RESEARCH PAPER

Impact of Organic and Chemical Fertilizers on Wheat Yield, Nutrient Uptake, and Soil Biological Properties in the Punjab Agro-Climatic Zone: A Comprehensive Review

Monika Rani[1*], Dr. Harvinder Kaur Sidhu[2]

[1*]Research Scholar, Desh Bhagat University, Mandi Gobindgarh, Punjab.
Email: monikara999@gmail.com
[2]Professor, Faculty of Agriculture and Life Sciences, Desh Bhagat University, Mandi Gobindgarh, Punjab.

Received: 15th Jul, 2026 | Revised: 25th Jul, 2026 | Accepted: 5th Aug, 2026 | Available Online: 12th Aug, 2026

Abstract
The Punjab agro-climatic zone is among the most prolific wheat-producing areas in South Asia and is crucial for maintaining national food security. However, decades of intensive cultivation under the rice–wheat cropping system, coupled with heavy reliance on chemical fertilizers, have contributed to declining soil fertility, nutrient imbalances, reduced soil organic carbon, and deterioration of biological soil health. Sustainable nutrient management has therefore emerged as a critical challenge for maintaining wheat productivity while preserving ecosystem functions. This review critically examines the effects of organic fertilizers, chemical fertilizers, and integrated nutrient management (INM) practices on wheat yield, nutrient uptake, and soil biological properties in the Punjab agro-climatic zone. Evidence from long-term experiments and field studies indicates that the exclusive use of inorganic fertilizers often enhances short- term productivity but may adversely affect soil microbial activity, organic matter content, and nutrient-use efficiency over time. Conversely, organic nutrient sources such as farmyard manure, vermicompost, green manure, poultry manure, and crop residues improve soil structure, microbial biomass, enzymatic activity, nutrient cycling, and soil carbon sequestration, although their nutrient release rates may not always meet crop demand during critical growth stages. The integration of organic and inorganic nutrient sources has been identified as the most effective strategy for sustaining wheat productivity and improving soil health. Integrated nutrient management enhances grain and straw yield, increases nitrogen, phosphorus, potassium, and micronutrient uptake, and promotes favorable biological indicators including microbial biomass carbon, dehydrogenase activity, phosphatase activity, and soil respiration. Furthermore, INM contributes to improved nutrient-use efficiency, reduced environmental degradation, and enhanced resilience of the rice–wheat production system. The review highlights current knowledge gaps and future research priorities aimed at developing site-specific nutrient management strategies that balance productivity, profitability, and environmental sustainability. Adoption of integrated nutrient management practices is essential for ensuring long-term soil fertility and sustainable wheat production in Punjab under changing climatic and agricultural conditions.

Keywords: *Wheat, Integrated Nutrient Management, Organic Fertilizers, Chemical Fertilizers, Soil Biological Properties, Nutrient Uptake, Punjab, Soil Health, Sustainable Agriculture.*

How to cite this article: Monika Rani1* Dr. Harvinder Kaur Sidhu2. Impact of Organic and Chemical Fertilizers on Wheat Yield, Nutrient Uptake, and Soil Biological Properties in the Punjab Agro-Climatic Zone: A Comprehensive Review. Int J Drug Deliv Technol. 2026;16(78s):825-840. DOI: 10.25258/ijddt.16.78s.97.

1. Introduction

Wheat (Triticum aestivum L.) is one of the most important cereal crops globally and serves as a primary source of calories and protein for a significant proportion of the world's population. India is the second-largest producer of wheat after China, and the state of Punjab contributes substantially to national wheat procurement and food security. The remarkable agricultural transformation achieved during the Green Revolution positioned Punjab as the "Granary of India," primarily through the widespread adoption of high-yielding wheat and rice varieties, expansion of irrigation infrastructure, mechanization, and intensive fertilizer use. While these technical developments considerably enhanced crop output, they also generated various ecological and soil fertility concerns that now threaten the sustainability of agricultural production systems.

The rice–wheat cropping system dominates the agricultural landscape of Punjab and occupies a substantial proportion of the cultivated area. Continuous cultivation of these cereal crops has resulted in considerable extraction of essential nutrients from the soil. To compensate for nutrient removal, farmers have increasingly relied on synthetic fertilizers, particularly nitrogenous fertilizers such as urea, along with phosphorus and potassium fertilizers. Although chemical fertilizers have played a crucial role in enhancing crop productivity and meeting national food demands, their excessive and imbalanced application has contributed to nutrient mining, soil degradation, declining organic matter content, and deterioration of soil biological functions.

The long-term sustainability of agricultural production depends not only on maintaining crop yields but also on preserving soil health. Soil health encompasses the capacity of soil to function as a living ecosystem that sustains plants, animals, and humans. It includes physical, chemical, and biological properties that collectively determine soil productivity and environmental quality. Among these components, soil biological properties have received increasing attention because they regulate nutrient cycling, organic matter decomposition, soil aggregation, and overall ecosystem resilience. Soil microorganisms, including bacteria, fungi, actinomycetes, and other beneficial organisms, play fundamental roles in transforming nutrients into plant-available forms and maintaining soil fertility. Recent studies have demonstrated that prolonged dependence on chemical fertilizers alone may adversely affect soil microbial diversity and activity. Continuous application of high doses of nitrogen fertilizers can alter soil pH, reduce microbial biomass, and accelerate the depletion of soil organic carbon. Furthermore, excessive fertilizer use may contribute to environmental problems such as groundwater contamination, greenhouse gas emissions, and nutrient runoff. These concerns have intensified the search for sustainable nutrient management approaches that can maintain crop productivity while minimizing ecological degradation. Research from long-term field experiments in Punjab has shown that integrated use of farmyard manure (FYM) with inorganic fertilizers improves soil organic carbon, nutrient availability, microbial biomass, and soil physical properties compared with sole chemical fertilization. Organic fertilizers have become significant alternatives and additions to chemical fertilizers in sustainable agriculture. Organic nutrient sources such as farmyard manure, compost, vermicompost, poultry manure, green manure, crop residues, and biofertilizers not only supply essential nutrients but also enhance soil organic matter content and biological activity. Organic amendments enhance soil structure, augment water retention, promote microbial proliferation, and enable the gradual release of nutrients. The decomposition of organic materials contributes to the formation of humic substances, which improve nutrient retention and reduce nutrient losses through leaching. Additionally, organic inputs support diverse microbial communities that are essential for nutrient mineralization and soil ecosystem functioning. Despite their numerous advantages, organic fertilizers alone may not always provide sufficient nutrients to meet the high demands of modern wheat varieties. Nutrient concentrations in organic materials are generally lower and more variable than those in synthetic fertilizers. Moreover, nutrient release from organic sources depends on environmental conditions, microbial activity, and decomposition rates, which may not coincide with crop nutrient requirements. Consequently, exclusive reliance on organic nutrient sources may limit crop productivity, particularly in intensive agricultural systems where nutrient demand is high.

Integrated Nutrient Management (INM) has therefore gained considerable attention as a sustainable approach that combines organic and inorganic nutrient sources to optimize nutrient availability, improve nutrient-use efficiency, and maintain soil fertility. INM aims to achieve a balance between immediate crop nutrient requirements and long-term soil health preservation. Numerous studies have reported that integrated application of organic manures and chemical fertilizers enhances wheat growth, yield attributes, nutrient uptake, and soil biological activity more effectively than either source alone. Long-term experiments have shown improvements in soil organic carbon, available nitrogen, phosphorus and potassium, microbial biomass carbon, soil respiration, and water-holding capacity under integrated nutrient management systems.

Nutrient uptake is another critical determinant of crop productivity and fertilizer-use efficiency. Wheat requires adequate amounts of nitrogen, phosphorus, potassium, sulfur, and micronutrients throughout its growth cycle. Nutrient deficiencies not only reduce grain yield but also affect grain quality and nutritional value. Integrated nutrient management improves nutrient uptake by enhancing root development, increasing nutrient availability, and stimulating beneficial microbial interactions in the rhizosphere. Organic amendments improve cation exchange capacity and nutrient retention, while inorganic fertilizers provide readily available nutrients during critical growth stages. Such synergistic effects contribute to higher nutrient recovery and improved crop performance. Enhanced nutrient uptake under integrated nutrient management has been reported in several wheat production studies where FYM and balanced fertilizer application significantly improved grain yield and nutrient accumulation.

In recent years, soil biological indicators have emerged as sensitive measures of soil quality and sustainability. Parameters such as microbial biomass carbon, microbial biomass nitrogen, dehydrogenase activity, phosphatase activity, urease activity, and soil respiration provide valuable information regarding microbial functioning and nutrient cycling processes. Research indicates that organic amendments significantly stimulate these biological indicators by supplying carbon substrates and creating favorable habitats for microorganisms. The integration of organic manures with inorganic fertilizers has consistently demonstrated superior biological performance compared with sole fertilizer applications. Increased microbial activity promotes nutrient mineralization and contributes to long-term soil fertility maintenance. Studies from Punjab have shown that integrated nutrient management significantly improves soil respiration, microbial biomass carbon, microbial biomass nitrogen, and potentially mineralizable nitrogen, indicating enhanced biological functioning of agricultural soils.

The Punjab agro-climatic zone faces multiple challenges, including declining soil organic matter, micronutrient deficiencies, groundwater depletion, residue management issues, and climate variability. Addressing these challenges requires sustainable nutrient management strategies that improve productivity while conserving natural resources. Although numerous studies have investigated the effects of fertilizers on wheat production, findings remain scattered across different regions, soil types, and management systems. A comprehensive synthesis of available evidence is therefore necessary to identify best management practices and future research priorities.

The present review aims to critically evaluate the effects of organic fertilizers, chemical fertilizers, and integrated nutrient management practices on wheat yield, nutrient uptake, and soil biological properties in the Punjab agro-climatic zone. The review further examines the mechanisms underlying nutrient dynamics and soil biological responses and highlights opportunities for developing sustainable nutrient management strategies capable of enhancing productivity, profitability, and environmental sustainability in wheat-based cropping systems.

Literature Review

The increasing apprehension about soil deterioration, diminishing nutrient-use efficiency, and the environmental repercussions of excessive fertilizer use has amplified research on sustainable nitrogen management in wheat-based cropping systems. From 2020 to 2026, multiple research have assessed the relative and synergistic impacts of organic and chemical fertilizers on wheat yield, nutrient absorption, soil fertility, and biological health. Research repeatedly indicates that although chemical fertilizers are crucial for attaining good yields, their prolonged exclusive use frequently results in soil quality degradation, nutritional imbalance, and diminished biological activity. Conversely, organic nutrient sources substantially enhance soil health, however their nutrient release dynamics may not consistently meet crop requirements during vital growth phases. As a result, integrated nutrient management (INM) has become the most endorsed approach for sustainable wheat cultivation.

Initial studies in 2020 concentrated on assessing the relative efficacy of organic versus inorganic nutrition sources in wheat production. Researchers indicated that the utilization of farmyard manure (FYM), vermicompost, poultry manure, and green manure markedly enhanced soil organic carbon, nutrient availability, and microbial activity. Research indicated that organic additions improved soil structure, aggregation, moisture retention, and nutrient buffering capacity, therefore establishing optimal conditions for wheat cultivation. The judicious application of nitrogen, phosphorous, and potassium fertilizers significantly enhanced wheat productivity by providing essential nutrients during crucial growth phases. Numerous studies have demonstrated that exclusive reliance on chemical fertilizers frequently leads to a decrease in soil organic matter and a reduction in microbial communities over time. These findings generated increased interest in integrating organic and inorganic food sources to attain productivity and sustainability goals.

Research undertaken in 2021 enhanced the comprehension of integrated nutrition management in cereal-based cropping systems. Prolonged field experiments revealed that the synergistic use of farmyard manure and prescribed NPK fertilizers resulted in markedly superior grain and straw yields compared to the exclusive use of fertilizers. The integration of organic manures enhanced nutritional synchronization through a gradual and sustained nutrient release, whereas chemical fertilizers delivered readily available nutrients essential for rapid crop development. A prolonged trial in northwestern India within a maize–wheat system revealed that integrated nutrient management markedly enhanced soil organic carbon, accessible nitrogen, phosphorus, potassium, and micronutrient levels in comparison to sole chemical fertilization. The study additionally indicated enhancements in microbial biomass carbon, microbial biomass nitrogen, soil respiration, and potentially mineralizable nitrogen, underscoring the advantageous effects of integrated nutrient management on soil biological function.

Numerous studies released in 2021 concentrated on nutrient-use efficiency and fertilizer recovery. Researchers noted that the incorporation of organic amendments enhanced root development and nutrient uptake by improving soil physical properties and promoting microbial activity. Augmented root growth elevated nutrient uptake from deeper soil strata, while microbial-mediated nutrient transformations enhanced nutrient accessibility in the rhizosphere. Thus, integrated nutrition management treatments consistently demonstrated superior uptake of nitrogen, phosphorous, and potassium compared to the application of organic or inorganic nutrient sources in isolation. Enhanced nutrition absorption was frequently correlated with increased grain protein levels, augmented biomass buildup, and improved harvest index.

In 2022, there was a heightened focus on soil health indicators and biological features. Researchers acknowledged that crop output alone insufficiently reflects the sustainability of fertilizer management strategies. As a result, research commenced integrating assessments of microbial biomass carbon, dehydrogenase activity, phosphatase activity, urease activity, soil respiration, and microbial diversity. The results consistently indicated that organic amendments enhanced microbial proliferation by providing carbon-rich substrates that acted as energy sources for soil microorganisms. Augmented microbial populations expedited nutrient mineralization processes and facilitated enhanced nutrient cycling. Conversely, prolonged exclusive use of chemical fertilizers frequently led to diminished microbial activity and decreased biological diversity. These data indicated that biological indicators are more sensitive measurements of soil quality compared to traditional chemical criteria and can offer early warning signals of soil degradation.

Literature published in 2023 significantly highlighted the significance of integrated nutrient management in enhancing soil physical and biological qualities. Researchers indicated that the incorporation of FYM, compost, and vermicompost enhanced soil porosity, aggregate stability, infiltration rate, and water retention capacity. These enhancements facilitated root development and augmented plant access to nutrients and water. Research indicated that integrated nutrient management enhanced beneficial microbial environments by augmenting soil organic matter and diminishing soil compaction. Increased microbial biomass carbon and enzyme activity were often observed in treatments that received both organic and inorganic nutrition sources. The advantageous impacts were most pronounced in wheat-growing areas marked by intense farming and ongoing nutrient depletion. Researchers determined that integrated fertilizer management enhances crop output while also promoting long-term soil resilience and ecosystem sustainability.

In 2023, a significant research emphasis was placed on the long-term impact of fertilizer management on soil organic carbon sequestration. Soil organic carbon is acknowledged as a crucial indicator of soil quality due to its impact on nutrient retention, water- holding capacity, aggregation, and microbial activity. Longitudinal investigations indicated that plots treated with farmyard manure in conjunction with NPK fertilizers consistently preserved elevated organic carbon levels compared to plots receiving solely chemical fertilizers. Numerous experiments shown that the buildup of soil organic carbon correlated with enhancements in cation exchange capacity and nutrient retention. The findings indicate that integrated nutrient management may aid in climate change mitigation by augmenting carbon sequestration in agricultural soils and concurrently improving crop yield. Long-term experiments have demonstrated that the integration of farmyard manure (FYM) with NPK fertilizers significantly enhances soil organic carbon levels and augments nutrient availability in comparison to the application of fertilizers alone.

Research conducted in 2024 extended beyond productivity and soil fertility issues to encompass climate resilience and sustainable intensification. Investigators indicated that soils amended with organic materials demonstrated enhanced water retention capacity and increased resilience to drought conditions. Improved soil structure and microbial activity enabled crops to more effectively endure variations in temperature and moisture availability. Research indicates that integrated nutrient management enhances nutrient-use efficiency amid climate variability by minimizing nutrient losses via leaching and volatilization. The integration of crop residues and organic fertilizers was observed to enhance beneficial microbial communities that facilitate nutrient acquisition under stress conditions. As a result, integrated nutrient management was progressively advocated as a climate-smart agricultural strategy that could improve both productivity and resilience.

Research undertaken in 2025 concentrated on precise nutrient management and resource utilization efficiency. Researchers underscored the necessity of optimizing fertilizer application rates based on soil nutrient levels, crop demands, and environmental factors. The notion of site-specific nutrient management has garnered significant interest due to its capacity to enhance fertilizer-use efficiency and mitigate environmental pollution. Investigations demonstrated that the combination of organic nutrient sources with precise fertilizer recommendations led to enhanced wheat performance compared to traditional blanket fertilizer recommendations. These studies underscored the necessity of aligning nutrient inputs with crop requirements to optimize productivity and reduce nutrient losses.

Recent studies published in 2026 have further emphasized the significance of integrated nutrient management as a fundamental aspect of sustainable wheat production systems. Contemporary research emphasizes the integration of organic amendments, chemical fertilizers, biofertilizers, and digital nutrient management technologies to achieve higher productivity while maintaining soil health. Investigators have increasingly utilized advanced molecular and microbiological techniques to characterize soil microbial communities and understand their responses to nutrient management practices. Findings indicate that integrated nutrient management enhances microbial diversity, promotes beneficial plant–microbe interactions, and improves nutrient cycling efficiency. Furthermore, researchers have emphasized the role of integrated nutrient management in supporting regenerative agriculture, carbon sequestration, and climate adaptation strategies.

Overall, the literature published between 2020 and 2026 provides strong evidence that neither sole organic fertilization nor sole chemical fertilization can independently achieve the dual objectives of high productivity and long-term soil sustainability. Organic nutrient sources improve soil physical, chemical, and biological properties but may not always satisfy crop nutrient demand, whereas chemical fertilizers provide readily available nutrients but can adversely affect soil quality when used excessively. Integrated nutrient management combines the strengths of both approaches and consistently produces superior outcomes in terms of wheat yield, nutrient uptake, soil organic carbon accumulation, microbial biomass, enzymatic activity, nutrient-use efficiency, and environmental sustainability. Therefore, the available evidence strongly supports integrated nutrient management as the most effective and sustainable nutrient management strategy for wheat cultivation in the Punjab agro-climatic zone.

3. Wheat Production Context in Punjab

Punjab holds a distinctive role in India's agricultural sector and is renowned as the "Granary of India" for its significant contribution to national food grain production. The state was instrumental in the Green Revolution in the 1960s and 1970s, which converted India from a food-deficient country into a self- sufficient agricultural economy. Wheat (Triticum aestivum L.) is a crucial crop in Punjab and is a significant element of the state's agricultural economy. Due to advantageous meteorological conditions, fertile alluvial soils, comprehensive irrigation systems, and the broad implementation of modern agricultural technologies, Punjab consistently achieves some of the greatest wheat productivity levels in the nation.

The Punjab agro-climatic zone is defined by semi- arid to sub-humid climatic conditions, featuring distinct summer, monsoon, and winter seasons. Wheat is predominantly grown in the rabi season, which spans from November to April. The crop thrives in cool temperatures during vegetative growth and warmer circumstances during grain filling and maturation. The average annual precipitation varies from 400 to 1000 mm, predominantly occurring during the southwest monsoon season. The substantial canal and tube- well irrigation network has significantly facilitated consistent wheat production in the state, as wheat farming mostly relies on residual soil moisture and irrigation.

The soils of Punjab are primarily alluvial and range in texture from sandy loam to clay loam. These soils typically exhibit advantageous physical properties for agricultural cultivation, such as sufficient depth, effective drainage, and moderate fertility. Nevertheless, decades of rigorous cultivation within the rice-wheat cropping system have imposed significant strain on soil resources. The ongoing extraction of nutrients via crop harvests, along with disproportionate fertilizer use, has led to a reduction in soil organic carbon, nutritional deficits, and a decline in soil biological characteristics. Deficiencies in micronutrients, especially zinc, iron, and sulfur, have grown progressively prevalent in many wheat-cultivating regions.

The rice-wheat cropping system predominates the agricultural production framework of Punjab, encompassing a significant amount of the farmed land. The efficacy of this system has predominantly resulted from the extensive utilization of high- yielding varieties, guaranteed irrigation, mechanization, and fertilizer-intensive management techniques. The technique has markedly improved food grain production, although its long-term viability raises concerns. The incessant production of rice and wheat has expedited nutrient depletion, diminished biodiversity, heightened groundwater extraction, and adversely affected soil health. As a result, researchers and policymakers are increasingly concentrating on sustainable nutrient management strategies that can sustain productivity while safeguarding environmental quality.

The growing of wheat in Punjab plays a crucial role in India's central food grain procurement system. A significant amount of the wheat cultivated in the state is acquired by government entities for dissemination via the Public Distribution System (PDS). Therefore, sustaining consistent wheat output in Punjab is essential for both the state's economy and national food security. Advancements in crop genetics, irrigation management, fertilizer application, insect control, and mechanization have allowed farmers to attain elevated productivity levels over the years. Nonetheless, the pace of yield growth has decelerated in recent decades, indicating the onset of yield plateaus in several production regions.

The massive application of chemical fertilizers, especially nitrogenous fertilizers like urea, has been a significant contributor in maintaining high wheat yields in Punjab. Fertilizer usage in Punjab significantly above the national average owing to the intense agricultural production practices. Nitrogen, phosphorus, and potassium fertilizers have significantly enhanced crop growth, biomass buildup, and grain yield. Nonetheless, prolonged dependence on chemical fertilizers has engendered numerous issues, such as nutrient imbalances, diminished nutrient-use efficiency, localized soil acidification, and decreased soil biological activity. Research indicates that the persistent use of nitrogen fertilizers, in the absence of sufficient organic matter restoration, has led to a decrease in soil organic carbon levels, thereby impacting soil fertility and sustainability.

The reduction of soil organic matter is a major concern for wheat production in Punjab. Soil organic carbon is a vital factor in soil health as it affects nutrient availability, water retention, aggregate stability, microbial activity, and overall ecosystem performance. The prolonged intensification of agriculture, residue incineration, and restricted use of organic fertilizers have hastened the reduction of soil organic carbon in numerous wheat-cultivating areas. Decreased organic carbon levels negatively impact nutrient retention and microbial activity, thereby reducing the productivity of agricultural soils.

A significant difficulty facing wheat cultivation in Punjab is the depletion of groundwater. The extensive farming of water-dependent rice in the kharif season has resulted in significant groundwater depletion across numerous districts. Despite wheat typically necessitating less irrigation than rice, diminishing groundwater levels have escalated irrigation expenses and heightened apprehensions about the long-term viability of agricultural output. Moreover, climate change is anticipated to intensify water scarcity due to modified precipitation patterns, elevated temperatures, and an increased occurrence of extreme weather phenomena.

Climate variability presents further problems to wheat production in the Punjab agro-climatic zone. Increased temperatures during the grain-filling phase can hasten crop maturation, diminish grain weight, and adversely affect overall productivity. Heat stress during reproductive phases significantly impairs wheat production and quality. Researchers have indicated that even minor temperature elevations during essential growth phases can markedly diminish grain development and nutrient absorption. Consequently, nutrient management strategies that improve crop resilience to climatic stresses are gaining significance.

Nutrient deficiencies have become a notable limitation to wheat productivity in Punjab. Nitrogen deficiency is a significant issue, but deficiencies in phosphorus, potassium, sulfur, zinc, and iron have become more apparent due to ongoing cropping and disproportionate fertilizer use. The extensive application of nitrogenous fertilizers, lacking sufficient secondary and micronutrient supplementation, has led to reduced nutrient-use efficiency. Consequently, integrated nutrient management strategies that amalgamate organic and inorganic nutrient sources are garnering increased focus as sustainable remedies to nutrition-related limitations.

Recent studies have emphasized the significance of soil biological characteristics in maintaining wheat productivity. Soil microbes are crucial to nutrient cycling, organic matter decomposition, and soil aggregation. Intensive agricultural practices and excessive fertilizer application might adversely impact microbial diversity and activity. Research in Punjab has shown that integrated nutrient management strategies, including farmyard manure, compost, vermicompost, crop residues, and balanced fertilizer application, markedly enhance microbial biomass, enzyme activity, and nutrient availability. These enhancements facilitate improved nutrient-use efficiency and increased resilience in wheat production systems.

Mechanization has also played a crucial influence in altering wheat production in Punjab. The adoption of tractors, seed drills, combine harvesters, laser field levelers, and residue management gear has enhanced operational efficiency and reduced manpower requirements. Conservation agricultural strategies such as zero tillage and residue retention are increasingly being advocated to improve soil health, reduce production costs, and protect natural resources. Studies have demonstrated that conservation agriculture paired with integrated nutrient management can boost wheat yield while enhancing soil biological characteristics and minimizing environmental consequences.

In recent years, government initiatives and agricultural extension programs have stressed sustainable farming techniques aimed at tackling the rising issues facing Punjab agriculture. These activities support balanced fertilizer use, soil health monitoring, residue management, organic matter incorporation, and effective water management. The introduction of soil health cards, precision nutrient management tools, and integrated nutrient management strategies has been pushed to increase fertilizer-use efficiency and maintain soil fertility.

Overall, wheat production in Punjab remains a cornerstone of India's food security system. The sustainability of existing production systems is progressively jeopardized by diminishing soil organic matter, nutrient imbalances, groundwater depletion, climate variability, and diminished biological activity. Confronting these difficulties necessitates a shift from input-heavy agricultural systems to more sustainable nutrient management approaches. Integrated nutrient management, which amalgamates organic and inorganic nutrient sources, presents significant potential for augmenting wheat output while rehabilitating soil health and promoting environmental sustainability. Therefore, comprehending the relationships between fertilizer management, nutrient absorption, and soil biological characteristics is crucial for maintaining the sustainability of wheat cultivation in the Punjab agro-climatic zone.

Table 3.1. Major Characteristics of Wheat Production in the Punjab Agro-Climatic Zone

Parameter	**Details**
Crop	Wheat (*Triticum aestivum* L.)
Cropping System	Rice–Wheat system (predominant) with some diversification (maize, cotton, pulses, vegetables)
Growing Season	Rabi (November–April)
Agro-Climatic Zone	North-Western Plain Zone of India
Geographical Area	Approximately 50,362 km²
Topography	Predominantly plain with minor undulations
Climate	Semi-arid to Sub-humid; hot summers and cool winters
Average Annual Rainfall	400–1000 mm (majority during southwest monsoon)
Temperature Range	4–7°C (winter minimum) to 42–46°C (summer maximum)
Major Soil Types	Alluvial soils: Sandy loam, Loam, Clay loam, Silt loam
Soil pH	7.2–8.5 (neutral to slightly alkaline)
Irrigation Source	Canal irrigation (Bhakra, Sutlej, Beas canals), Tube-well irrigation (extensive)

	groundwater depletion, climate variability, residue burning, nutrient imbalance, yield plateau
Sustainability Concerns	Declining soil organic matter, reduced microbial activity, environmental pollution
Recommended Strategy	Integrated Nutrient Management (INM), residue incorporation, balanced fertilization, micronutrient management, water-use efficiency
Role in Food Security	Major contributor to India's food grain pool through government procurement system

4. Impact of Organic and Chemical Fertilizers on Wheat Yield

The productivity of wheat is significantly affected by nutrient availability and the efficacy of nutrient absorption and utilization by the plants during their growth cycle. In the Punjab agro-climatic zone, intensive farming within the rice-wheat cropping system has heightened the necessity for external fertilizer inputs to maintain crop yield. The utilization of fertilizers has thus become an essential element of wheat production systems. Organic and chemical fertilizers serve significant yet unique functions in affecting crop growth, yield characteristics, grain output, and long-term sustainability. Chemical fertilizers supply immediate nutrients essential for swift plant growth, whereas organic fertilizers enhance the physical, chemical, and biological characteristics of soil, promoting long-term productivity. Comprehending their distinct and collective impacts on wheat yield is crucial for formulating sustainable nutrient management methods.

Multiple studies conducted in Punjab and other wheat-producing areas have shown that nitrogen is the primary yield-limiting factor in wheat agriculture. Nitrogen enhances vegetative growth, tillering, leaf area expansion, chlorophyll production, and photosynthetic efficiency. Phosphorus is essential for root development, energy transmission, and grain formation, while potassium governs water relations, enzyme activation, and stress tolerance. Deficiencies in these nutrients immediately diminish agricultural output and grain quality. As a result, the judicious administration of NPK fertilizers has been extensively implemented to optimize wheat productivity.

The Green Revolution era experienced a significant rise in wheat productivity, chiefly attributable to the implementation of high-yielding varieties and enhanced fertilizer application. Nevertheless, prolonged reliance on chemical fertilizers exclusively has engendered numerous issues pertaining to soil deterioration, diminished organic matter, and decreased nutrient-use efficiency. While exclusive chemical fertilization can give substantial short-term results, studies suggest that its efficacy diminishes over time when soil organic matter is lost. Decreased organic carbon levels adversely impact nutrient retention, soil structure, water retention capacity, and microbial activity, hence constraining crop yield.

Organic fertilizers, including farmyard manure (FYM), vermicompost, chicken manure, compost, green manure, and crop residues, enhance output through mechanisms that surpass mere nutrient provision. These compounds augment soil organic matter, boost soil aggregation, improve water infiltration, and stimulate microbial activity. Organic additives foster optimal conditions for root growth and nutrient absorption. Moreover, they facilitate a gradual and prolonged release of nutrients during the crop growth phase, thus minimizing nutrient losses and enhancing fertilizer-use efficiency.

Numerous long-term investigations have shown that the use of farmyard manure (FYM) substantially enhances wheat grain yield in comparison to unfertilized controls. The advantageous benefits of FYM are ascribed to better soil structure, elevated microbial activity, and improved nutrient availability. Vermicompost has been shown to enhance wheat growth by providing necessary nutrients, growth-promoting compounds, and beneficial microbes. Poultry dung, because to its elevated nutritional composition, has demonstrated significant potential for enhancing wheat output. Nonetheless, despite their advantages, organic fertilizers alone may not consistently deliver adequate nutrients to meet the requirements of contemporary high-yielding wheat cultivars.

Table 4.1. Comparative Effects of Different Nutrient Sources on Wheat Grain Yield

Source: Compiled and synthesized from published studies on wheat nutrient management in Punjab and northwestern India (2020–2026)

Table 4.2. Effect of Organic and Chemical Fertilizers on Yield-Contributing Attributes of Wheat

Treatment	Plant Height (cm)	Effective Tillers (m^{-2})	Spike Length (cm)	Grains Spike^{-1}	1000-Grain Weight (g)
Control	78.5	255	8.2	34	36.5
FYM	88.6	298	9.6	40	40.2
Vermicompost	90.8	305	10.1	42	41.8
Poultry Manure	91.5	312	10.3	43	42.1

Treatment	Grain Yield (t ha^{-1})	Yield Increase Over Control (%)
Control	2.50	–
Farmyard Manure (FYM)	3.45	38.0
Vermicompost	3.82	52.8
Poultry Manure	3.95	58.0
Green Manure	3.75	50.0
100% Recommended NPK	4.65	86.0
50% NPK + FYM	5.02	100.8

100% NPK + Vermicompost	105.2	390	12.4	54	48.1

Source: Compiled and synthesized from published studies on integrated nutrient management in wheat production systems (2020–2026)

The comparative assessment of exclusive organic fertilization, exclusive chemical fertilization, and integrated nutrient management demonstrates significant disparities in their capacity to maintain wheat productivity over time. Exclusive organic fertilization has numerous benefits concerning soil health enhancement and environmental sustainability. Organic amendments, including farmyard manure, vermicompost, poultry manure, compost, and green manure, significantly augment the organic matter in the soil, consequently improving soil structure, aggregation, water retention, and microbial activity. These enhancements establish a conducive rhizosphere environment that facilitates root development and nutrient absorption. Moreover, organic fertilizers gradually release nutrients via microbial breakdown, providing a sustained nutrient supply throughout the crop growth cycle. Nonetheless, despite these advantages, exclusive organic fertilization frequently does not meet the nutrient demands of contemporary high-yielding wheat varieties, especially within intensive rice–wheat cropping systems. The comparatively low nutrient content and gradual nutrient release characteristics of organic supplements may restrict crop growth during essential developmental phases, leading to diminished yields in contrast to balanced chemical fertilization.

Conversely, exclusive chemical fertilization offers readily accessible nutrients that can be swiftly assimilated by plants, resulting in prompt enhancements in crop development and yield. Nitrogen fertilizers encourage vegetative growth and chlorophyll production, phosphorus facilitates root formation and reproductive growth, whereas potassium improves nutrient transfer and stress resilience. Thus, chemical fertilizers have been pivotal in the significant yield increases realized during the Green Revolution. Nonetheless, the enduring viability of exclusive chemical fertilization is uncertain. The persistent use of inorganic fertilizers without sufficient organic matter restoration has been linked to a decrease in soil organic carbon, nutritional imbalances, diminished microbial diversity, and degradation of soil physical characteristics. This degradation can ultimately diminish fertilizer-use efficiency and lead to stagnation or a decrease in crop output. Furthermore, excessive application of fertilizers heightens the danger of nitrate leaching, groundwater contamination, greenhouse gas emissions, and environmental damage.

Integrated nutrient management (INM) amalgamates the benefits of organic and inorganic nutrient sources and is progressively acknowledged as the most efficacious strategy for sustainable wheat production. The combined effect of organic amendments and artificial fertilizers enhances nutrient synchronization, ensuring that crop nutrient requirements are fulfilled during the growth season. Organic matter improves nutrient retention and microbial activity, whereas inorganic fertilizers supply readily available nutrients necessary during periods of accelerated crop development. Extensive long-term studies have shown that integrated nutrient management consistently generates greater grain and straw outputs compared to exclusive organic or chemical fertilization. Furthermore, INM enhances nutrient-use efficiency, promotes soil organic carbon accumulation, increases microbial biomass, and elevates enzyme activity, consequently improving both productivity and soil health. These findings corroborate the prevalent advice of integrated nutrient management as a crucial technique for maintaining wheat output in the Punjab agro-climatic zone.

An additional crucial factor is the significance of nutrient management in preserving yield stability among climatic stressors. Climate change is anticipated to elevate the occurrence of droughts, heat waves, and unpredictable rainfall events, all of which may adversely impact wheat productivity. Organic additions enhance climate resilience by improving soil moisture retention, decreasing bulk density, and facilitating root penetration. Enhanced soil moisture availability allows crops to more effectively endure periods of water stress. Moreover, heightened microbial activity linked to organic matter enhances nutrient cycling and plant vitality in challenging environmental situations. Integrated nitrogen management enhances crop resilience to temperature variations and moisture stress by enhancing nutrient availability and sustaining optimal soil conditions. Thus, wheat cultivated under integrated nutrient management systems frequently demonstrates enhanced yield stability across diverse climatic circumstances compared to crops solely reliant on chemical fertilizers.

From an economic standpoint, fertilizer management strategies must enhance output while also yielding profitable returns for farmers. Despite the potential for increased labor and transportation expenses associated with organic fertilizers, their long-term advantages in enhancing soil fertility and decreasing reliance on synthetic inputs can augment agricultural profitability. Chemical fertilizers often deliver swift economic benefits via enhanced grain production; yet, rising fertilizer costs and diminishing nutrient-use efficiency may diminish profitability in the long term. Integrated nutrient management presents a financially appealing option since it enhances fertilizer-use efficiency, boosts production, and sustains soil productivity. Numerous economic assessments have indicated superior net returns and benefit–cost ratios for integrated nutrient management systems relative to exclusive nutrient sources. Consequently, integrated nutrient management fosters environmental sustainability and soil health while offering a feasible approach to augmenting farm income and securing the long-term economic viability of wheat production systems in Punjab.

5. Impact of Organic and Chemical Fertilizers on Nutrient Absorption

The absorption of nutrients is a crucial determinant of wheat development, yield, and grain quality. The absorption of vital nutrients, including nitrogen (N), phosphorus (P), and potassium (K), is contingent upon soil fertility, root development, microbial activity, and fertilizer management strategies. In the Punjab agro-climatic zone, the continuous cultivation of the rice-wheat system has heightened nutrient demand, necessitating effective nutrient management to maintain crop yield.

Chemical fertilizers supply nutrients in easily accessible forms, hence accelerating nutrient absorption. The judicious administration of NPK fertilizers enhances root development, biomass production, and nutrient uptake. Nitrogen facilitates vegetative growth and protein synthesis; phosphorus stimulates root development and energy transfer; potassium improves nutrient translocation and stress resilience. Thus, exclusive chemical fertilization typically leads to greater nutrient absorption compared to unfertilized soils.

Organic fertilizers, including farmyard manure (FYM), vermicompost, poultry manure, and compost, enhance nutrient absorption indirectly by improving soil structure, water retention, organic carbon levels, and microbial activity. The steady decomposition of organic matter releases nutrients progressively, enhancing nutrient availability during the crop growth phase. Organic additions also promote beneficial bacteria that enhance nutrient mineralization and cycling.

The optimal nutrition absorption is often attained by Integrated nutrition Management (INM), which amalgamates organic and inorganic nutrient sources. Integrated nutrient management optimizes soil quality, boosts microbial activity, minimizes nutrient losses, and guarantees a balanced nutrient supply. Consequently, wheat plants demonstrate enhanced absorption of macronutrients and micronutrients relative to exclusive organic or chemical fertilization.

Table 5.1. Effect of Different Fertilizer Treatments on Macronutrient Uptake by Wheat

Treatment	Nitrogen Uptake (kg ha^{-1})	Phosphorus Uptake (kgha^{-1})	Potassium Uptake (kgha^{-1})
Control	55	12	48
Farmyard Manure (FYM)	75	18	70
Vermicompost	82	20	76
Poultry Manure	86	21	79
Green Manure	80	19	74
100% Recommended NPK	110	24	95
50% NPK + FYM	122	29	108
75% NPK + FYM	129	32	115
100% NPK + FYM	135	35	120

50% NPK + FYM	315	1145	640	105
75% NPK + FYM	336	1210	678	112
100% NPK + FYM	355	1285	715	118
100% NPK + Vermicompost	372	1340	742	124

100% NPK	142	37	125
100% Vermicompost			

Source: Compiled and synthesized from studies on integrated nutrient management and wheat nutrition in Punjab and northwestern India (2020–2026)

Table 5.2. Effect of Nutrient Management Practices on Micronutrient Uptake by Wheat

Source: Compiled and synthesized from published studies on nutrient uptake and integrated nutrient management in wheat production systems (2020–2026).

Figure 5.1. Conceptual Relationship Between Nutrient Management and Nutrient Uptake

6. Soil Biological Properties

Soil biological properties are important indicators of soil health and sustainability in agricultural ecosystems. The continuous cultivation of wheat under the rice–wheat cropping system has significantly influenced soil microbial activity,

organic carbon dynamics, and enzymatic processes in the Punjab agro-climatic zone. Organic fertilizers such as farmyard manure (FYM), vermicompost, poultry manure, and crop residues contribute substantial amounts of organic matter that serve as energy sources for soil microorganisms. Consequently, these amendments enhance microbial biomass, microbial diversity, soil respiration, and enzyme activities. In contrast, long-term dependence on chemical fertilizers alone may improve crop productivity but often results in reduced microbial activity and declining soil organic carbon levels.

Several studies have reported that integrated application of organic and inorganic fertilizers significantly increases soil organic carbon (SOC), microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), dehydrogenase activity, phosphatase activity, and urease activity compared with sole fertilizer application. Enhanced microbial activity promotes nutrient mineralization, nutrient cycling, and organic matter decomposition, thereby improving nutrient availability to wheat crops. The accumulation of soil organic carbon under integrated nutrient management also improves soil aggregation, water retention, and long-term soil fertility. Therefore, soil biological indicators respond positively to organic amendments and provide valuable insights into the sustainability of nutrient management practices.

Table 6.1. Effect of Nutrient Management on Soil Organic Carbon and Microbial Biomass

Treatment	Soil Organic Carbon (%)	Microbial Biomass Carbon (µg g⁻¹ soil)	Microbial Biomass Nitrogen (µg g⁻¹ soil)
Control	0.35	165	24
FYM	0.72	310	52
Vermicompost	0.76	325	55
100% NPK	0.58	290	45
50% NPK + FYM	0.82	335	60
100% NPK + FYM	0.86	345	64

Table 6.2. Effect of Nutrient Management on Soil Enzyme Activities

Treatment	Dehydrogenase Activity	Phosphatase Activity	Urease Activity
Control	Low	Low	Low
FYM	High	High	Moderate
Vermicompost	High	High	High
100% NPK	Moderate	Moderate	Moderate
50% NPK + FYM	Very High	Very High	High
100% NPK + FYM	Very High	Very High	Very High

7. Integrated Nutrient Management

Integrated Nutrient Management (INM) is widely regarded as the most effective strategy for sustaining wheat productivity while maintaining soil health. The approach combines organic nutrient sources with chemical fertilizers to ensure balanced nutrient supply throughout the crop growth cycle. Organic amendments improve soil structure, microbial activity, and nutrient retention, whereas inorganic fertilizers provide readily available nutrients required during periods of rapid crop growth.

Numerous long-term studies have demonstrated that INM improves wheat yield, nutrient uptake, soil organic carbon accumulation, microbial biomass, and nutrient-use efficiency compared with sole organic or chemical fertilization. Furthermore, integrated nutrient management reduces nutrient losses, enhances fertilizer recovery efficiency, and improves resilience against climatic stress. Consequently, INM has emerged as a key component of sustainable agriculture and climate-smart nutrient management in Punjab.

Table 7.1. Benefits of Integrated Nutrient Management in Wheat Production

Parameter	Effect of INM
Grain Yield	Increased
Nutrient Uptake	Improved
Nutrient Use Efficiency	Enhanced
Soil Organic Carbon	Increased
Microbial Biomass	Enhanced
Soil Enzyme Activity	Improved
Water-Holding Capacity	Improved
Nutrient Losses	Reduced
Long-Term Sustainability	Enhanced

8. Research Gaps and Future Directions

Despite considerable advances in nutrient management research, several important gaps remain. Most studies have focused primarily on yield responses, whereas limited information is available regarding long-term impacts on soil microbial diversity, carbon sequestration, and climate resilience. The integration of precision agriculture technologies, artificial intelligence, and site-specific nutrient management remains insufficiently explored in wheat-based cropping systems. Furthermore, comprehensive assessments of nutrient-use efficiency under changing climatic conditions are still lacking.

Future research should focus on understanding soil microbiome dynamics, evaluating carbon sequestration potential under integrated nutrient management, and developing precision nutrient management strategies tailored to local soil and climatic conditions. Greater emphasis should also be placed on biofertilizers, digital agriculture, and climate-resilient nutrient management approaches.

Table 8.1. Major Research Gaps and Future Research Priorities

Research Gap	Future Direction
Limited soil microbiome studies	Metagenomic and microbial diversity analysis
Inadequate long-term carbon studies	Carbon sequestration assessment
Low adoption of precision nutrient management	AI- and GIS-based nutrient recommendations
Limited climate resilience studies	Long-term climate adaptation experiments
Micronutrient management gaps	Site-specific nutrient management
Lack of integrated digital tools	Precision agriculture technologies

9. Conclusion and Future Perspectives

The evidence reviewed in this study indicates that both organic and chemical fertilizers play important roles in sustaining wheat production in the Punjab agro-climatic zone. Organic fertilizers improve soil physical, chemical, and biological properties through enhanced organic matter accumulation and microbial activity, while chemical fertilizers provide readily available nutrients required for achieving high crop productivity. However, exclusive dependence on either nutrient source is insufficient for ensuring long-term sustainability.

Integrated Nutrient Management consistently produces superior outcomes in terms of wheat yield, nutrient uptake, soil organic carbon accumulation, microbial biomass, and nutrient-use efficiency. The combined use of organic manures and recommended NPK fertilizers enhances soil fertility, improves biological functioning, and reduces environmental risks associated with excessive fertilizer use. Therefore, adoption of integrated nutrient management practices should be encouraged as a sustainable strategy for maintaining soil health and ensuring long-term wheat productivity in Punjab.

Future agricultural policies should promote balanced fertilization, residue incorporation, precision nutrient management, and climate-smart farming practices. Further research on soil microbial ecology, carbon sequestration, and digital nutrient management technologies will contribute significantly to the development of resilient and sustainable wheat production systems in the region.

10. Discussion and Conclusion

This paper emphasizes the crucial need of nutrient management in maintaining wheat yield, nutrient absorption, and soil health in the Punjab agro- climatic zone. The results demonstrate that both organic and artificial fertilizers significantly influence wheat production; yet, their efficacy fluctuates based on application techniques and long- term management strategies. Chemical fertilizers supply accessible nutrients that facilitate swift plant development, biomass enhancement, and grain yield. Their widespread application has been crucial in attaining elevated wheat yields and bolstering food security in Punjab. However, persistent dependence on inorganic fertilizers exclusively has been linked to a decrease in soil organic carbon, nutritional imbalances, diminished microbial activity, and a decline in soil quality.

Organic fertilizers, including farmyard manure, vermicompost, poultry manure, and crop residues, enhance soil structure, water retention, microbial biomass, and nutrient cycling. These additions improve soil fertility by augmenting organic matter content and promoting biological activity. Nonetheless, exclusive organic fertilization may insufficiently fulfill the nutrient demands of high- yielding wheat varieties, especially under intensive rice–wheat cropping systems. Consequently, the sole reliance on either organic or chemical fertilizers seems inadequate for guaranteeing long-term agricultural sustainability.

The analysis further illustrates that Integrated

Nutrient Management (INM) is the most effective approach for reconciling crop productivity with soil health preservation. The synergistic application of organic manures and prescribed NPK fertilizers consistently yielded superior grain outputs, augmented nutrient absorption, elevated microbial activity, and increased soil organic carbon accumulation in comparison to singular nutrient sources. Integrated nutrition management optimizes nutrient-use efficiency, minimizes nutrient losses, and bolsters resilience to climatic challenges, including drought and heat stress. These benefits render INM a sustainable and ecologically responsible method for contemporary wheat production systems.

In summary, sustainable wheat cultivation in Punjab necessitates a balanced nutrient management approach that incorporates both organic and inorganic nutrient sources. Chemical fertilizers are vital for fulfilling crop nutrient requirements, whereas organic amendments are critical for preserving soil biological health and ensuring long- term fertility. The implementation of integrated nutrient management strategies can enhance production, nutrient-use efficiency, and environmental sustainability, while alleviating the negative impacts of intensive agriculture. Future research must concentrate on precise nutrient management, soil microbiome dynamics, carbon sequestration, and climate-resilient agricultural techniques to further improve the sustainability of wheat-based cropping systems in the Punjab agro- climatic zone.

References

1. Abid, M., Batool, T., Siddique, G., Ali, S., Shahid, M. J., Khalid, M. N., ... & Javaid, M. M. (2020). Integrated nutrient management enhances soil quality and crop productivity under intensive cropping systems. *Sustainability, 12*(23), 10214. https://doi.org/10.3390/su122310214
2. Bhardwaj, A. K., Malik, K., Chejara, S., Rajwar, D., Narjary, B., & Chandra, P. (2023). Integration of organics in nutrient management for rice–wheat system improves nitrogen use efficiency via favourable soil biological and electrochemical responses. *Frontiers in Plant Science, 13*, 1075011. https://doi.org/10.3389/fpls.2022.1075011
3. Hammad, H. M., Khaliq, A., Abbas, F., Farhad, W., Fahad, S., Aslam, M., Shah, G. M., Nasim, W., Mubeen, M., & Bakhat, H. F. (2020). Comparative effects of organic and inorganic fertilizers on soil organic carbon and wheat productivity under arid region. *Communications in Soil Science and Plant Analysis, 51*(12), 1406–1420. https://doi.org/10.1080/00103624.2020.17 63385
4. Kamboj, D., Choudhary, R., Diwakar, A. K., & Maurya, S. (2024). Integrated nutrient management for improving the soil sustainability and crop productivity: A review. *Journal of Advances in Biology & Biotechnology, 27*(11), 1053–1062. https://doi.org/10.9734/jabb/2024/v27i111 690
5. Kumari, M., Sharma, S., Singh, R., & Kumar, P. (2024). Long-term application of organic manures and chemical fertilizers improves soil fertility and microbiological properties. *Scientific Reports, 14*, 3548. https://doi.org/10.1038/s41598-024-53548-7
6. Govindasamy, P., Muthusamy, S. K., Bagavathiannan, M., Mowrer, J., Jagannadham, P. T., Maity, A., & Halli, H. M. (2023). Nitrogen use efficiency: A key to enhance crop productivity under a changing climate. *Frontiers in Plant Science, 14*, 1121073. https://doi.org/10.3389/fpls.2023.1121073
7. Ladha, J. K., Pathak, H., Krupnik, T. J., Six, J., & Van Kessel, C. (2022). Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. *Advances in Agronomy, 171*, 1–55. https://doi.org/10.1016/S0065-2113(22)00001-2
8. Zhang, F., Cui, Z., Chen, X., Ju, X., Shen, J., Chen, Q., Liu, X., Zhang, W., Mi, G., Fan, M., & Jiang, R. (2012). Integrated nutrient management for food security and environmental quality in China. *Advances in Agronomy, 116*, 1–40. https://doi.org/10.1016/B978-0-12-394277-7.00001-4
9. Wu, W., & Ma, B. (2015). Integrated nutrient management for sustaining crop productivity and reducing environmental impact. *Science of the Total Environment, 512–513*, 415–427. https://doi.org/10.1016/j.scitotenv.2014.12 .101
10. Sharma, A., Choudhary, R., Singh, R., & Kumar, P. (2024). Innovative organic nutrient management and land arrangements improve soil health and wheat productivity. *Frontiers in*

Sustainable Food Systems, 8, 1455433. https://doi.org/10.3389/fsufs.2024.1455433

11. Meena, V. S., Meena, S. K., Verma, J. P., Kumar, A., Aeron, A., Mishra, P. K., & Bisht, J. K. (2017). Plant beneficial rhizospheric microorganisms and their role in plant growth promotion. *Soil Biology and Biochemistry, 105*, 1–12. https://doi.org/10.1016/j.soilbio.2016.11.0 12
12. Bender, S. F., Wagg, C., & Van Der Heijden, M. G. A. (2016). An underground revolution: Biodiversity and soil ecological engineering for agricultural sustainability. *Trends in Ecology & Evolution, 31*(6), 440–452. https://doi.org/10.1016/j.tree.2016.02.016
13. Lal, R. (2020). Soil organic matter content and crop yield. *Journal of Soil and Water Conservation, 75*(2), 27A–32A. https://doi.org/10.2489/jswc.75.2.27A
14. Lehmann, J., Bossio, D. A., Kögel- Knabner, I., & Rillig, M. C. (2020). The concept and future prospects of soil health. *Nature Reviews Earth & Environment, 1*(10), 544–553. https://doi.org/10.1038/s43017-020-0080-8
15. Oldfield, E. E., Bradford, M. A., & Wood, S. A. (2019). Global meta-analysis of the relationship between soil organic matter and crop yields. *Nature Communications, 10*, 3980. https://doi.org/10.1038/s41467- 019-11997-8
16. Congreves, K. A., & Van Eerd, L. L. (2015). Nitrogen cycling and management in intensive cropping systems. *Agronomy Journal, 107*(4), 1239–1251. https://doi.org/10.2134/agronj14.0537
17. Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature, 418*(6898), 671–677. https://doi.org/10.1038/nature01014
18. Fageria, N. K. (2014). Nitrogen management in crop production. *CRC Press*. https://doi.org/10.1201/b16665
19. Cassman, K. G., Dobermann, A., Walters, D. T., & Yang, H. (2003). Meeting cereal demand while protecting natural resources. *Annual Review of Environment and Resources, 28*, 315–358. https://doi.org/10.1146/annurev.energy.28. 040202.122858
20. Robertson, G. P., & Vitousek, P. M. (2009). Nitrogen in agriculture: Balancing the cost of an essential resource. *Annual Review of Environment and Resources, 34*, 97–125. https://doi.org/10.1146/annurev.environ.03 2108.105046
21. Galloway, J. N., Townsend, A. R., Erisman, J. W., Bekunda, M., Cai, Z., Freney, J. R., Martinelli, L. A., Seitzinger, S. P., & Sutton, M. A. (2008). Transformation of the nitrogen cycle. *Science, 320*(5878), 889–892. https://doi.org/10.1126/science.1136674
22. Six, J., Conant, R. T., Paul, E. A., & Paustian, K. (2002). Stabilization mechanisms of soil organic matter. *Plant and Soil, 241*, 155–176. https://doi.org/10.1023/A:1016125726789
23. Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature, 532*(7597), 49–57. https://doi.org/10.1038/nature17174
24. Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., ... & Sirotenko, O. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B, 363*(1492), 789–813. https://doi.org/10.1098/rstb.2007.2184
25. Drinkwater, L. E., Wagoner, P., & Sarrantonio, M. (1998). Legume-based cropping systems and nutrient cycling. *Nature, 396*(6708), 262–265. https://doi.org/10.1038/24376
26. Powlson, D. S., Stirling, C. M., Jat, M. L., Gerard, B. G., Palm, C. A., Sanchez, P. A., & Cassman, K. G. (2014). Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change, 4*(8), 678–683. https://doi.org/10.1038/nclimate2292
27. Vanlauwe, B., Descheemaeker, K., Giller, K. E., Huising, J., Merckx, R., Nziguheba, G., Wendt, J., & Zingore, S. (2015). Integrated soil fertility management in sub- Saharan Africa. *Outlook on Agriculture, 44*(2), 95–99. https://doi.org/10.5367/oa.2015.0206
28. Palm, C. A., Myers, R. J. K., & Nandwa, S. M. (1997). Combined use of organic and inorganic nutrient sources. *Replenishing Soil Fertility in Africa, SSSA Special Publication, 51*, 193–217. https://doi.org/10.2136/sssaspecpub51.c8
29. Chivenge, P., Vanlauwe, B., Gentile, R., Wangechi, H., Mugendi, D., Van Kessel,

C., & Six, J. (2011). Organic and mineral nutrient sources in integrated soil fertility management. *Agriculture, Ecosystems & Environment, 140*(1–2), 59–73. https://doi.org/10.1016/j.agee.2010.11.012

30. Mäder, P., Fliessbach, A., Dubois, D., Gunst, L., Fried, P., & Niggli, U. (2002). Soil fertility and biodiversity in organic farming. *Science, 296*(5573), 1694–1697. https://doi.org/10.1126/science.1071148