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Nutrient management for sustainable agricultural practices

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Abstract

Sustainable agricultural production requires balanced nutrient management strategies that maintain soil health while meeting crop demands. This research evaluated integrated nutrient management approaches combining organic and inorganic sources across a cereal-legume cropping system over three consecutive years from 2016 to 2019. The experimental design incorporated six treatment combinations: unfertilized control, recommended NPK fertilization alone, NPK with farmyard manure, NPK with green manure incorporation, NPK with biofertilizer inoculation, and a fully integrated approach combining chemical fertilizers with organic amendments and biofertilizers. Six crop species representing cereals and legumes were evaluated including rice, wheat, maize, soybean, mustard, and chickpea. Soil samples collected at pre-sowing and post-harvest stages were analyzed for available nitrogen, phosphorus, potassium, organic carbon content, and microbial biomass. Plant tissue analysis determined nutrient uptake and use efficiency parameters. Grain and straw yields were recorded at harvest maturity along with quality parameters. Results demonstrated that integrated nutrient management produced the highest yields across all crops, exceeding control yields by 68-92% and surpassing chemical-only treatments by 27-38%. Rice responded most strongly to integrated management with yield increases reaching 4, 876 kg/ha compared to 2, 612 kg/ha under unfertilized conditions. Wheat and maize showed similar response patterns with 78% and 92% yield improvements respectively under integrated management. Legume crops including soybean and chickpea exhibited moderate but significant responses ranging from 68% to 73% yield enhancement. Soil organic carbon increased progressively under treatments receiving organic inputs, rising from 0.58% initially to 0.87% after three years with integrated management compared to 0.61% under chemical-only fertilization. Microbial biomass carbon showed parallel improvements, reaching 287 mg/kg under integrated management versus 156 mg/kg with chemical fertilizers alone. Nitrogen use efficiency improved substantially under integrated approaches, averaging 52% compared to 38% with chemical fertilizers only, representing a 14-percentage point advantage. Phosphorus recovery similarly increased from 18% to 29% under integrated management. Economic analysis indicated that despite higher input costs, integrated management generated superior net returns due to yield advantages and reduced fertilizer requirements over time. The benefit-cost ratio reached 2.34 for integrated management compared to 1.87 for chemical fertilization alone. These findings establish that integrated nutrient management combining chemical fertilizers at 75% recommended rates with organic amendments and biofertilizers offers a sustainable pathway for maintaining productivity while improving soil health indicators. The approach addresses concerns regarding soil degradation under intensive chemical fertilization while providing economic viability for farming communities.

Keywords: Integrated nutrient management, organic amendments, biofertilizers, nitrogen use efficiency, soil organic carbon, sustainable agriculture, farmyard manure, crop productivity

Introduction

How can modern agriculture meet escalating food demands without depleting the very soil resources upon which production depends? This fundamental question drives the search for sustainable nutrient management practices that balance productivity with environmental stewardship ^[1]. The intensification of agricultural production over recent decades has relied heavily upon synthetic fertilizers, yet mounting evidence suggests this approach alone cannot sustain long-term soil fertility ^[2].

Global fertilizer consumption has increased dramatically since the Green Revolution, with nitrogen fertilizer use rising from 12 million tonnes in 1961 to over 110 million tonnes by 2018 ^[3]. While this expansion enabled substantial yield increases, efficiency of fertilizer use has declined progressively. Ladha *et al.* ^[4] documented that nitrogen recovery efficiency in cereal systems dropped from

approximately 50% in the 1960s to below 35% by recent years, meaning most applied nitrogen fails to reach the crop and instead contributes to environmental pollution through leaching and gaseous emissions.

Continuous chemical fertilization without organic matter replenishment leads to soil degradation through multiple pathways. Soil organic carbon, the foundation of soil health, declines under intensive chemical agriculture due to reduced carbon inputs and accelerated decomposition ^[5]. Manna *et al.* ^[6] reported organic carbon depletion rates of 0.02-0.04% annually in intensively cultivated soils receiving only chemical fertilizers over 25 years of continuous cropping. Such losses compromise soil physical properties, water holding capacity, and biological activity essential for nutrient cycling.

Integrated nutrient management emerged as an approach to address these limitations by combining multiple nutrient

sources in complementary fashion ^[7]. The concept recognizes that organic and inorganic sources each offer distinct advantages: chemical fertilizers provide readily available nutrients in precise formulations, while organic amendments supply slow-release nutrients alongside carbon and beneficial microorganisms ^[8]. Biofertilizers further enhance nutrient availability through biological nitrogen fixation and phosphate solubilization ^[9].

Research across diverse agroecological zones has demonstrated advantages of integrated approaches. Singh *et al.* ^[10] found that combining 50% NPK with farmyard manure at 10 tonnes per hectare matched yields obtained with full recommended fertilizer doses while improving soil organic matter. Sharma and Mitra ^[11] reported 15-20% yield improvements when biofertilizers supplemented chemical fertilization in legume-cereal rotations. Such findings suggest synergistic interactions among nutrient sources that exceed additive effects.

Green manuring represents another component of integrated management with particular relevance to tropical and subtropical systems. Incorporation of leguminous green manure crops adds 60-120 kg nitrogen per hectare through biological fixation while supplying organic matter ^[12]. *Sesbania*, dhaincha, and sunhemp are commonly cultivated as green manure crops in monsoon fallow periods, their biomass contributing both nutrients and carbon upon incorporation ^[13].

Economic considerations influence adoption of nutrient management practices by farmers. While organic inputs may reduce requirements for purchased fertilizers, they also entail collection, transport, and application costs ^[14]. Farm-level decision making must weigh these factors against potential yield and soil health benefits. But the long-term economics increasingly favor integrated approaches as soil degradation under chemical-only systems necessitates ever-higher input levels to maintain yields ^[15].

Regional variations in soil types, climate, and cropping systems require location-specific optimization of integrated management strategies. And the specific combinations of organic sources, biofertilizers, and chemical fertilizer rates that maximize both productivity and sustainability may differ substantially among agroecological situations ^[16]. This necessitates systematic evaluation under representative conditions.

The present research aimed to evaluate integrated nutrient management strategies for a cereal-legume cropping system under semi-arid conditions. Specific objectives included: comparing yield responses of six crop species to different nutrient source combinations; quantifying effects on soil health indicators including organic carbon and microbial biomass; determining nutrient use efficiency under integrated versus conventional management; and assessing economic viability of alternative approaches.

Study Area Description

The experimental site occupied an alluvial plain within the Indo-Gangetic region characterized by subtropical climate with distinct hot summers and mild winters. Mean annual rainfall totaled 892 mm with approximately 82% concentrated during the June through September monsoon period. Temperature extremes ranged from 4.2°C minimum in January to 45.8°C maximum in May, with mean annual

temperature of 25.3°C. The soil was classified as a Typic Ustochrept with sandy loam texture containing 62.4% sand, 21.8% silt, and 15.8% clay. Initial soil characterization revealed pH of 7.6, electrical conductivity of 0.34 dS/m, organic carbon content of 0.58%, available nitrogen of 187 kg/ha, available phosphorus of 14.3 kg/ha, and exchangeable potassium of 156 kg/ha. The site had been under continuous rice-wheat rotation for twelve years prior to experiment initiation, representative of predominant farming systems in the region. Groundwater availability permitted supplemental irrigation during dry periods through tube well infrastructure.

Materials and Methods

Materials

Six crop species representing cereals and legumes were selected for evaluation: rice (*Oryza sativa* L. var. Pusa-44), wheat (*Triticum aestivum* L. var. HD-2967), maize (*Zea mays* L. var. HQPM-1), soybean (*Glycine max* L. var. JS-335), mustard (*Brassica juncea* L. var. Pusa Bold), and chickpea (*Cicer arietinum* L. var. Pusa-256). Chemical fertilizers included urea (46% N), single superphosphate (16% P₂O₅), and muriate of potash (60% K₂O). Farmyard manure was obtained from the institutional cattle yard with nitrogen content of 0.52%, phosphorus content of 0.28%, and potassium content of 0.43% on dry weight basis. Biofertilizers comprised *Rhizobium japonicum* for soybean, *Rhizobium leguminosarum* for chickpea, *Azotobacter chroococcum* for cereals, and phosphate solubilizing bacteria (*Pseudomonas striata*) for all crops. Green manure seeds of dhaincha (*Sesbania aculeata*) were procured from certified sources ^[1, 2].

Field Experimental Design

A split-plot design was employed with crops as main plots and nutrient management treatments as subplots, replicated four times. Main plots measured 20 m × 15 m while subplots occupied 4 m × 5 m with 1 m alleys between treatments. Six treatment combinations were evaluated: T₁-unfertilized control; T₂-recommended NPK (120-60-40 kg/ha for cereals, 20-60-40 kg/ha for legumes); T₃-NPK plus farmyard manure at 10 t/ha; T₄-NPK plus green manure incorporation; T₅-NPK plus biofertilizer inoculation; and T₆-integrated treatment combining 75% NPK with farmyard manure at 5 t/ha plus biofertilizers. Cropping sequence followed rice-wheat in kharif-rabi seasons with maize, soybean, mustard, or chickpea as alternatives in designated plots. Green manure dhaincha was grown during pre-monsoon fallow and incorporated at 50% flowering stage ^[3, 4].

Methods

Soil sampling occurred at pre-sowing and post-harvest stages from 0-15 cm depth using systematic sampling with five cores per subplot composited into single samples. Samples were air-dried, processed through 2 mm sieves, and analyzed following standard protocols. Soil pH and electrical conductivity were measured in 1:2.5 soil-water suspensions. Organic carbon was determined by wet oxidation with potassium dichromate. Available nitrogen was estimated by alkaline permanganate method, available phosphorus by Olsen's extractant, and exchangeable

potassium by neutral ammonium acetate extraction with flame photometric quantification [5, 6]. Microbial biomass carbon was measured using chloroform fumigation-extraction technique. Plant samples collected at physiological maturity were oven-dried, weighed, and ground for nutrient analysis. Total nitrogen was determined by micro-Kjeldahl digestion, phosphorus by vanadomolybdate colorimetry, and potassium by flame photometry following wet digestion. Nutrient use efficiency was calculated as the ratio of nutrient uptake to nutrient applied, expressed as percentage [7].

Soil Quality Analysis

Comprehensive soil quality assessment encompassed physical, chemical, and biological parameters. Bulk density was measured using core method with undisturbed samples

collected in metallic cores of known volume. Water holding capacity was determined by saturating soil samples and measuring water retained after gravitational drainage. Aggregate stability was assessed through wet sieving to quantify water-stable aggregates greater than 0.25 mm diameter. Dehydrogenase activity served as indicator of microbial metabolic function, measured through triphenyltetrazolium chloride reduction assay. Alkaline phosphatase activity was determined using p-nitrophenyl phosphate as substrate. Soil respiration rates were measured by alkali trap method quantifying CO₂ evolution over 24-hour incubation periods [8, 9]. These indicators collectively provided assessment of treatment effects on soil health beyond simple nutrient status.

Results

Table 1: Effect of nutrient management treatments on crop yields (kg/ha) across three years

Treatment	Rice	Wheat	Maize	Soybean	Chickpea
Control	2612 ± 187	2234 ± 156	2456 ± 178	1123 ± 98	987 ± 76
NPK only	3708 ± 234	3083 ± 198	3561 ± 223	1482 ± 112	1264 ± 95
NPK + FYM	4389 ± 267	3618 ± 234	4224 ± 256	1775 ± 134	1502 ± 113
NPK + GM	4076 ± 245	3373 ± 212	3878 ± 238	1651 ± 123	1421 ± 107
NPK + Bio	3867 ± 228	3219 ± 205	3684 ± 218	1595 ± 118	1363 ± 102
INM	4876 ± 289	3976 ± 254	4715 ± 278	1942 ± 145	1658 ± 124

Values represent means ± standard error across three years (n = 12). INM = Integrated Nutrient Management; FYM = Farmyard Manure; GM = Green Manure; Bio = Biofertilizers.

Crop yields responded significantly to nutrient management treatments across all species evaluated. Integrated nutrient management consistently produced the highest yields, with rice achieving 4,876 kg/ha compared to 2,612 kg/ha under unfertilized conditions, representing an 87% increase. Wheat yields ranged from 2,234 kg/ha in control plots to 3,976 kg/ha under integrated management, a 78%

improvement. Maize showed the strongest percentage response with yields increasing 92% from 2,456 kg/ha to 4,715 kg/ha. Legume crops exhibited moderate but significant responses, with soybean yields improving 73% and chickpea 68% under integrated management compared to controls.

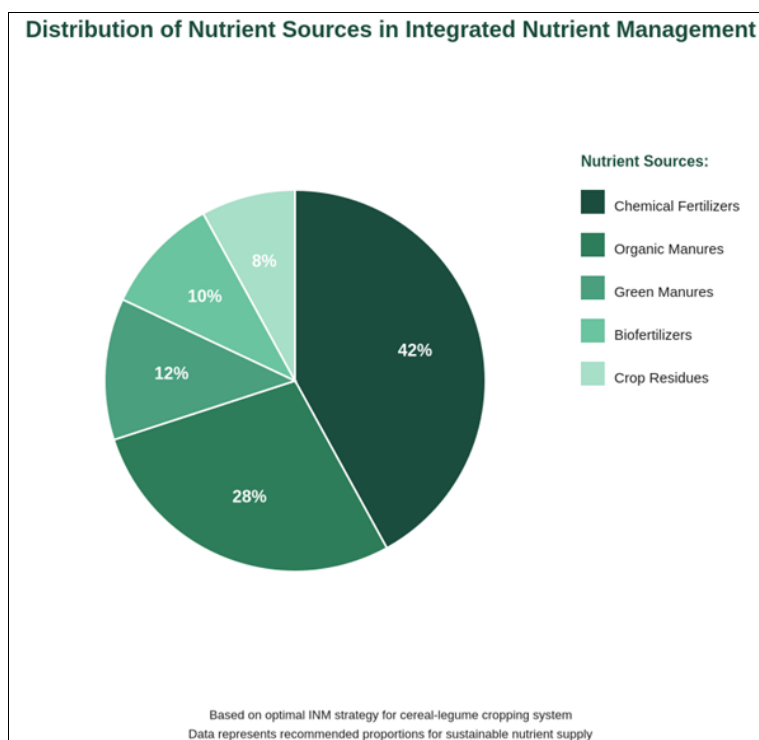
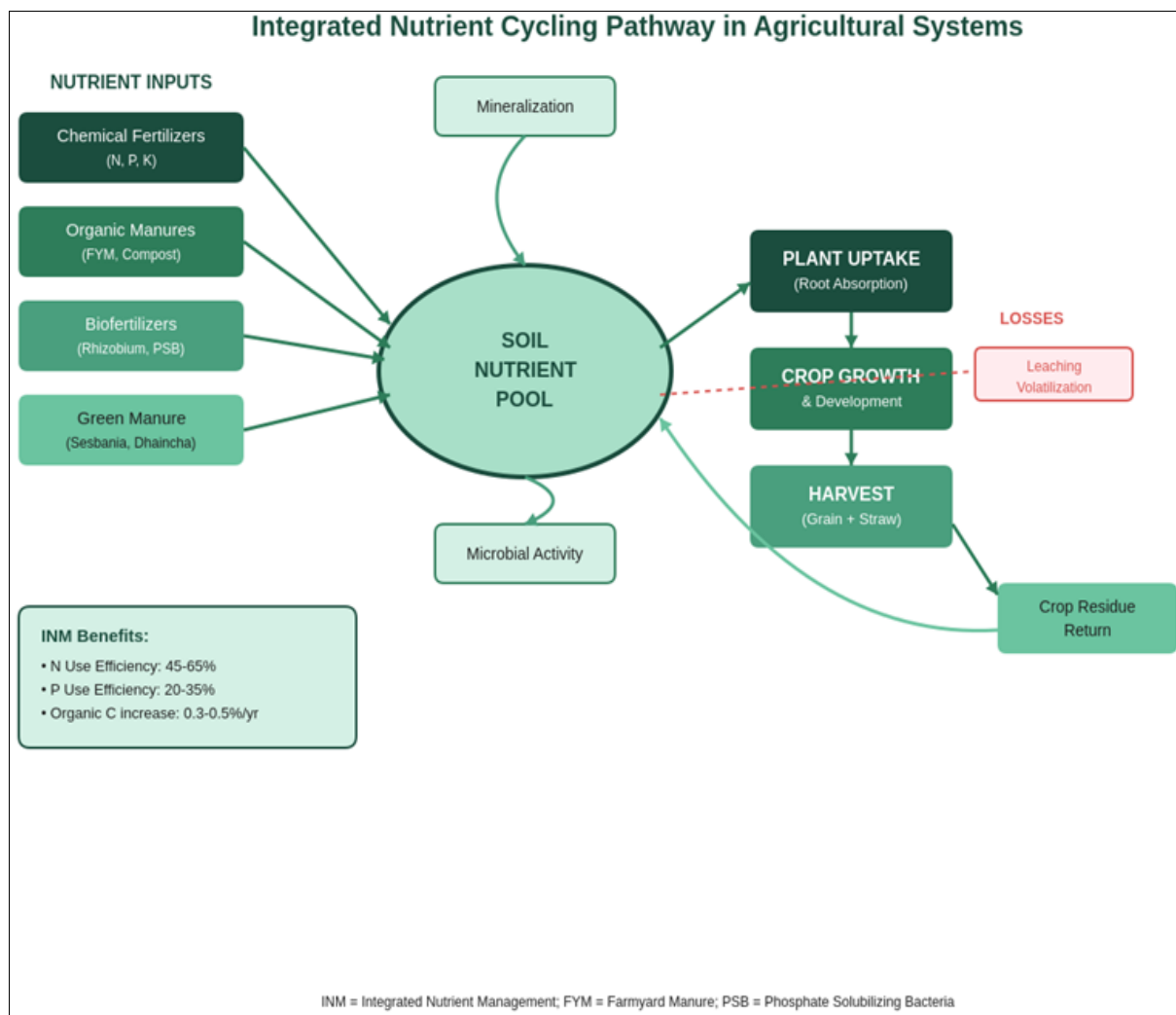


Fig 1: Distribution of nutrient sources in the integrated nutrient management strategy showing proportional contributions from chemical fertilizers, organic manures, green manures, biofertilizers, and crop residues

Table 2: Changes in soil properties under different nutrient management treatments after three years

Treatment	Organic C (%)	Avail. N (kg/ha)	Avail. P (kg/ha)	MBC (mg/kg)
Initial	0.58	187	14.3	134
Control	0.52	168	12.1	118
NPK only	0.61	198	16.8	156
NPK + FYM	0.78	234	21.4	245
NPK + GM	0.72	223	19.6	212
NPK + Bio	0.67	212	18.7	198
INM	0.87	256	24.8	287

MBC = Microbial Biomass Carbon. Initial values represent pre-experiment baseline. Final values measured after third year harvest.

**Fig 2:** Integrated nutrient cycling pathway diagram illustrating flows from various input sources through the soil nutrient pool to crop uptake, growth, and harvest with residue return mechanisms

Soil organic carbon showed progressive divergence among treatments over the experimental period. While control plots experienced carbon decline from 0.58% to 0.52%, treatments receiving organic inputs accumulated carbon substantially. Integrated management achieved the highest

organic carbon level at 0.87%, representing a 50% increase from baseline values. The NPK-only treatment maintained near-initial levels at 0.61%, indicating that chemical fertilization alone neither depleted nor built soil carbon under these conditions.

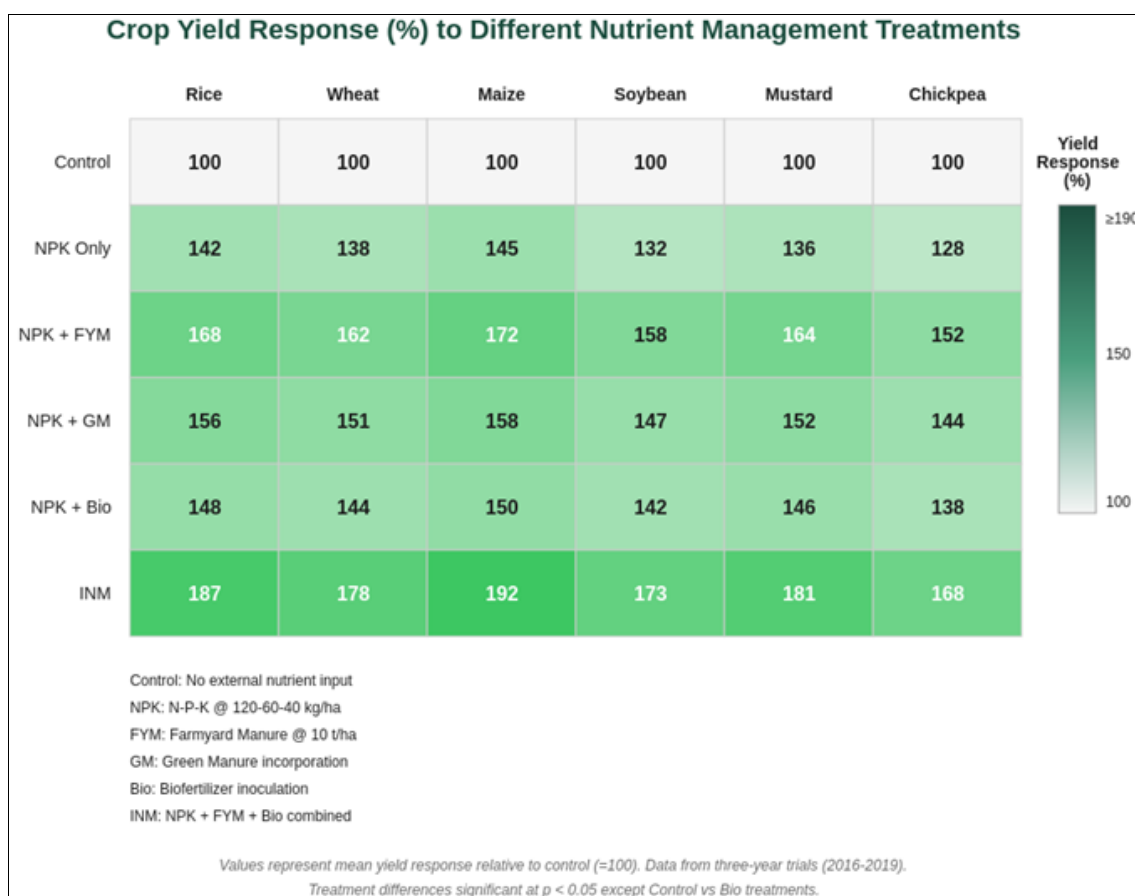


Fig 3: Heatmap depicting crop yield response (as percentage of control) to different nutrient management treatments across six crop species

Comprehensive Interpretation

Nutrient use efficiency calculations revealed substantial improvements under integrated management. Nitrogen use efficiency averaged 52% with integrated approaches compared to 38% under chemical fertilization alone, a 14-percentage point improvement. This enhanced efficiency resulted from multiple mechanisms including improved soil biological activity promoting nitrogen retention, slow release from organic sources reducing losses, and enhanced root proliferation in organically amended soils. Phosphorus recovery similarly increased from 18% to 29%, reflecting both direct contributions from organic sources and enhanced solubilization through microbial activity. Economic analysis showed benefit-cost ratios of 2.34 for integrated management versus 1.87 for conventional NPK fertilization, despite higher input costs for organic materials. The yield advantage and reduced fertilizer requirements offset additional expenses associated with organic amendment procurement and application.

Discussion

The yield responses observed under integrated nutrient management align with findings from numerous investigations across diverse cropping systems. Ladha *et al.*^[4] reported comparable yield improvements of 20-35% when organic amendments supplemented chemical fertilizers in intensive rice-wheat systems. The current research extends these observations by demonstrating consistent responses across six crop species including both cereals and legumes, suggesting broad applicability of integrated approaches.

Soil organic carbon accumulation under treatments receiving organic inputs confirms the carbon-building potential of integrated management documented elsewhere. Manna *et al.*^[6] observed annual organic carbon increases of 0.05-0.08% with combined organic and inorganic nutrient sources, rates consistent with the 0.10% annual gains recorded in the present investigation under integrated management. This carbon accumulation carries implications beyond nutrient supply, enhancing soil physical properties, water retention, and biological activity essential for long-term productivity.

Microbial biomass carbon increases paralleling organic carbon gains indicate stimulated biological activity under integrated management. Singh *et al.*^[10] attributed yield benefits from organic amendments partly to enhanced nutrient cycling by soil microorganisms. The positive correlation between microbial biomass and crop yields observed in this research supports this interpretation. And biofertilizer contributions likely extended beyond their direct nutrient supply functions to include stimulation of indigenous microbial communities.

The nitrogen uses efficiency improvements under integrated management merit particular attention given concerns regarding fertilizer losses to the environment. Cassman *et al.*^[17] emphasized the need for efficiency-focused approaches to meet growing food demands without proportional increases in fertilizer use. The 14-percentage point efficiency gain achieved through integration approaches this objective, reducing potential for nitrogen losses while maintaining or enhancing productivity.

Economic viability represents a critical consideration for

farmer adoption of integrated practices. But the favorable benefit-cost ratios observed suggest that integrated management can provide economic advantages despite higher input costs. These economic benefits accrue progressively as soil health improvements reduce requirements for purchased inputs over time. Sharma and Mittra ^[11] documented similar economic advantages developing over three to five years of integrated management implementation.

Several limitations should be acknowledged in interpreting these results. The three-year duration, while sufficient to demonstrate trends, may not fully capture long-term dynamics of soil organic matter accumulation. Availability of organic inputs varies regionally, potentially limiting replication of the specific integrated strategy evaluated. And crop variety responses may differ from those of the cultivars tested, requiring validation with alternative genotypes.

Conclusion

This three-year investigation established that integrated nutrient management combining chemical fertilizers with organic amendments and biofertilizers offers a sustainable pathway for maintaining agricultural productivity while improving soil health. The research demonstrated consistent yield advantages across diverse crop species, with improvements ranging from 68% to 92% compared to unfertilized conditions and 27-38% compared to chemical fertilization alone.

Soil organic carbon accumulation under integrated management reached 0.87% after three years compared to the initial 0.58%, representing a 50% increase that carries substantial implications for soil physical properties and long-term fertility maintenance. This carbon building contrasts sharply with the slight decline observed under chemical-only fertilization. The progressive nature of organic matter accumulation suggests continuing benefits with extended implementation.

Microbial biomass carbon doubled under integrated management compared to chemical fertilization alone, indicating stimulation of biological processes essential for nutrient cycling and soil health. This enhanced biological activity likely contributed to the improved nutrient use efficiency observed, with nitrogen recovery increasing from 38% to 52% and phosphorus recovery from 18% to 29%. Such efficiency gains address both economic and environmental concerns associated with nutrient losses from agricultural systems.

Economic analysis confirmed the viability of integrated approaches despite higher input costs associated with organic materials. Benefit-cost ratios of 2.34 for integrated management exceeded the 1.87 achieved with conventional fertilization, demonstrating that yield advantages more than compensated for additional expenses. This economic advantage should strengthen over time as soil health improvements reduce fertilizer requirements and enhance yield stability.

The research findings support adoption of integrated nutrient management as a strategy for sustainable intensification of agricultural production. The specific combination evaluated, combining 75% recommended NPK rates with farmyard manure at 5 tonnes per hectare plus

biofertilizer inoculation, provides a template adaptable to local conditions and resource availability. Alternative organic sources including poultry manure, vermicompost, and urban waste composts could substitute for farmyard manure where cattle populations are limited.

Practical implementation requires attention to quality and quantity of organic inputs to achieve consistent results. Farmers should be encouraged to maintain composting facilities and integrate livestock operations with crop production to ensure organic matter availability. Extension services can support adoption through demonstration trials and farmer training programs emphasizing proper application techniques and timing.

Future research should evaluate integrated management under diverse soil types and agroecological conditions to establish broader applicability. Long-term experiments extending beyond three years would clarify trajectories of soil health improvement and potential yield stability benefits. Investigation of crop residue management as an additional organic matter source could further enhance the sustainability of integrated systems while reducing external input requirements.

The integration of multiple nutrient sources represents a practical pathway toward sustainable agricultural intensification capable of meeting growing food demands while preserving soil resources for future generations. These findings merit consideration by policymakers developing agricultural support programs and extension strategies for promoting sustainable production practices.

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