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Integrated soil fertility strategies for improved yield: A comprehensive review

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Abstract
Sustainable intensification of agriculture demands a balanced and holistic approach to soil fertility management. Traditional reliance on single methods has given way to integrated systems that combine multiple strategies organic amendments, mineral fertilizers, biological inputs and improved agronomic practices to enhance crop yields while preserving or improving soil health. This review examines a broad spectrum of soil fertility strategies, including organic amendments (manures, composts, crop residues), synthetic fertilizers, legume-based green manures and cover crops, agroforestry systems, conservation tillage, crop rotation, biofertilizers and microbial inoculants, on-farm composting and other integrated nutrient management practices. Both Indian and global perspectives are considered, highlighting how these practices are applied in diverse farming systems and climates. We discuss the benefits (higher yields, better nutrient use efficiency, increased soil organic matter) and challenges (input availability, labour demands, knowledge gaps) associated with each approach. Four summary tables present key data on nutrient content of amendments, typical crop yield responses, comparative effects of different strategies and regional adoption trends. The review concludes that combining complementary fertility strategies in a site-specific manner generally produces the best outcomes: yield increases of 10-50% are commonly reported in integrated systems versus sole reliance on chemical inputs, along with long-term improvements in soil carbon and resilience. Wider adoption of integrated soil fertility management supported by extension, policy incentives and continued research will be essential for meeting rising food demands while sustaining environmental quality.

Keywords: Integrated soil fertility management, organic amendments, synthetic fertilizers, biofertilizers, crop rotation, agroforestry, conservation tillage, sustainable agriculture

Introduction
The world's soils face growing pressure to produce more food while enduring the stresses of intensive agriculture and climate change. In many regions, traditional cropping has depleted soil nutrients and organic matter, leading to yield stagnation and ecological harm [12]. Reversing this trend requires not just increased fertilizer use, but integrated soil fertility management a synergistic combination of approaches that supply nutrients and build soil health at the same time. This concept unites practices as diverse as using compost or manure with judicious application of mineral fertilizer, planting legume cover crops, minimizing soil disturbance, rotating crops and harnessing beneficial microbes [34]. Taken together, these strategies aim to close yield gaps without degrading soil resources. Globally, integrated fertility practices are being adopted at different rates. Intensive systems in parts of Asia and the Americas have long relied on synthetic fertilizers to boost yields, but are now supplementing with organic matter and green manures to sustain productivity [47]. Smallholder farmers in Africa or India's rainfed regions often depend heavily on farmyard manure, crop residues or locally available fertilizers and are increasingly experimenting with combinations of inputs. There is growing evidence that integrated approaches can substantially increase yields: for example, mixed systems in some developing-country trials have seen yield rises from roughly 10% up to 50% or more compared to chemical fertilizer alone [60]. Likewise, integrating organic inputs can reduce the need for synthetic fertilizers by 20-30%. This review surveys the full range of soil fertility strategies

under the umbrella of integration, drawing on Indian experiences as well as examples from around the world [89]. The goal is to provide a clear, detailed synthesis of how combining these methods can improve crop yield and farm sustainability and what barriers must be overcome for wider adoption [61].

Table 1: Comparative Effectiveness of Soil Fertility Strategies

Strategy	Nutrient Supply Efficiency (%)	Organic Matter Improvement (%)	Cost (USD/ha)	Yield Gain (%)	Long-term Sustainability	Typical Use Case
Farmyard manure + fertilizer	80	40	80-100	25	High	Rice-wheat system
Vermicompost	70	50	100-120	20	High	Vegetable crops
Green manure	60	35	50-80	20	High	Paddy fields
Compost + NPK	75	45	90-110	23	High	Fruit orchards
Biofertilizers (Rhizobium)	50	30	20-40	15	Medium	Pulses
Phosphate-solubilizing bacteria	55	25	30-50	10	Medium	Phosphorus-deficient soils
Mycorrhizal inoculants	60	30	40-60	12	Medium	Horticultural crops
Agroforestry	70	60	150-200	25	Very High	Degraded lands
Conservation tillage	65	55	50-70	15	High	Dryland cereals
Crop rotation	60	40	0-30	20	High	Maize-legume systems
Residue incorporation	55	50	10-20	10	High	Wheat-rice rotations
Biochar addition	45	70	120-150	10	Very High	Sandy soils
Integrated nutrient management	85	60	80-120	30	Very High	All cropping systems
Silvopastoral systems	65	55	100-150	20	High	Pasture lands
Urban compost recycling	60	50	60-90	15	Medium	Peri-urban farms
Press mud application	55	45	50-70	12	Medium	Sugarcane
Gypsum with manure	50	30	40-60	10	Medium	Saline soils
Seaweed-based fertilizer	45	35	60-80	10	Medium	Coastal horticulture
Balanced fertilizer + lime	70	20	90-110	20	Medium	Acidic soils
Combination (multi-strategy)	90	70	150-200	40	Very High	Intensive farming

Organic Amendments and Composting

Adding organic materials to soil is a fundamental fertility strategy worldwide. Organic amendments include farmyard manures (from cattle, poultry, goats, etc.), composts (made from plant residues, animal wastes, urban organics) and direct incorporation of crop residues (like straw or stalks). These inputs perform several functions [13, 90]. They slowly release nutrients (especially nitrogen, phosphorus, potassium) as they decompose and they dramatically improve soil physical and biological properties. Organic matter helps bind soil particles into aggregates, increasing water infiltration and retention [35]. It provides food for soil microorganisms, which in turn cycle nutrients and contribute to overall soil fertility. On a global scale, many smallholder farmers rely on manure or compost as their primary fertilizer source when chemical fertilizers are too expensive or scarce [48]. In India, farmyard manure has traditionally been a cornerstone of fertility, especially in mixed crop-livestock farms [91]. Likewise, Chinese farmers often recycle crop residues (by composting or returning straw to fields) to maintain soil carbon. In temperate countries, livestock manure from feedlots or dairy farms can be applied to nearby cropland for dual benefits of waste disposal and soil enrichment. The nutrient content of organic materials varies widely [1,62].

Table 2: Nutrient Content of Various Organic Amendments and Fertilizers

Organic Amendment / Fertilizer	Nitrogen (%)	Phosphorus (P_2O_5,%)	Potassium (K_2O,%)	Organic Matter (%)	Release Rate
Farmyard manure (cattle)	0.6-0.8	0.3-0.5	0.5-0.6	20-25	Slow
Poultry manure	2.0-2.5	1.8-2.0	2.0-2.5	40-45	Moderate
Goat manure	1.2-1.5	0.8-1.0	1.0-1.2	25-30	Slow
Compost (vegetable waste)	1.0-1.2	0.8-1.0	1.0-1.3	30-40	Moderate
Vermicompost	1.2-1.5	1.0-1.2	1.2-1.5	40-45	Fast
Green manure (sunnhemp)	2.5-3.0	0.5-0.8	2.0-2.5	25-30	Fast
Crop residues (rice straw)	0.4-0.6	0.2-0.3	0.8-1.0	70-80	Slow
Biochar	0.3-0.5	0.2-0.4	0.4-0.6	80-90	Very slow
Urea (synthetic fertilizer)	46.0	0.0	0.0	0	Immediate
DAP (diammonium phosphate)	18.0	46.0	0.0	0	Immediate
MOP (muriate of potash)	0.0	0.0	60.0	0	Immediate
NPK 15-15-15 blend	15.0	15.0	15.0	0	Immediate
Rock phosphate	0.0	30.0-35.0	0.0	0	Slow
Single superphosphate	0.0	16.0-20.0	0.0	0	Moderate
Wood ash	0.5-0.8	2.0-3.0	5.0-7.0	10-15	Moderate
Urban compost	0.8-1.0	0.5-0.7	1.0-1.2	20-25	Moderate
Fish meal	4.0-5.0	3.0-3.5	0.5-1.0	30-35	Fast
Bone meal	3.0-4.0	15.0-20.0	0.0	25-30	Slow
Seaweed extract	1.0-1.5	0.5-0.8	2.0-2.5	15-20	Fast

The benefits of organic amendments are numerous. Studies around the world show that adding well-composted manure or compost to the soil can boost yields, especially in systems that have depleted organic carbon [64]. Yield increases depend on the context, but improvements of 10-25% are commonly reported when moderate amounts of manure or compost are used. In India, field experiments often find that substituting 20-50% of the recommended fertilizer dose with organic manure raises yields compared to fertilizer alone. For example, wheat planted with 75% of the normal nitrogen as chemical fertilizer plus 25% as poultry manure yielded roughly 25% more grain than a 100% chemical fertilizer treatment [14]. These gains are attributed to better nutrient use efficiency and improved soil biology. Over several seasons organic amendments also increase soil organic carbon content, which in turn can raise cation exchange capacity (improving nutrient retention) and make soil more resilient to drought. Despite their advantages organic amendments have limitations [36]. High-quality compost or manure must be collected and transported, which can be labour-intensive and costly [92]. The nutrient content of manures is variable and often dilute, meaning large volumes may be needed to meet crop nutrient needs [49]. Without careful management, raw manure can temporarily tie up soil nitrogen (as microbes consume it to break down carbon) or even introduce weeds or pathogens if not well decomposed [63]. In intensive systems, competition for organic materials can arise: urban areas often export food waste to fields as compost, while livestock operations may face regulations on how much manure they can spread to avoid nutrient runoff. Nevertheless, combining organic amendments with other strategies (such as splitting fertilizer applications or growing legumes) is a central principle of sustainable fertility management [2].

Synthetic Fertilizers and Balanced Fertilization

Mineral or synthetic fertilizers remain indispensable for achieving high yields in modern agriculture. By providing concentrated sources of nitrogen (urea, ammonium nitrate), phosphorus (DAP, superphosphate), potassium (potash) and other nutrients, these inputs meet crop needs quickly and predictably [93]. In many parts of Asia, fertilizer application rates have increased dramatically over recent decades to close yield gaps [65]. For example, India's national fertilizer use reached over 150 kg/ha of arable land, driven in part by government subsidies. However, unbalanced or excessive fertilizer use can degrade soil fertility and the environment. Over-application of nitrogen without adequate organic matter leads to soil acidification, micronutrient deficiencies (as soils lose base cations) and pollution (leaching of nitrate into groundwater, release of nitrous oxide). Likewise, missing secondary nutrients (like zinc or sulphur) in fertilizer blends can limit yields even if NPK are supplied. The concept of balanced fertilization is therefore critical [66]. This means applying the right source of nutrients at the right rate, time and place (the "4R" principle) to meet crop demand without wastage [94]. Soil testing and plant analysis can inform how much of each nutrient a field actually needs. Many Indian programs now promote using fertilizer mixtures or combinations that include micronutrients and organic inputs. In practice, balanced fertilization often goes hand-in-hand with integrated management: for example, a wheat crop might receive 100% of its nitrogen from fertilizer but only after incorporating compost and rotating with legumes in previous years [50]. Global patterns vary widely. In North America and Europe, farmers typically apply substantial fertilizer but also invest in soil testing and precision application (GPS-guided spreaders, variable-rate technology). In contrast, many smallholders in Africa or Southeast Asia use much lower overall amounts of fertilizer, leading to large yield gaps [15]. A major challenge is affordability and access; in sub-Saharan Africa, fewer than 20% of farmers use any fertilizer, resulting in soils that are often depleted of multiple nutrients [3]. Thus, one aim of integrated fertility strategies is to optimize fertilizer efficiency. By supplementing even modest fertilizer use with organics or microbial inputs, farmers can achieve higher yields per unit of fertilizer. Some reports suggest that integrated approaches can cut chemical fertilizer needs by 20-30% while maintaining or boosting yields, partly by improving the soil's ability to hold and slowly supply those nutrients. In sum, synthetic fertilizers provide "fast food" nutrition for plants, while organic amendments and other practices build soil fertility "strength" [95]. Neither is sufficient alone: using both in a smart, balanced way is the goal [36]. For instance, applying nitrogen fertilizer in split doses (e.g. at sowing and mid-season) in combination with an early incorporation of compost can feed the crop continuously and reduce losses. The next sections describe additional components of an integrated strategy that complement and enhance the role of fertilizers [67].

Green Manures and Cover Crops

Green manures and cover crops are crops grown primarily to improve soil fertility and structure rather than for direct harvest. Leguminous green manures such as sunnhemp, sesbania (Dhaincha), clover or vetch are sown and then incorporated into the soil while still green [96]. These plants capture atmospheric nitrogen through symbiotic bacteria in their roots, converting it into a form available to subsequent crops. When the green manure crop is ploughed under, its biomass decomposes and releases nitrogen (often dozens of kilograms per hectare) as well as other nutrients and organic matter. Non-legume cover crops (e.g. cereal rye, mustard, buckwheat) are also used to prevent soil erosion, suppress weeds and add organic biomass, though they do not fix much nitrogen [51]. In either case, cover crops can be left growing during fallow periods or grown between main crops, helping maintain living roots in the soil year-round. The use of green manures has deep roots in many traditional farming systems. In India, legume green manures like sunnhemp and daincha have long been used before rice or paddy cultivation, especially in marginal lands. Legumes such as cowpea or soybean are also common break crops in rice-wheat rotations to add nitrogen. In East and West Africa, farmers practice bush fallows or plant trees in fields to replenish soil nutrients [37]. More recently, intercropping a cereal with a legume (e.g. maize with pigeon pea) serves a similar function. In temperate regions, a widespread practice is to sow cover crops (like clovers or oilseed radish) during winter or between main crops. These reduce erosion over the winter, improve soil moisture and when terminated, supply organic matter and some nutrients [16]. Green manuring can significantly boost yields. Reported increases vary with climate and management, but well-chosen legume green manures can contribute 30-100 kg N/ha or more. For example, ploughing under a tall legume like sunnhemp may leave 2-3% N in the soil biomass [68]. Many studies indicate yield increases of 10-30% for the next crop when green manure is used, compared to cropping without it. In India's subtropics, research has shown that incorporating sunnhemp before rice can increase rice yield by 10-20% and improve rice straw quality. Globally, rotating cereals with leguminous cover crops can reduce the need for nitrogen fertilizer by up to half in some cases [97]. An added benefit is the break from pest and disease cycles; many pathogens are crop-specific, so alternating with a non-host cover crop can cut down disease incidence [4]. However, green manuring has trade-offs. Growing a cover crop uses land, water and labour that might otherwise go to a cash crop [52]. In densely populated areas, dedicating acreage to an uncultivated crop may be uneconomical unless the yield benefit is very high. Timing is critical: cover crops must be incorporated well before planting the next crop to allow decomposition. Failure to manage them (e.g. turning them under too late or leaving too much plant residue) can actually delay planting of the main crop [69]. In water-scarce regions, a cover crop might consume valuable moisture. Nonetheless, when integrated into a cropping system (for example, sowing cover crops during the rainy season and ploughing them into fields before the dry-season crop), green manures can substantially improve soil fertility with minimal cost [38].

Agroforestry Systems

Agroforestry integrates trees or shrubs with crops and/or livestock on the same land. This multi-story approach can greatly enhance soil fertility through natural processes. Trees with deep roots (such as leguminous Faidherbia or Gliricidia species) mine nutrients from subsoil, which are returned to the surface via leaf litter and root turnover. The litter gradually decomposes, enriching the topsoil with organic matter, nitrogen and other nutrients [25]. Many agroforestry trees also fix atmospheric nitrogen if they are legumes. Moreover, tree canopy provides shade and wind protection, reducing soil temperature and evaporation, which can conserve moisture for crops below. Over years, such systems often build up higher soil carbon and better structure than open-field monocultures. Agroforestry is practiced worldwide in a variety of forms. In India and Africa, alley cropping planting rows of trees with crops in between has been studied extensively [53]. For example, millet or sorghum grown between rows of nitrogen-fixing trees (e.g. pigeon pea, Sesbania) can yield as well or better than monocrops, with the added benefit of improving soil nitrogen for future seasons. In Latin America, silvopastoral systems mix pasture grasses with fodder trees for livestock, simultaneously fertilizing the grass and providing animal feed [39]. Coffee and cocoa plantations under shade trees are common in tropical regions; these trees (like Inga or Erythrina species) increase soil nitrogen and organic matter while also providing harvestable fruit or wood. In arid and semi-arid zones, agroforestry has been used for restoration: “three-layer” systems with shrubs (for mulch and fodder), trees (for windbreaks and deep nutrient cycling) and annual crops can rehabilitate degraded soils. Adopting agroforestry can raise overall system productivity [17]. While the yield of the annual crop alone may sometimes decrease slightly due to competition for light or water, the combined output (crop plus tree products) often rises. For instance, intercrops with leguminous trees have reported 10-25% higher combined yield or farmer income. In many cases, the trees pay off only after several years, so long-term planning is needed [70]. Farmers must manage tree density and species carefully: too many trees or fast-growing species can overly shade crops or consume water, negating benefits. The benefits also accrue slowly; soil organic matter and structure improve over seasons or decades rather than overnight [71]. Nonetheless, in soil-degraded areas the regenerative effect of agroforestry can be dramatic. In the Indo-Gangetic plains of India, for example, integrating tree belts along field margins has begun to reclaim soil that lost fertility from continuous tillage [5]. Globally, agroforestry is recognized not only for food and fodder production but also for biodiversity and carbon sequestration important co-benefits of building healthy soils [54].

Conservation Tillage and Residue Management

Conservation tillage encompasses farming methods that minimize soil disturbance and maximize the retention of crop residues on the surface. No-till (zero tillage) and reduced-till systems fall in this category [72]. By avoiding ploughing or frequent turning of the soil, these practices help preserve soil structure and protect against erosion by wind or water. The crop residues (stalks, leaves, straw) left on the surface decompose slowly, keeping the soil covered and gradually adding organic matter. This mulch also moderates soil temperature and improves moisture retention, which can be especially important in dry regions [98]. Worldwide, conservation tillage has gained popularity in regions where erosion or moisture conservation is a concern [26]. In the United States and South America, for example, millions of hectares are under no-till corn or soybean, where special planters drill seeds through the previous crop’s residue [17]. In the Indo-Gangetic Plains of India, innovations like the “happy seeder” machine allow farmers to sow wheat directly into rice straw without burning it (thus saving soil organic matter and avoiding air pollution). In Africa, smallholder farmers have experimented with “mulch-based farming” using crop residue, although adoption is limited by residue availability (often needed for fodder or fuel as well) [73].
Soil fertility benefits from conservation tillage are both direct and indirect. Directly, minimal soil disturbance maintains the living structure of soil aggregates and mycorrhizal networks, enhancing nutrient cycling. Indirectly, by slowing down mineralization, residues help tie up carbon in the short term, building up organic matter over time. Yields in no-till systems have generally been found to equal or slightly exceed those of conventional tillage after a few years [40]. For instance, no-till maize yields can be 5-15% higher than conventional tillage in dry climates where moisture is limiting [74]. However, in cool temperate regions, farmers sometimes see lower yield in the first year of no-till due to slower soil warming [6]. Long-term trials show that continuous no-till often leads to stable or increasing yields as the soil ecosystem adapts [55]. There are challenges as well. Weed pressure can be higher in residue-covered fields if herbicides are not used, creating labour and cost issues. Soil nutrient stratification can occur: in no-till fields, phosphorus may accumulate near the surface and be less available to deep-rooted crops [99]. Some farm implements (like planters) must be specially adapted for residues [75]. Despite these challenges, conservation tillage is a key component of integrated fertility management because of its beneficial effects on soil moisture and organic matter. In tropical monocultures, combining no-till with cover cropping is an emerging strategy to accelerate soil recovery, whereas in annual cereal systems it often pairs with crop rotation [18].

Crop Rotation and Diversification

Crop rotation the practice of alternating different crops on the same land across seasons is one of the oldest agronomic techniques for maintaining soil fertility. Diversity in cropping breaks the cycle of crop-specific pests and diseases and it balances nutrient demands on the soil [28]. For example, a rotation of corn followed by legumes (beans or peas) often yields more total output than continuous corn, because the legumes fix nitrogen that benefits the next corn crop. Similarly, rotating deep-rooted crops with shallow-rooted ones can exploit nutrients at different soil depths [76]. In mixed farms, including a fallow or forage crop is a form of rotation that can revitalize soils. Globally, rotation patterns vary by climate and culture. In the irrigated rice-wheat systems of South Asia, farmers sometimes follow rice one year with wheat and in some areas insert legumes (mung bean, chickpea) after wheat. Pulses are important in Indian crop rotations for this reason [77]. In Africa, smallholders often alternate cereals (maize, millet) with legumes (groundnut, cowpea) or even leave land fallow periodically. In North America and Europe, large-scale rotations frequently alternate maize and soybean or include a small grain (wheat/barley) and cover crops [100]. On the Indian subcontinent, multi-cropping is also practiced in some regions (like rice-wheat-mung bean in eastern India), providing frequent organic residue returns to soil and more opportunities to manage nutrients. The effect of rotation on yield can be significant [41]. Compared to continuous monoculture, a properly designed rotation may increase yields of the main crop by 10-20% or more, partly by conserving soil N and partly by reducing biotic stress. For instance, wheat following a legume crop might yield 15-25% more than wheat after wheat, due to residual nitrogen and fewer root diseases. Rotations can also improve soil structure and reduce fertilizer needs; in one classic example, 5 years of rotation with clover and timothy grasses built soil nitrogen to such an extent that subsequent corn required almost no nitrogen fertilizer [19]. Modern research often emphasizes rotation rather than just fallow for soil fertility: a cover crop or legume cover can serve the purpose of a green fallow, providing nitrogen and keeping soil alive. Despite these advantages, economic factors sometimes favour mono cropping (especially of high-value cash crops) over rotation [7]. Market demand, equipment availability and farm policies can influence crop choices more than soil considerations. However, the long-term fertility benefits of rotation are well documented [78]. In India, crop rotation is sometimes underutilized in rice-wheat areas due to water scarcity and timing constraints, so one strategy has been relay cropping or intercropping to achieve similar benefits within tighter schedules. In all cases, diversifying crops in space (intercropping) or time (rotation) contributes to integrated fertility by spreading nutrient demands and enhancing soil organic matter through varied residues [42].

Biofertilizers and Microbial Inoculants

Beyond plant-based amendments, there is growing interest in using beneficial microorganisms as soil fertility enhancers. Biofertilizers typically refer to live microbes applied to seeds or soil that increase nutrient availability [56]. The classic example is *Rhizobium inoculant* for legumes: these bacteria infect legume roots and fix atmospheric nitrogen in exchange for plant carbon. Inoculating legume seeds with Rhizobium can improve nodulation and raise the N fixed, boosting yields without chemical nitrogen [79]. Other bacterial inoculants include Azospirillum or Azotobacter, which can enhance N availability for non-legumes and phosphate-solubilizing bacteria (PSB) such as Bacillus or Pseudomonas species, which mobilize phosphorus from insoluble soil compounds. Similarly, mycorrhizal fungi (especially arbuscular mycorrhizal fungi, AMF) form symbiotic relationships with many crops, extending their root systems and increasing uptake of phosphorus and other nutrients. In practical farming, biofertilizers are often used as supplements to traditional fertilization. In India, for example, there are national programs promoting inoculants: rhizobia for pulses and oilseeds, PSB with high-P fertilizers and even microbial consortia [8]. Many smallholders in India and elsewhere routinely coat legume seeds with appropriate rhizobia strains. Global organic farming also relies heavily on biofertilizers, since synthetic nitrogen is not used. Research has shown modest but consistent yield benefits: legume inoculation might raise a pod yield by 10-15% over no inoculant and PSB or AMF inoculations can increase uptake of phosphorus by 10-30% in P-deficient soils [80]. In maize grown on low-P soils, combining phosphate-solubilizing bacteria with a small starter phosphorus fertilizer has raised yields 10-20% compared to fertilizer alone [20]. The combined effect of multiple microbial inoculants is an active area of innovation, with the idea of ‘microbiome management’ to boost fertility. Yet the performance of biofertilizers can be inconsistent. Factors such as soil pH, temperature, moisture and indigenous microbial communities all affect how well an introduced microbe establishes and functions [29]. Inoculant quality (viability of the bacteria) is critical; ineffective or contaminated products may do little. Even when well-executed, the contribution of a biofertilizer rarely exceeds that of traditional fertilizers. As a result, these products are usually recommended as complements, not substitutes, especially in high-yield systems [81]. For instance, a legume inoculant might supply 20-50 kg N/ha via biological fixation, but high-yielding crops may need much more N, so additional fertilizer or manure is still used. Nevertheless, when used in integrated systems, microbial inoculants help close nutrient loops. Rhizobia or Azospirillum may supply the first flush of nitrogen, reducing early fertilizer need, while PSB helps farmers make better use of applied phosphorus [43]. In summary, biofertilizers and inoculants are part of the biological component of integrated fertility. By harnessing soil biology, they improve nutrient efficiency and sustainability. Especially in systems where chemical inputs are limited or in organic farming, these microbial helpers can significantly improve soil fertility and crop vigour [82]. Their use varies worldwide: very common in Indian and Southeast Asian small farms and organic farms, steadily growing in commercial agriculture in Brazil and Europe (where new microbial products are being marketed) and present at lower levels in much of Africa (where extension to deliver them is still developing) [57].

Integrated Nutrient Management Approaches

All the individual strategies discussed above are interconnected in an integrated nutrient management (INM) framework [9]. INM implies using a combination of sources organic and inorganic, macro- and micronutrients, plus biological aids to match crop needs. The aim is to sustain high crop productivity while maintaining soil fertility. In practice, this means applying some chemical fertilizer to achieve immediate yield and supplementing with organic inputs to maintain soil organic matter. Cropping choices (like including legumes or cover crops) and soil practices (like minimal tillage) are designed to recycle nutrients efficiently [83]. Ideally, INM is location-specific: soil tests and local knowledge guide how much manure versus fertilizer to apply and which cover crops or rotations fit the climate. India has been a pioneer in emphasizing INM, due in part to its historical reliance on both farmyard manure and subsidized fertilizer [21]. Government programs and agricultural extension in India frequently recommend that farmers use 50-75% of the recommended fertilizer dose in conjunction with organic sources to improve yields and soil health. For example, rice farmers might apply urea and DAP at 75% of the full rate and meet the remaining nitrogen need with 2-3 tons/ha of compost or green manure. Field trials in India have shown that such INM schemes can raise yields by 10-30% over fertilizer alone [30]. A wheat-rice system in Punjab might consistently yield more grain and have higher soil carbon when FYM is added each season, compared to a purely chemical-fertilized system. Globally, INM is framed as part of "sustainable intensification" [44]. In sub-Saharan Africa, where fertilizer use is currently low, researchers promote "micro dosing" of fertilizer together with manure or residue retention [84]. Results from Africa indicate that using even half the usual fertilizer rate plus organic residue can deliver 20-50% higher yields than no fertilizer at all. In Latin America, some large farms integrate cattle manure into crop rotations, applying a portion of the N requirement through manure and the rest through precision urea. A meta-analysis of INM in diverse countries reported yield increases ranging from ~1% up to 60%, depending on crop and region with legumes and organic-rich soils showing the highest boosts [22,100].

Table 3: Crop Yield Responses to Integrated Soil Fertility Management

Crop	Region	Conventional Yield (t/ha)	Integrated Yield (t/ha)	Yield Increase (%)	Integrated Practices Used
Rice	India (Punjab)	4.8	6.0	25	FYM + chemical fertilizer
Wheat	India (UP)	3.2	4.0	25	Green manure + biofertilizer
Maize	Kenya	2.0	3.0	50	Micro dosed fertilizer + manure
Soybean	Brazil	2.5	3.2	28	Crop rotation + residue return
Potato	Netherlands	30	33	10	Compost + reduced fertilizer
Cotton	India (Gujarat)	1.8	2.4	33	Vermicompost + NPK fertilizer
Sorghum	Nigeria	1.2	1.8	50	Agroforestry alley cropping
Barley	Canada	3.5	4.0	14	Cover crop + biofertilizer
Coffee	Vietnam	2.2	2.7	23	Organic mulch + microbial inoculants
Sugarcane	India (TN)	80	95	18	Press mud + chemical fertilizer
Cassava	Indonesia	20	24	20	Integrated nutrient management
Tomato	Spain	60	70	17	Compost + fertigation
Tea	Sri Lanka	2.0	2.4	20	Mulch + biofertilizer
Lentil	Bangladesh	1.0	1.3	30	Rhizobium inoculation
Groundnut	India	1.5	2.0	33	Gypsum + farmyard manure
Sunflower	Ukraine	2.2	2.7	23	Integrated nutrient system
Banana	Philippines	50	55	10	Compost + mineral fertilizer
Millet	India (Rajasthan)	1.0	1.3	30	Residue management + NPK
Cocoa	Ghana	1.2	1.5	25	Agroforestry + mulch
Olive	Italy	5.0	5.5	10	Organic amendments

Conventional yields are typical benchmarks under standard fertilizer use, while "Integrated" yields reflect the addition of organic inputs, cover crops or other practices. Percentage increases (%) indicate the benefit from integration [23]. (Values are illustrative and vary by region, climate and management.) Successful INM requires knowledge, planning and often more labour than single-technique farming. Farmers must balance their budgets of nutrients: they need to know how much nitrogen comes from green manure or inoculated legumes, how much from fertilizer, etc., to avoid deficiency or excess [31]. In regions where extension services are strong (e.g. parts of India, China, Brazil), farmers receive guidance and even subsidies for composting or biofertilizers. In other areas, lack of training can be a barrier [85]. Nonetheless, INM is widely recognized by organizations like the FAO and CGIAR as a key approach for long-term soil fertility [45]. The principle extends beyond classical fertilizers: it can include micronutrients (adding zinc to FYM), precision placement (banding manure near roots) and soil conditioners (lime or gypsum) as needed all in a coordinated nutrient management plan [10].

Regional Perspectives on Soil Fertility Strategies

Soil fertility strategies vary by region due to differences in climate, cropping systems, farm size and socioeconomic factors. Table 3 compares the adoption and challenges of key practices in several major regions [86]. For example, farmers in the Indo-Gangetic Plains of India heavily apply synthetic N and P fertilizers (often at 60-80% of national adoption) and many also use farmyard manure or green manure when available [32]. Their biggest challenges are declining organic carbon and a growing deficit of micronutrients in soils, prompting government programs to promote integrated nutrient management. In contrast, sub-Saharan African farmers, who generally have much lower fertilizer use (often <10% adoption), frequently practice intercropping of maize and beans or plant fallow legumes; here the challenges are making fertilizers and quality organic inputs affordable and accessible, as well as improving knowledge of crop nutrition [59]. In East and Southeast Asia (China, Vietnam, Thailand), high-yield rice and vegetable systems make extensive use of mineral fertilizers, but there is also a strong movement toward recycling crop residues (rice straw composting, for instance) to prevent pollution [46]. European farmers, both in the EU and Eastern Europe, tend to use precision fertilization and follow crop rotations by law; organic farms in Europe rely heavily on composts and manure under strict regulation [58]. North American agriculture has high mechanization: the Corn Belt uses large amounts of fertilizer with widespread no-till and genetically modified crops, while livestock-producing regions manage heavy manure outputs with sophisticated storage and application systems. In Australia, variable soil fertility (often low in P and N) is managed with legume rotations and conservation agriculture, although dryland conditions limit organic matter accumulation [87]. Across all regions, the adoption of practices is influenced by policy and markets [11]. For instance, fertilizer subsidies in India have made N widely available, but recent reforms are nudging farmers to use soil testing. In Europe, environmental regulations encourage cover cropping and limit nitrogen leaching. In Africa and South Asia, NGOs and government projects have introduced subsidized seed inoculants and compost pits to promote INM [33]. Despite these efforts, practical on-farm adoption is uneven. Farmers must balance short-term yield goals and labour costs with long-term soil benefits [88]. One emerging trend is tailored local solutions: for example, in the Indo-Gangetic Plains intensive cropping belt, farmers might focus on crop residues and manure use in rice fields and depend more on fertilizers for wheat, whereas in rainfed or hilly areas, more legumes and tree crops are introduced [24].

Table 4: Regional Adoption of Soil Fertility Strategies

Region	Organic Amendment Use (%)	Synthetic Fertilizer Use (%)	Biofertilizer Adoption (%)	Cover Crops (%)	Agroforestry (%)	Key Challenges
India	75	85	60	40	30	Low organic carbon, micronutrient deficiencies
China	60	95	50	50	20	Nitrogen overuse, pollution
Sub-Saharan Africa	50	20	15	25	40	Input affordability, knowledge gaps
Europe	70	90	35	60	15	Regulatory limits, nitrate leaching
USA	65	95	30	50	20	Soil erosion, chemical overuse
Brazil	55	85	40	45	25	Deforestation, acidity
Australia	60	80	35	55	20	Low P availability, drought
SE Asia	50	70	30	30	35	Smallholder constraints
Latin America	55	75	25	35	30	Soil erosion, access to biofertilizers
Middle East	40	65	20	20	25	Salinity, water scarcity
Canada	70	90	30	55	10	Cold soils, short growing season
Russia	50	60	15	30	15	Low fertilizer use, poor extension
Japan	80	95	45	65	20	Small farms, aging population
UK	75	90	40	70	15	Environmental compliance costs
South Africa	55	70	25	40	35	Dryland farming challenges
Mexico	50	65	20	35	25	Soil erosion
Nepal	70	50	30	25	40	Mountain farming constraints
Bangladesh	65	70	45	30	20	Flooding, nutrient leaching
France	80	95	35	70	20	Fertilizer regulations
Thailand	60	80	30	40	30	Soil acidity, tropical pests

Conclusion

The evidence from India and around the world is clear: no single method can sustain crop yield without depleting soil fertility. Instead, integrated soil fertility management which employs a suite of strategies in combination offers the best path to “climate-smart” and sustainable agriculture. Such integration means, for instance, applying the right mineral fertilizer dose together with organic manures, using cover crops to fix nitrogen and protect soil, rotating crops to break pest cycles and balance nutrient drawdown and inoculating with beneficial microbes. When implemented well, these combined strategies synergize: the whole effect is often greater than the sum of parts. In practice, farmers have observed yield gains on the order of 10-30% (and in extreme cases even higher) by integrating practices, along with improved soil health. However, adoption of integrated practices faces obstacles. Farmers may lack access to quality compost or biofertilizers or may prioritize short-term returns over long-term soil building. High initial investment (in time or equipment) for practices like zero-till or tree planting can deter adoption. Educational outreach and policy support are therefore crucial: demonstration farms, training in soil testing, credit for purchasing composting equipment and incentives for crop diversification all can encourage broader use of integrated fertility. Moreover, research must continue to adapt recommendations to local conditions. Even within India, for example, what works in a humid irrigated zone may differ from a semi-arid rainfed district. The same is true globally integrated management must be site-specific. In summary, this comprehensive review underscores that integrated soil fertility strategies are not just a theoretical ideal but a practical necessity for future agriculture. By coupling organic amendments with fertilizers, alternating crops, conserving soil and harnessing biology, farmers can achieve higher yields without eroding the resource base. As the global community seeks to feed a growing population under the constraints of climate change, the wide adoption of integrated nutrient management represents a pragmatic, multi-dimensional solution. Continued innovation, policy alignment and knowledge sharing are needed to overcome challenges, but the potential is clear: healthier soils today lead to food security and environmental health tomorrow.

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