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Soil Fertility Management Practices for Enhancing Crop Yield: A Review

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ABSTRACT

Soil fertility is the foundation of crop productivity, yet nutrient depletion, organic matter loss and physical degradation currently affect roughly a third of the world's agricultural soils, threatening food security under a growing global population. This review synthesizes recent evidence on the major soil fertility management (SFM) practices used to sustain and enhance crop yield, including organic amendments (farmyard manure, compost, crop residues and biochar), inorganic and precision nutrient management, biological approaches (biofertilizers and plant growth-promoting rhizobacteria), legume-based crop rotation and cover cropping, conservation tillage, and Integrated Soil Fertility Management (ISFM), which combines these approaches with locally adapted germplasm. Drawing on global meta-analyses, the review shows that organic amendments increase yields by an average of 27% relative to mineral-only fertilization, with farmyard manure alone contributing up to 49%; biofertilizer inoculation raises yields by 8.5–20% depending on climate; biochar effects are strongly context-dependent, ranging from negligible in temperate soils to 25% in the tropics; legume-based rotations raise subsequent crop yields by approximately 20%; and no-till alone tends to reduce yields by around 5.7% unless combined with residue retention and diversified rotation. The evidence converges on a central conclusion: no single input consistently maximizes yield across all environments, and the largest, most stable gains arise from integrating organic and inorganic nutrient sources with biologically and physically sound soil management, tailored to local soil, crop and climatic conditions. The review closes by identifying key constraints to adoption and priority directions for future research and extension.

INTRODUCTION

Global food production must rise substantially over the coming decades to meet the demands of an expanding population, even as the land area available for agricultural expansion continues to shrink (Bilalis et al., 2024). Soil fertility — the capacity of soil to supply nutrients, water and a physically and biologically favourable rooting environment — is the primary biophysical determinant of achievable crop yield on any given piece of land. Yet soils worldwide are under mounting pressure: the Food and Agriculture Organization estimates that a substantial share of agricultural land is moderately to highly degraded through erosion, nutrient depletion, acidification, salinization and organic matter loss, with yield gaps reaching up to 70% below potential in parts of sub-Saharan Africa and South Asia (Gomiero, 2016).

Historically, agricultural intensification relied heavily on mineral fertilizers to close nutrient gaps. While effective in the short term, sole reliance on inorganic inputs has, in many systems, been accompanied by declining soil organic matter, reduced nutrient use efficiency, and rising costs and environmental externalities such as nitrate leaching and greenhouse gas emissions (Sainju et al., 2003). This has renewed interest in a broader portfolio of soil fertility management

(SFM) practices — organic amendments, biological inputs, crop diversification, conservation tillage and, increasingly, integrated approaches that combine these tools in locally adapted ways (Bayu, 2020; Kugedera et al., 2023).

This review synthesizes evidence from recent primary studies and global meta-analyses to (i) describe the major categories of soil fertility management practices used to enhance crop yield, (ii) quantify, where possible, their reported effects on yield, and (iii) identify the conditions under which each practice is most effective. The review is organized around six practice categories — organic amendments, precision nutrient management, biological inputs, crop rotation and cover cropping, tillage management, and integrated soil fertility management — before closing with a comparative synthesis and discussion of constraints and future directions.

ORGANIC SOIL FERTILITY MANAGEMENT PRACTICES

Farmyard Manure and Compost

Organic amendments remain among the most consistently effective tools for building soil fertility. In a global meta-analysis of 690 independent field experiments, Luo et al. (2018) found that organic amendments increased crop yield by an average of 27% relative to mineral-only fertilization, with farmyard manure producing the largest single effect (49% increase), particularly in wheat cropping systems. The yield benefit was closely linked to improvements in soil organic carbon (+38%), total nitrogen (+20%) and microbial biomass carbon (+51%), indicating that organic inputs act primarily by enhancing microbially mediated nutrient cycling rather than through nutrient addition alone.

Field-scale evidence corroborates these findings. In a nine-year rotation trial in the Hetao Irrigation District of China, combined manure and mineral fertilizer application increased wheat and sunflower yields by 6–39% and raised economic returns substantially, with each additional 20 Mg ha^{-1} of manure associated with a measurable yield increment attributable to improved soil organic matter and nutrient supply (Zhao, N. et al., 2024). At a national scale, a meta-analysis of 173 Chinese studies found that manure application alone increased crop yields by 70.4%, exceeding the effect of straw return alone (14.4%), although the combination of straw and manure did not outperform manure alone (Zhao, Z. et al., 2024).

Crop Residue and Straw Management

Returning crop residues to the field is a low-cost strategy for recycling nutrients and rebuilding soil organic carbon. Its yield benefits are generally more modest and more variable than those of manure, reflecting the slower decomposition and lower nutrient concentration of straw relative to manure (Zhao, Z. et al., 2024). Residue retention nonetheless plays an important complementary role, particularly when combined with reduced tillage and diversified rotations, where it also contributes to erosion control and moisture conservation.

Biochar Amendments

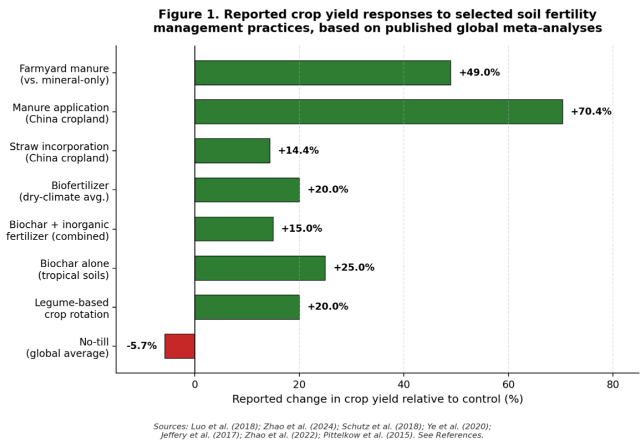
Biochar — a carbon-rich material produced by pyrolysis of organic feedstocks — has attracted growing attention as a soil amendment. Its effects on yield are strongly mediated by soil and climatic context. A global meta-analysis of 109 studies found that biochar had, on average, no significant effect on crop yield in temperate latitudes, but increased yield by 25% in the tropics, an effect attributed to biochar's liming action and nutrient contribution in acidic, low-fertility tropical soils (Jeffery et al., 2017). When applied together with inorganic fertilizer, biochar produced a further 15% yield increase relative to fertilizer alone, with the largest gains observed in very acidic soils (pH ≤ 5) (Ye et al., 2020). A subsequent meta-analysis focused specifically on biochar-based fertilizers confirmed that co-formulation with mineral nutrients improves both the consistency and magnitude of the yield response compared with biochar applied alone (Melo et al., 2022). Collectively, this evidence indicates that biochar functions best as a complement to, rather than a substitute for, conventional nutrient sources.

INORGANIC FERTILIZERS AND PRECISION NUTRIENT MANAGEMENT

Mineral fertilizers remain indispensable for correcting acute nutrient deficiencies and achieving high yield potential, particularly for nitrogen (N), phosphorus (P) and potassium (K), the three macronutrients most often limiting crop growth (Table 2). However, average nitrogen recovery efficiency in major cereal systems is estimated at only around 39%, meaning that a majority of applied N is lost to the environment through leaching, volatilization and denitrification rather than being taken up by the crop. Precision nutrient management strategies — matching fertilizer rate, source, timing and placement to crop demand and soil supply — have been shown to substantially narrow this gap. Right-source, right-rate, right-time and right-place ('4R') practices, including split N application, deep placement, use of urease and nitrification inhibitors, and diagnostic tools such as leaf colour charts and chlorophyll meters, can maintain or increase yield while reducing fertilizer requirements, improving both economic and environmental outcomes.

Importantly, evidence from long-term rotation studies shows that the yield benefit of mineral N is not independent of soil organic status: at higher soil organic carbon concentrations, a given increment of nitrogen fertilizer produces a larger yield response, because organic matter improves soil structure, water-holding capacity and the supply of other essential nutrients. This interaction underscores why inorganic fertilizer management cannot be considered in isolation from organic soil fertility building — the two are complementary rather than competing strategies (Sainju et al., 2003).

Figure 1. Reported crop yield responses (%) to selected soil fertility management practices relative to their respective controls, compiled from published global meta-analyses. Positive values indicate a yield increase; the negative value for no-till reflects its effect when applied without complementary residue retention or crop rotation.



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Nutrient Roles and Common Management Sources

Table 2 summarizes the principal role of the major plant nutrients and the soil fertility management sources typically used to supply them, providing a reference framework for the practice-specific discussion that follows.

Table 2: *Principal roles of major nutrients in crop growth and common soil fertility management sources.*

Nutrient / element	Principal role in crop growth	Common soil fertility management source
Nitrogen (N)	Amino acid, chlorophyll and protein synthesis; drives vegetative growth and yield potential	Mineral fertilizer (urea, ammonium nitrate), farmyard manure, legume N fixation, biofertilizers
Phosphorus (P)	Energy transfer (ATP), root development, flowering and seed formation	Rock phosphate, DAP/SSP fertilizers, compost, phosphate-solubilizing microbes
Potassium (K)	Osmoregulation, stomatal function, disease resistance, grain filling	Muriate/sulphate of potash, crop residue return, wood ash, manure
Soil organic carbon	Improves aggregation, water-holding capacity, cation exchange and microbial habitat	Compost, manure, straw/residue incorporation, cover crops, biochar
Micronutrients (Zn, B, Fe, Mo)	Enzyme cofactors; deficiency limits yield even when N-P-K is adequate	Balanced fertilization, foliar sprays, organic amendments, biofortified inputs

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BIOLOGICAL APPROACHES: BIOFERTILIZERS AND PLANT GROWTH-PROMOTING RHIZOBACTERIA

Biofertilizers — formulations containing living microorganisms such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria and arbuscular mycorrhizal fungi (AMF) — represent a biologically based complement to conventional fertilization. Plant growth-promoting rhizobacteria (PGPR) enhance crop performance through multiple mechanisms, including biological nitrogen fixation, solubilization of fixed soil phosphorus, production of phytohormones such as indole-3-acetic acid, siderophore-mediated iron acquisition, and induced systemic resistance to pathogens (Vejan et al., 2016).

A global meta-analysis of 171 peer-reviewed studies found that biofertilizer application increased crop yield by 8.5–20.0%, with the largest response observed in dry climates (+20.0%) and the smallest in continental climates (+8.5%); efficacy also increased with soil phosphorus status, in the order AMF < P-solubilizers < N-fixers (Schutz et al., 2018). At the field scale, inoculation of wheat with biofilm-forming PGPR strains increased grain yield by 17.5–29.6% and significantly improved nitrogen and phosphorus content in grain under both controlled and field conditions (Rafique et al., 2024). These findings position biofertilizers as a particularly valuable tool in low-input systems and in soils where chemical fertilizer access is constrained, though their performance remains more variable than that of organic amendments and is sensitive to strain selection, soil conditions and existing nutrient status.

CROP ROTATION, LEGUME INTEGRATION AND COVER CROPPING

Diversifying cropping sequences, particularly through the inclusion of nitrogen-fixing legumes, is one of the most extensively documented SFM practices. A global systematic review synthesizing 11,768 paired yield observations from 462 field experiments across 53 countries found that legume pre-crops increased the yield of a subsequent cereal crop by approximately 20% on average, with substantially larger benefits (around 32%) in low-yielding, low-input environments compared with high-input systems (around 7%) (Zhao, J. et al., 2022). The yield advantage of legume rotation was found to decline as mineral nitrogen fertilization and cropping-system diversity increased, indicating that legume-derived nitrogen and non-nitrogen effects — such as improved soil structure and reduced pest and disease pressure — are most valuable where other inputs are limited.

Cover cropping, whether legume- or non-legume-based, delivers complementary benefits. Legume cover crops have been shown to raise subsequent cash-crop yield while simultaneously increasing soil organic carbon, although this benefit can come with a trade-off of increased nitrous oxide emissions that may be mitigated through combination with no-till, deficit irrigation or diversified rotations. Non-legume cover crops generally show a smaller or non-significant direct yield effect but contribute to erosion control, weed suppression and nutrient scavenging, making crop rotation and cover cropping design an important lever within a broader soil fertility management strategy rather than a stand-alone yield intervention.

TILLAGE AND CONSERVATION AGRICULTURE

Conservation agriculture, built on the three principles of minimal soil disturbance, permanent soil cover and crop rotation, has been widely promoted as a means of sustaining yield while improving soil and environmental quality. However, evidence on the yield effect of no-till specifically — as distinct from the full conservation agriculture package — is more cautionary. In the most comprehensive assessment to date, based on 5,463 paired yield observations from 610 studies across 48 crops and 63 countries, no-till alone reduced yields by an average of 5.7% relative to conventional tillage, with declines most pronounced for maize and wheat in humid climates (Pittelkow et al., 2015a, 2015b). Critically, however, the same analysis found that when no-till was combined with residue retention and crop rotation, its negative yield impact was substantially reduced or eliminated, and rainfed productivity in dry climates was significantly increased, suggesting conservation tillage may function as an important climate-adaptation strategy in water-limited regions.

These findings have practical implications for soil fertility management: no-till should not be recommended as an isolated intervention for yield enhancement, but rather integrated with organic residue management and diversified rotations, with expectations calibrated to local climate — particularly rainfall regime — and crop type.

INTEGRATED SOIL FERTILITY MANAGEMENT (ISFM)

The evidence reviewed above converges on a common theme: individual SFM practices each have context-dependent strengths and limitations, and the largest and most reliable yield gains typically arise from combining practices rather than relying on any single input. This principle is formalized in the concept of Integrated Soil Fertility Management (ISFM), defined as a set of soil fertility management practices that necessarily includes the use of fertilizer, organic inputs and improved germplasm, combined with knowledge of how to adapt these practices to local conditions, with the aim of maximizing agronomic nutrient use efficiency and improving crop productivity (Bayu, 2020).

Empirical support for ISFM is substantial. A synthetic review of smallholder farming systems in the semi-arid areas of sub-Saharan Africa reported that ISFM practices increased maize yields by 15–145%, with maize yields under ISFM ranging from 4,200–5,500 kg ha^{-1} compared with far lower yields under farmer practice using sub-optimal manure rates (Kugedera et al., 2023). Complementing this, a continent-scale meta-analysis of combined organic and mineral fertilizer use as a climate-smart ISFM practice across sub-Saharan Africa confirmed that combining reduced rates of mineral fertilizer with organic inputs consistently outperformed either input applied alone, while also improving resilience and reducing the greenhouse gas intensity of production per unit of yield (Gram et al., 2020).

The practical strength of ISFM lies in its explicit recognition that soils, climates and farmer resource endowments vary widely, and that no universal fertilizer recommendation or amendment rate can be optimal everywhere. Instead, ISFM provides a decision framework — combine organic and inorganic nutrient sources, use improved varieties responsive to those inputs, and adapt combinations to local soil fertility status and market access — rather than a fixed technical prescription.

COMPARATIVE SYNTHESIS

Table 1 summarizes the reported yield effects, primary mechanisms and contextual notes for the major soil fertility management practices discussed in this review, drawn from the meta-analyses and large-scale field studies cited above. The comparison highlights several consistent patterns: (i) organic and combined organic–inorganic strategies generally outperform mineral fertilizer alone; (ii) biological inputs offer meaningful but more modest and context-sensitive gains; (iii) biochar and no-till are strongly conditioned by climate and soil acidity, performing best in tropical, acidic or water-limited environments; and (iv) integrated approaches that combine multiple practices consistently deliver the largest and most robust yield improvements, particularly in low-input smallholder systems.

CONSTRAINTS AND FUTURE DIRECTIONS

Despite strong evidence for the yield benefits of improved soil fertility management, adoption remains limited in many regions. Recurring constraints identified across the literature reviewed include:

- Limited and inconsistent access to organic inputs (manure, compost) at the volumes required for measurable soil fertility improvement, particularly for smallholder farmers without livestock.
- High cost, poor availability or inconsistent quality of mineral fertilizers, biofertilizer inoculants and biochar in many developing regions.
- Knowledge and extension gaps regarding site-specific combinations of practices, since the effectiveness of any single practice depends strongly on local soil type, climate and cropping system.
- Trade-offs between practices and other sustainability outcomes, such as the increased nitrous oxide emissions associated with legume cover crops or the initial yield penalty commonly observed during the first years of no-till adoption.
- Insufficient long-term, multi-site trials that combine practices (e.g., biochar with biofertilizer, or ISFM with precision nitrogen management) under farmer-managed conditions, which limits the precision of context-specific recommendations.

Future research should prioritize long-term, multi-factorial field trials that quantify interactions among organic, inorganic and biological inputs under farmer-relevant conditions; development of decision-support tools that translate soil testing and climatic data into site-specific ISFM recommendations; and continued investment in extension systems and input supply chains that make combined, evidence-based soil fertility management economically accessible to smallholder farmers, who manage a disproportionate share of the world's degraded agricultural land.

CONCLUSION

Enhancing and sustaining crop yield ultimately depends on maintaining soil fertility through practices matched to local conditions rather than on any single universal input. The evidence reviewed here demonstrates that organic amendments, precision inorganic nutrient management, biological inputs, legume-based

Table 1: *Comparative summary of major soil fertility management practices, reported yield effects and evidence sources.*

Practice	Primary mechanism	Reported yield effect	Context / notes	Source
Farmyard manure / organic amendments	Adds SOC, N/P/K, stimulates microbial C-, N-, P-cycling enzymes	**+27% vs. mineral-only fertilizer; +49% for farmyard manure specifically**	Global meta-analysis, 690 experiments	Luo et al. (2018)
Combined manure application	Long-term nutrient and organic matter buildup	**+70.4% vs. control**	173 studies, Chinese croplands	Zhao et al. (2024)
Crop residue / straw incorporation	Returns C and nutrients, improves soil structure	**+14.4% vs. no residue return**	China croplands; effect smaller than manure alone	Zhao et al. (2024)
Biofertilizers (PGPR, AMF, N-fixers)	N fixation, P solubilization, phytohormone production	**+8.5% to +20.0% depending on climate zone**	171 studies; highest response in dry climates	Schutz et al. (2018)
Biochar (alone)	Liming effect, improved CEC and water retention, nutrient sorption	**+25% in tropical soils; ~0% in temperate soils**	Global meta-analysis, 109 studies	Jeffery et al. (2017)
Biochar + inorganic fertilizer	Synergistic nutrient retention and reduced leaching	**+15% relative to fertilizer alone**	Meta-analysis of field studies with separate controls	Ye et al. (2020)
Legume-based crop rotation	Biological N fixation, break in pest/disease cycles	**+20% on average (up to +32% in low-input systems)**	11,768 paired observations, 53 countries	Zhao et al. (2022)
No-till (alone, without rotation/residue)	Reduced soil disturbance and erosion	**-5.7% on average; positive in dry rainfed climates**	5,463 paired observations, 610 studies	Pittelkow et al. (2015a)
Integrated Soil Fertility Management (ISFM)	Combines organic + mineral inputs with improved germplasm	**+15% to +145% for maize in semi-arid systems**	Smallholder systems, sub-Saharan Africa	Kugedera et al. (2023)

rotations, conservation tillage and, above all, integrated combinations of these approaches each contribute measurable and, in many cases, substantial yield gains. Organic amendments and combined organic–inorganic (ISFM) strategies generally deliver the largest and most consistent benefits, while biochar, biofertilizers and no-till are more context-dependent, performing best under specific soil, climatic or management conditions. As global agriculture faces the dual pressures of rising food demand and continued soil degradation, the integration of these complementary practices — guided by local diagnosis and adaptive management — represents the most promising pathway toward sustained crop productivity.

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