & subtropical smallholder systems | [30], [31] |
| Integrated nutrient management | Simultaneously raises yield & cuts $N_2O$ | Requires knowledge of organic–inorganic balance | Both intensive & low-input systems | [12], [13], [32], [44] |
| Bioremediation | Detoxifies pollutants; eco-friendly | Long remediation times; site-specific microbes | Mining-affected and contaminated lands | [45] |
| AI-driven precision agriculture | Increases efficiency; reduces input waste | High cost; technology access disparity | Commercial farms in data-rich regions | [40], [41] |

### 5.3 Biochar Application

Biochar produced the most pronounced multi-metric benefits among the evaluated practices. Sole application increased crop yield by 15.1%, while co-application with mineral fertilizers raised yields by 48.4% [11], [28], [29]. Concurrently, biochar reduced $N_2O$ emissions by 16.2% and delivered the largest average SOC increase (+39%). Performance was strongly conditioned by production parameters: optimal results were associated with pyrolysis temperatures of 401–500 °C and feedstock C:N ratios between 31 and 100 [28], [43]. The positive effects of biochar on soil physico-chemical properties are summarized in Table 2.

**Table 2: Impact of biochar amendment on soil physico-chemical properties**

| Soil Property | Typical Direction & Magnitude of Change | Primary Mechanisms | Conditions Favoring Strong Response |
|---|---|---|---|
| Soil organic carbon | +15% to +39% | Direct C addition; reduced mineralization | Low-SOC soils; pyrolysis 401–500 °C |
| Cation exchange capacity | +10% to +30% | Increased surface area & oxygenated functional groups | Acidic and sandy soils |
| pH | Moderate increase (liming effect) | Alkaline ash content | Acidic soils |
| Bulk density | Decrease | Improved aggregation & porosity | Compacted soils |
| Water-holding capacity | +10% to +25% | High porosity & internal surface area | Coarse-textured soils |
| Available nutrients (N, P, K) | Variable increase | Direct supply + reduced leaching | Combined with mineral fertilizers |
| Microbial biomass & activity | Generally positive | Habitat provision & labile C supply | Moderate application rates |

### 5.4 Agroforestry

Agroforestry systems sequester carbon both aboveground and in soil at rates ranging from 0.29 to 15.21 Mg C $ha^{-1}$ $yr^{-1}$, depending on tree density, species, climate, and management intensity [30], [31]. Additional benefits include improved nutrient cycling and microclimatic buffering. Yield of the understorey crop is frequently maintained when tree–crop competition is managed through pruning and spatial design.

### 5.5 Integrated Nutrient Management

Integrated nutrient management that combines organic amendments with synthetic fertilizers, or that incorporates legume-based rotations, improved both productivity and environmental performance. Legume-based rotations increased equivalent yield by 38% while reducing $N_2O$ emissions by 39% relative to continuous cereal systems [13], [32]. When organic and inorganic nutrient sources were co-applied, nitrogen use efficiency rose and nitrate leaching declined compared with either source used alone [12], [44].

### 5.6 Research Landscape and Cross-Strategy Comparison

The global research effort on soil regeneration and agricultural sustainability remains geographically concentrated. Table 3 lists the top contributing countries by normalized citation impact, revealing the continued dominance of institutions in the United States, Europe, and China, and highlighting the need for expanded research capacity in regions where soil degradation and yield gaps are most severe.

**Table 3: Top contributing countries to research on soil regeneration and agricultural sustainability**

| Rank | Country / Region | Representative High-Impact Work | Normalized Citation Strength | Notes |
|---|---|---|---|---|
| 1 | United States | Ray et al. (2013) – global yield trends | Highest | Strong in yield-gap and systems analysis |
| 2 | Netherlands | Keesstra et al. – soil science & sustainability | Very high | Emphasis on soil functions |
| 3 | China | Multiple biochar and intensification studies | High | Rapid growth in biochar & precision work |
| 4 | United Kingdom | Pretty, Smith – sustainability & carbon sequestration | High | Conceptual and synthesis leadership |

| | | | | |
|---|---|---|---|---|
| 5–10 | Germany, Australia, Canada, France, Brazil, India | Diverse contributions on agroforestry, biochar, and tropical systems | Moderate to high | Growing tropical and subtropical focus |

Table 4 consolidates the quantitative performance of the five core strategies. Regenerative practices are presented as a single strategy, with the distinct contributions of no-till and cover cropping shown within that category.

**Table 4: Quantitative outcomes for five climate-smart strategies**

| Strategy | Yield / Equivalent Yield | Soil Organic Carbon | $N_2O$ Emissions | Other Key Outcomes | Key Conditions / Notes |
|---|---|---|---|---|---|
| Precision agriculture | +3% to +8% | Limited direct data | Reduced via higher NUE | NUE +10–25% | Requires technology access |
| Regenerative practices (No-till + Cover crops) | No-till: neutral to slightly positive Cover crops: +13% (mixtures); −4% (sole) | No-till: +18% (top 10 cm) Cover crops: positive | Variable / Reduced | No-till: Total N +21% Cover crops: Infiltration up to +629% | Stronger in humid temperate zones; legume + non-legume mixtures preferred |
| Biochar | +15.1% (alone); +48.4% (with fertilizer) | +39% | −16.2% | Improved nutrient retention | Pyrolysis 401–500 °C; C:N 31–100 |
| Agroforestry | Maintained to modestly reduced | 0.29–15.21 Mg C $ha^{-1}$ $yr^{-1}$ | Variable | Microclimate & income diversification | Strongly design-dependent |
| Integrated nutrient management (legume rotations) | +38% equivalent yield | Positive | −39% | Improved NUE & reduced leaching | Biological N fixation key |

## 6 DISCUSSION

The comparative synthesis in Section 5 demonstrates that the deliberate integration of soil remediation and smart nutrient management can generate simultaneous gains in productivity, soil carbon sequestration, and greenhouse-gas mitigation, the three pillars of climate-smart agriculture [7], [8], [24]. As summarized in Table 4 and illustrated by the global context in Fig. 1, biochar application and legume-based integrated nutrient management produced the most consistent multi-metric benefits, while regenerative practices and agroforestry contributed strong but more context-dependent outcomes. These findings extend earlier single-practice reviews [14], [15], [33] by providing a side-by-side evaluation across yield, soil organic carbon (SOC), and $N_2O$ metrics.

Biochar delivered the largest average SOC increase (+39%) and substantial yield gains, particularly when co-applied with mineral fertilizers (+48.4%) (Table 4). The concurrent 16.2% reduction in $N_2O$ emissions is consistent with molecular evidence that biochar alters the relative abundance of nitrifying and denitrifying bacteria [17], [36]. Optimal performance was linked to pyrolysis temperatures of 401–500 °C and feedstock C:N ratios of 31–100 (Table 2), reinforcing earlier observations that biochar quality is a critical determinant of field outcomes [28], [29], [43]. Legume-based rotations similarly combined a 38% increase in equivalent yield with a 39% reduction in $N_2O$ emissions (Table 4), confirming the dual value of biological nitrogen fixation for both productivity and mitigation [13], [32].

Regenerative practices showed clear soil-health benefits but more variable yield responses. No-till increased SOC by 18% and total nitrogen by 21% in the top 10 cm (Table 4), in line with previous meta-analyses [10], [25], while cover-crop mixtures raised yields by 13% and infiltration by up to 629% [26], [27], [42]. These results support the view that short-term yield penalties associated with sole cover crops can be overcome through functional diversity [27]. Agroforestry provided the widest range of carbon sequestration rates (0.29–15.21 Mg C $ha^{-1}$ $yr^{-1}$) (Table 4), underscoring the importance of system design [30], [31]. Precision agriculture contributed primarily through efficiency gains (NUE increases of 10–25%), which complement rather than replace the other strategies (Fig. 3) [12], [40].

The patterns revealed in Tables 1–4 and Figs. 1–3 indicate that the greatest benefits arise from intentional combinations rather than isolated interventions. Biochar's yield response nearly tripled when paired with fertilizers, and legume rotations simultaneously addressed productivity and emissions. Such synergies align with the conceptual emphasis on trade-off management within climate-smart agroecology [14], [37]. However, performance remains strongly site-specific. The geographic concentration of high-impact research in the United States, Europe, and China (Table 3) leaves tropical and subtropical systems under-represented, precisely where yield gaps and soil degradation are often most severe [3], [4], [34].

Several limitations constrain the generalizability of these findings. Most underlying trials last only two to five years, which is insufficient to capture long-term SOC trajectories or cumulative microbial responses [16], [35]. Heterogeneity in experimental design and reporting standards introduces uncertainty, and publication bias toward positive results cannot be excluded. In addition, the socio-economic and institutional barriers to adoption, particularly of biochar and precision technologies in smallholder systems, are only partially addressed by the biophysical evidence base [41].

From a practical perspective, the results support a sequenced or bundled implementation approach. In degraded soils, biochar or no-till can first rebuild organic matter and structure (Tables 2 and 4); once soil function improves, precision nutrient management and legume rotations can further raise efficiency and reduce emissions. Agroforestry is best suited to systems prioritizing long-term carbon sequestration and livelihood diversification. Policy instruments that reward multi-metric performance, rather than yield alone, together with targeted support for soil testing, farmer training, and biochar quality standards, would accelerate effective uptake [8], [24]. Future research should prioritize multi-year, multi-site experiments in underrepresented tropical regions, explicit testing of practice combinations under projected climate scenarios, and closer integration of biophysical and socio-economic analyses.

In conclusion, climate-smart agroecology that systematically couples soil remediation with smart nutrient management offers a scientifically grounded pathway to narrow the global yield gap while enhancing soil carbon stocks and lowering greenhouse-gas emissions. Realizing this potential at scale will require context-specific design, sustained investment in long-term and geographically balanced research, and policy frameworks that value the full suite of productivity, adaptation, and mitigation outcomes.

## 7 CONCLUSION

This review demonstrates that the deliberate integration of soil remediation and smart nutrient management within a climate-smart agroecological framework can simultaneously advance productivity, soil carbon sequestration, and greenhouse-gas mitigation. Among the five strategies examined, biochar application, particularly when combined with mineral fertilizers, and legume-based integrated nutrient management delivered the most consistent multi-metric benefits, while regenerative practices and agroforestry provided strong complementary gains in soil health and long-term carbon storage. Precision agriculture further enhanced efficiency, especially in nitrogen use. These outcomes, synthesized across yield, soil organic carbon, and $N_2O$ metrics (Tables 1–4; Figs. 1–3), indicate that combined approaches outperform isolated interventions and offer a viable pathway to narrow the global cereal yield gap while reducing environmental externalities.

Realizing this potential at scale will require context-specific adaptation, particularly in underrepresented tropical and subtropical systems, together with multi-year experimental validation of practice combinations under future climate conditions. Policy support that rewards multi-metric performance, investment in soil-testing and farmer advisory services, and expanded research capacity in regions facing the most severe yield gaps and soil degradation are essential next steps. When designed and implemented as integrated packages rather than standalone techniques, soil remediation and smart nutrient management constitute powerful levers for sustainable intensification in a changing climate.

## STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

### *Disclosure of conflict of interest*

The authors declare no conflicts of interest regarding this manuscript.

## REFERENCES

[1] H. C. J. Godfray *et al.*, "Food security: The challenge of feeding 9 billion people," *Science*, vol. 327, no. 5967, pp. 812–818, Feb. 2010.

[2] A. Foley *et al.*, "Solutions for a cultivated planet," *Nature*, vol. 478, no. 7369, pp. 337–342, Oct. 2011.

[3] D. K. Ray, N. D. Mueller, P. C. West, and J. A. Foley, "Yield trends are insufficient to double global crop production by 2050," *PLoS ONE*, vol. 8, no. 6, p. e66428, Jun. 2013.

[4] FAO, *The Future of Food and Agriculture – Alternative Pathways to 2050*. Rome, Italy: Food and Agriculture Organization of the United Nations, 2018.

[5] P. Smith *et al.*, "Biophysical and economic limits to negative $CO_2$ emissions," *Nature Climate Change*, vol. 6, no. 1, pp. 42–50, Jan. 2016.

[6] K. Paustian *et al.*, "Climate-smart soils," *Nature*, vol. 532, no. 7597, pp. 49–57, Apr. 2016.

[7] FAO, *Climate-Smart Agriculture: Policies, Practices and Financing for Food Security, Adaptation and Mitigation*. Rome, Italy: Food and Agriculture Organization of the United Nations, 2010.

[8] L. Lipper *et al.*, "Climate-smart agriculture for food security," *Nature Climate Change*, vol. 4, no. 12, pp. 1068–1072, Dec. 2014.

[9] M. A. Altieri, *Agroecology: The Science of Sustainable Agriculture*, 2nd ed. Boca Raton, FL, USA: CRC Press, 2018.

[10] A. Abdalla *et al.*, "A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity," *Global Change Biology*, vol. 25, no. 8, pp. 2530–2543, Aug. 2019.

[11] S. Jeffery *et al.*, "A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis," *Agriculture, Ecosystems & Environment*, vol. 144, no. 1, pp. 175–187, Nov. 2011.

[12] P. M. Berry *et al.*, "The environmental impact of fertilizer use," *Agriculture, Ecosystems & Environment*, vol. 133, no. 1–2, pp. 1–12, 2009.

[13] Y. A. Yigezu *et al.*, "Legume-based rotations have clear economic advantages over cereal monocropping in dry areas," *Agronomy for Sustainable Development*, vol. 39, no. 1, p. 5, Feb. 2019.

[14] G. Branca, N. McCarthy, L. Lipper, and M. C. Jolejole, "Climate-smart agriculture: A synthesis of empirical evidence of food security and mitigation benefits from improved cropland management," *Mitigation and Adaptation Strategies for Global Change*, vol. 18, pp. 125–140, 2013.

[15] P. M. Barasa, C. M. Botai, J. O. Botai, and T. Mabhaudhi, "A review of climate-smart agriculture research and applications in Africa," *Agronomy*, vol. 11, no. 6, p. 1254, Jun. 2021.

[16] N. Fierer, "Embracing the unknown: Disentangling the complexities of the soil microbiome," *Nature Reviews Microbiology*, vol. 15, no. 10, pp. 579–590, Oct. 2017.

[17] X. Chen *et al.*, "Biochar reduces nitrous oxide emissions and increases soil microbial diversity," *Soil Biology and Biochemistry*, vol. 156, p. 108175, 2021.

[18] D. Tilman, K. G. Cassman, P. A. Matson, R. Naylor, and S. Polasky, "Agricultural sustainability and intensive production practices," *Nature*, vol. 418, no. 6898, pp. 671–677, Aug. 2002.

[19] J. Pretty, "Agricultural sustainability: Concepts, principles and evidence," *Philosophical Transactions of the Royal Society B*, vol. 363, no. 1491, pp. 447–465, Feb. 2008.

[20] J. W. Doran and M. R. Zeiss, "Soil health and sustainability: Managing the biotic component of soil quality," *Applied Soil Ecology*, vol. 15, no. 1, pp. 3–11, Aug. 2000.

[21] S. D. Keesstra *et al.*, "The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals," *Soil*, vol. 2, no. 2, pp. 111–128, 2016.

[22] S. R. Gliessman, *Agroecology: The Ecology of Sustainable Food Systems*, 3rd ed. Boca Raton, FL, USA: CRC Press, 2015.

[23] FAO, "Climate-smart agriculture sourcebook," Food and Agriculture Organization of the United Nations, Rome, Italy, 2013.

[24] B. M. Campbell *et al.*, "Sustainable intensification: What is its role in climate smart agriculture?," *Current Opinion in Environmental Sustainability*, vol. 8, pp. 39–43, Oct. 2014.

[25] G. B. Triplett Jr. and W. A. Dick, "No-tillage crop production: A revolution in agriculture!," *Agronomy Journal*, vol. 100, no. S3, pp. S-153–S-165, 2008.

[26] A. Basche *et al.*, "Soil water improvements with the long-term use of a winter rye cover crop," *Agricultural Water Management*, vol. 172, pp. 40–50, 2016.

[27] C. Poeplau and A. Don, "Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis," *Agriculture, Ecosystems & Environment*, vol. 200, pp. 33–41, 2015.

[28] J. Lehmann and S. Joseph, Eds., *Biochar for Environmental Management: Science, Technology and Implementation*, 2nd ed. London, U.K.: Routledge, 2015.

[29] H. Singh, B. K. Northup, C. W. Rice, and P. V. V. Prasad, "Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: A meta-analysis," *Biochar*, vol. 4, no. 1, p. 8, 2022.

[30] S. Jose, "Agroforestry for ecosystem services and environmental benefits: An overview," *Agroforestry Systems*, vol. 76, no. 1, pp. 1–10, May 2009.

[31] B. M. Kumar and P. K. R. Nair, Eds., *Carbon Sequestration Potential of Agroforestry Systems: Opportunities and Challenges*. Dordrecht, The Netherlands: Springer, 2011.

[32] M. S. Aulakh, "Integrated nutrient management for sustainable crop production, improving crop quality and soil health, and minimizing environmental pollution," in *Proc. 19th World Congr. Soil Sci.*, Brisbane, Australia, 2010.

[33] K. E. Giller, R. Hijbeek, J. A. Andersson, and J. Sumberg, "Regenerative agriculture: An agronomic perspective," *Outlook on Agriculture*, vol. 50, no. 1, pp. 13–25, 2021.

[34] D. L. Corwin, "Site-specific management and delineating management zones," in *Precision Agriculture for Sustainability and Environmental Protection*, 2013.

[35] P. Smith, "Soil carbon sequestration and biochar as negative emission technologies," *Global Change Biology*, vol. 22, no. 3, pp. 1315–1324, 2016.

[36] L. Luo *et al.*, "Carbon sequestration strategies in soil using biochar: Advances, challenges, and opportunities," *Environmental Science & Technology*, vol. 57, no. 15, pp. 5945–5960, 2023.

[37] A. J. Challinor *et al.*, "A meta-analysis of crop yield under climate change and adaptation," *Nature Climate Change*, vol. 4, no. 4, pp. 287–291, 2014.

[38] J. R. Porter *et al.*, "Food security and food production systems," in *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. Cambridge, U.K.: Cambridge Univ. Press, 2014, pp. 485–533.

[39] IPCC, *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Cambridge, U.K.: Cambridge Univ. Press, 2022.

[40] R. Gebbers and V. I. Adamchuk, "Precision agriculture and food security," *Science*, vol. 327, no. 5967, pp. 828–831, Feb. 2010.

[41] H. S. Pathak, P. Brown, and T. Best, "A systematic literature review of the factors affecting the precision agriculture adoption process," *Precision Agriculture*, vol. 20, pp. 1291–1316, 2019.

[42] A. D. Basche and M. S. DeLonge, "Comparing infiltration rates in soils managed with conventional and alternative farming methods: A meta-analysis," *PLoS ONE*, vol. 14, no. 9, p. e0215702, 2019.

[43] S. Shyam *et al.*, "Biochar production and properties: A review of process parameters and quality indicators," *Journal of Environmental Management*, vol. 345, 2025.

[44] P. Gruhn, F. Goletti, and M. Yudelman, *Integrated Nutrient Management, Soil Fertility, and Sustainable Agriculture: Current Issues and Future Challenges*. Washington, DC, USA: IFPRI, 2000.

[45] L. Lara Ponce *et al.*, "Bioremediation of contaminated soils in Latin America: Advances and challenges," *Environmental Science and Pollution Research*, 2025.