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Comparative evaluation of organic and inorganic fertilizers on growth and yield attributes of wheat (*Triticum aestivum* L.)

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Abstract

Wheat (*Triticum aestivum* L.) is the most crucial cereal crop in the world, and a key factor in meeting food and nutritional needs. Good nutrient management is crucial in promoting crop productivity and soil health by using organic and inorganic fertilizers. The present study was undertaken to compare the performances of organic and inorganic fertilizers on growth and yield parameters of the wheat crop. Various nutrient sources, such as farmyard manure (FYM), vermicompost, compost, and recommended doses of chemical fertilizers (NPK), were tested individually and in combination in the field. The study focused on significant growth traits, including plant height, tiller number, leaf area index, dry matter production, and chlorophyll content, as well as yield components such as spike length, number of grains per spike, test weight, grain yield, straw yield, and harvest index. The data showed that the use of integrated nutrient management practices (INMP) significantly improved the plant growth and yield performance over using only the organic or inorganic nutrients. The organic fertilizers enhanced the soil structure, microbial activity, nutrient availability, and the moisture-holding capacity of the soil, while inorganic fertilizers were able to provide readily available nutrients for quick growth and development of the crops. Applications of organic manure along with chemical fertilization led to an increased nutrient use efficiency, improved root development, and better grain quality. Furthermore, integrated fertilization practices helped to ensure sustainable soil fertility and minimized the negative environmental effects of over-fertilization with chemicals. Thus, the study highlights a balanced and integrated nutrient management approach as an effective measure for sustainable wheat production, wheat productivity, and long-term soil health under various agro-climatic conditions.

Keywords: Wheat, organic fertilizers, inorganic fertilizers, integrated nutrient management, crop productivity

Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops in the world and is a source of food for almost 35-40% of the world's population. It is an important source of daily calories and protein, and is an integral part in providing global food and nutritional security, especially in developing countries like India, China, and certain areas of Africa and Asia. The population growth and declining arable land, the climate variability, and the decreasing soil fertility have put greater pressure on sustainable wheat production systems that can sustain higher productivity by using resources more efficiently. Climate change, nutrient depletion, and imbalanced fertilizer use are increasingly posing a threat to wheat production, a fact that has been highlighted in recent reports and that puts food security and agricultural sustainability at risk (Penuelas *et al.*, 2023)^[23].

Nutrient management is one of the most critical agronomic factors that can affect wheat growth, yield components, grain quality, and soil health. An adequate and balanced nutrient supply supports plant physiological processes like tillering, photosynthesis, root establishment, grain filling, and nutrient efficiency. The essential nutrients are particularly significant in achieving optimum wheat productivity: nitrogen, phosphorus, potassium, and sulfur. The overreliance on chemical fertilizers and continued cultivation has led to nutrient imbalance, decreased soil organic carbon, a decline in the microbial activity of soil, and soil pollution. Inorganic fertilizers are rich in nutrients but are readily available and have made

significant contributions to the productivity of crops, but can also have negative impacts on soil fertility and ecological sustainability if they are used indiscriminately and over time. On the other hand, organic fertilizers like farmyard manure, compost, green manure, and vermicompost boost soil physical properties, microbial activity, soil nutrients, and long-term soil productivity, but the release of nutrients from organic sources is relatively slow compared to inorganic sources (Kaur *et al.*, 2024) ^[15].

Balanced fertilization practices are not only necessary for optimum wheat production, but also for efficiency of nutrient use and minimising environmental degradation. The modern agricultural systems present the issues of excessive application of nitrogenous fertilizer and insufficient application of secondary and micronutrients, which causes a reduction in factor productivity and consumption of nutrients from the soil. Balanced nutrient application along with organic amendments has proven to enhance soil nutrient transformations and boost microbial diversity and long-term productivity in rice-wheat and wheat-based cropping systems (Walia *et al.*, 2024) ^[40]. In addition, it has been reported that the use of organic and inorganic fertilizers together has led to a higher grain yield, a better protein content, an increase in soil organic matter, and a decrease in greenhouse gas emissions, as compared to the use of chemical fertilizers alone. Hence, sustainable fertilization is needed to meet the dual target of increasing wheat production and preserving natural resources. Most recent reviews also highlight the potential for positive economic returns and resilience of the wheat production system in the context of changing climatic conditions from the use of integrated fertilizer management (Ejigu *et al.*, 2024) ^[7].

Within this context, it becomes very important to evaluate organic and inorganic fertilizers on wheat growth and yield attributes in comparison. These estimates can be used to understand the relative importance of nutrient sources for plant growth, crop yield production, soil fertility enhancement, and sustainable crop production. Hence, adoption of balanced and integrated fertilization practices is now being seen as a major solution to increase wheat productivity, soil health, and food security in the long run.

2. Organic Fertilizers in Wheat Cultivation

Organic fertilizers are nutrient sources of natural origin (plant, animal, or microbial) that provide essential nutrients for crops as well as enhance soil fertility and biological

activity. Organic fertilizers are essential in the process of maintaining soil productivity, augmenting soil nutrient availability, and promoting crop growth in wheat production within environmentally friendly farming systems. The farmyard manure (FYM), compost, vermicompost, green manure, and biofertilizers are common organic nutrient sources used in wheat production. The manure made from decomposed cattle dung, urine, grain litter, and farm residues is a popular soil amendment that benefits the soil's structure, water holding capacity, aeration, and microbial activity. Another useful organic matter amendment that is made by decomposing organic wastes like weeds, crop residues, and domestic biodegradable wastes is called compost. Provides slow-release macro and micronutrients and increases SOC. Earthworm castings (Vermicompost) are an organic fertilizer created by earthworms feeding on organic waste materials, which is enriched with plant growth regulators, humic substances, beneficial microorganisms, and readily available nutrients that have a positive effect on wheat growth and soil enzyme activity (Ramazanoglu, 2024) ^[24]. Recently, the effects of vermicompost application on nutrient uptake, root growth, chlorophyll content, and yield parameters of wheat and other cereal crops have been highly significant, and it has also been revealed that the application of vermicompost in the soil improves the biological health of the soil (Rehman *et al.*, 2023) ^[27].

One more sustainable organic nutrient management practice is green manuring, which involves the cultivation of leguminous plants like dhaincha (*Sesbania aculeata*) or sunhemp (*Crotalaria juncea*) before they flower, and their subsequent incorporation into the soil. Green manure crops increase soil organic matter, biological nitrogen fixation, soil aggregation, and moisture holding capacity. In wheat production, beneficial microorganisms like *Azotobacter*, *Azospirillum*, phosphate-solubilizing bacteria, and mycorrhizae are increasingly applied for better nutrient mobilization and nutrient-use efficiency, among which mycorrhizae are playing a major role. They are microbial inoculants that aid in the process of atmospheric nitrogen fixation, phosphorus solubilization, synthesis of plant growth-promoting compounds, and stimulate root growth, thereby saving on the use of chemical fertilizers. Seal and organic manures or biofertilizers are reported to enhance wheat productivity and soil nutrient status in various agroecological conditions (Imran, 2024) ^[11].

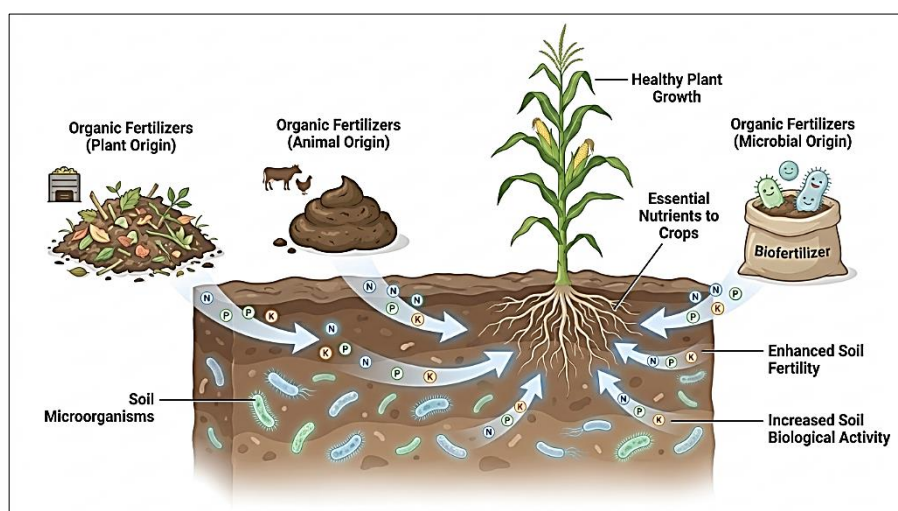


Fig 1: Organic fertilizers enhance sustainable crop productivity

Figure 1. This diagram shows how organic fertilizer based on plants, animals, and microorganisms can help to improve soil fertility, microbial activity, and nutrient availability to crops. The synergistic effects of organic amendments and soil biology enhance nutrient use, root development, and plant growth, which support sustainable and environmentally-friendly farming practices.

Organic nutrient sources have a number of advantages for soil and crop health. Organic fertilizers are beneficial to soil physical properties because they increase soil porosity, aggregation, and moisture holding capacity, all of which are crucial for improved root growth and uptake. They also help the soil to improve its chemical properties over time by making nutrients available gradually and increasing the Cation Exchange Capacity (C.E.C.), which prevents the loss of nutrients over time. Furthermore, organic amendments increase microbial biomass, soil enzyme activity, and soil beneficial microbial interactions, which help to increase nutrient cycling and restore soil fertility. The long-term use of FYM and ONS resulted in enhanced soil fertility, enzyme activity, and wheat cropping sustainability (Sheoran *et al.*, 2024) [33]. Organic fertilisers have also been associated with soil protection, reducing pollution of the soil and groundwater from excessive chemical fertiliser applications, and reducing greenhouse gas emissions. The benefits of integrated nutrient management practices using organic manures, vermicompost, and biofertilizers for improving the productivity, soil organic matter, and the resilience of wheat production systems in response to climate change have been highlighted in recent reviews (Sande *et al.*, 2024; Sharma *et al.*, 2024) [31, 32].

3. Inorganic Fertilizers in Wheat Production

Inorganic fertilizers are chemical products of nutrient sources that release the required plant nutrients in easily available forms to enable quick absorption and growth of plants. In the cultivation of wheat, inorganic fertilizer plays an important role in enhancing productivity, quality of grain, and fulfilling the increasing food demand of the growing

population of the world. Nitrogen is the most important nutrient for vegetative growth and yield formation, making nitrogenous fertilizers, like urea, ammonium sulfate, and calcium ammonium nitrate, the most commonly applied major chemical fertilizers in wheat production. The use of phosphatic fertilizers such as diammonium phosphate (DAP), single superphosphate (SSP), triple superphosphate (TSP), etc., to promote root growth, tillering, and energy flow is common practice. Potassium fertilizers (potassic fertilizers) like muriate of potash (MOP) and sulfate of potash (SOP) are used for water regulation, activation of enzymes, stress tolerance, and grain development. Hence, balanced application of nitrogen (N), phosphorus (P), and potassium (K) fertilizers is an essential requirement for optimal wheat growth, better nutrient-use efficiency, and sustainable wheat productivity (Roa *et al.*, 2024) [28].

Nitrogen is the most yield-limiting nutrient in wheat production due to its direct effects on chlorophyll formation, photosynthesis, protein synthesis, tillering, and grain filling. Proper N management increases leaf area development and the biomass, which results in better yield and protein content. But over-fertilization can lead to lodging, late maturity, nutrient imbalance, and contamination of the environment by releasing nitrates to the soil and by emitting greenhouse gases. Phosphorus is important for early crop growth, root establishment, energy transfer, and cell division. It also increases seed formation and the efficiency of nutrient absorption. Wheat plants frequently show signs of phosphorus deficiency with poor root development, delayed maturity, and reduced grain production. Potassium is also crucial for osmotic balance, enzyme activity, disease resistance, and tolerance to abiotic stresses like drought and salinity. Appropriate K levels will enhance grain quality, water use efficiency, and plant stress tolerance (Rawat *et al.*, 2024). Recent research has highlighted the importance of balanced NPK fertilizers in enhancing the productivity of wheat, nutrient uptake, and soil fertility under intensive cropping conditions (Yadav *et al.*, 2023) [26, 41].

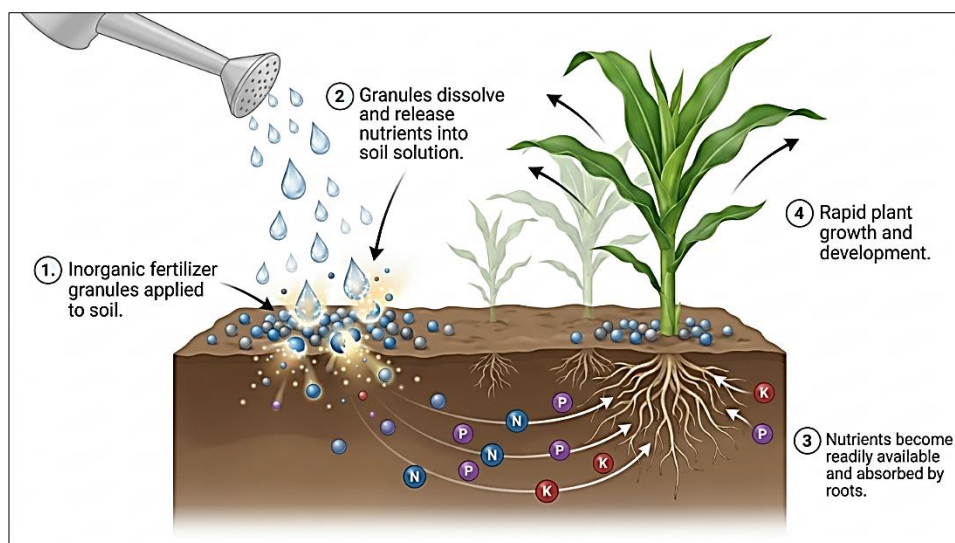


Fig 2: Inorganic fertilizers promote rapid crop growth.

Figure 2. This diagram illustrates the mechanism of application of inorganic fertilizer, in which the fertilizer granules dissolve in soil water and make available in the soil solution essential nutrients in the form of nitrogen (N),

phosphorus (P), and potassium (K), which are readily absorbed by the roots. These readily available nutrients support faster plant growth, better root development, and better productivity of the crop.

In modern wheat production systems, there are some advantages to using inorganic fertilizers. Chemical fertilizers are fertilizers with a high density of nutrients that are quickly absorbed by plants, causing a rapid reaction from the plants with increased yields. They have a standard nutrient composition, which makes it easier to manage a nutrient balance according to the crop's requirements and soil test recommendations. Inorganic fertilizers are also very transportable, easily stored, and readily available for widespread intensive crops. Much of the Green Revolution was based on the greater use of chemical fertilizers that helped boost the productivity of wheat and food security around the world. However, overuse and imbalance of inorganic fertilizers have been a concern for soil degradation, nutrient balance, decrease in soil organic matter, and contamination of the environment. The use of chemical fertilizers in high doses over time can have a negative impact on microbial activity, soil structure, and long-term soil health. Furthermore, the losses of nutrients (volatilization, leaching, and runoff) cause water pollution and greenhouse gas emissions (Penuelas *et al.*, 2023) ^[23]. Recent studies indicated that using integrated nutrient management systems (INM), which included the use of both inorganic fertilizers and organic manures and biofertilizers, was an environmentally friendly method for maximizing wheat productivity (Sande *et al.*, 2024) ^[31]. In this context, inorganic fertilizers are still essential for the production of high wheat yields, but their use in a balanced and efficient manner is vital to sustainable agricultural development and long-term soil fertility conservation.

4. Comparative Effects on Growth Parameters

4.1 Plant Height and Tiller Production

Plant height and tiller production are two growth parameters of wheat that directly impact wheat productivity and biomass. It has been observed that, in general, plant height and number of tillers were greater with the combined use of organic and inorganic fertilizers than with either fertilizer alone in comparative studies. The use of inorganic fertilizers, especially nitrogenous fertilizers, encourages the growth of plants and tillering because there is a quick supply of nutrients for the plants. Incorporation of farmyard manure (FYM), vermicompost, and compost with recommended doses of fertilizers, on the other hand, improves the availability of the nutrients for a longer period of time and also improves the soil physical conditions, which in turn improves plant growth for a longer period. Recent experiments showed that 75-125% of the recommended dose of fertilizers (RDF) along with vermicompost or FYM significantly enhanced the height of plants and tiller

formation in wheat in comparison to sole chemical fertilizer and control (Yadav *et al.*, 2023; Mishra *et al.*, 2024) ^[21, 41].

4.2 Leaf Area Development and Chlorophyll Content

Leaf area development and chlorophyll content are important measures of photosynthetic efficiency and wheat crop vigour. INM practices provide better leaf expansion, chlorophyll synthesis, and photosynthesis than sole inorganic fertilization. Chemical fertilizers contribute to the production of chlorophyll and green leaf area, while organic fertilizers can help maintain soil biological activity, micronutrient availability, and nutrient retention, all of which lead to an increase in leaf area index and the stability of chlorophyll. Research works have revealed that application of vermicompost along with inorganic fertilizers led to higher leaf area index and chlorophyll content (SPAD) than the use of inorganic fertilizers alone. Organic amendments also contain humic substances and beneficial microorganisms that enhance the enzymatic activities and nutrient absorption, resulting in healthier leaves and higher photosynthetic rates (Lamlom *et al.*, 2023). Likewise, innovative organic nutrient management methods were proven to enhance overall leaf area development and total chlorophyll content of wheat in a sustainable farming system (Sharma *et al.*, 2024) ^[19, 32].

4.3 Root Growth and Dry Matter Accumulation

The wheat plant's capacity to uptake nutrients and tolerate environmental stresses is related to root growth and dry matter accumulation. Comparative studies have shown that a combination of organic and inorganic fertilizers will help to penetrate the root deeper, provide better root branching and production of dry matter than inorganic fertilizers alone. Organic manures enhance soil aggregation, increase porosity and water holding capacity, providing optimum root growth and nutrient absorption. As a result of improved root development, increased dry matter accumulation and biomass production will occur during the life of the crop. Under wheat-based cropping systems, treatments with RDF along with vermicompost and FYM recorded a significant increase in DMC and biomass of roots compared to control and chemical fertilizer alone treatments (Dhaliwal *et al.*, 2023) ^[6]. Additionally, nutrient uptake efficiency and the partitioning of dry matter were increased through nutrient integration, which was beneficial for grain formation and overall crop productivity. Hence, continuous application of balanced sources of organic and inorganic nutrients results in improved establishment and efficient utilization of nutrients and leads to sustainable wheat production (Kajal *et al.*, 2024) ^[14].

Table 1: Comparative Effects of Organic and Inorganic Fertilizers on Growth Parameters of Wheat

Growth Parameter	Organic Fertilizers	Inorganic Fertilizers	Integrated Organic + Inorganic Fertilizers	Major Findings	References
Plant Height	Moderate increase due to slow nutrient release	Rapid increase because of immediate nutrient availability	Highest plant height observed	Integrated nutrient management produced superior growth and sustained nutrient supply.	Yadav <i>et al.</i> (2023); Mishra <i>et al.</i> (2024) ^[21, 41]
Tiller Production	Improves soil conditions for tillering	Enhances tiller initiation through nitrogen supply	Maximum tiller number recorded	Vermicompost + RDF significantly improved tiller count	Yadav <i>et al.</i> (2023); Singh <i>et al.</i> (2025) ^[35, 41]
Leaf Area Development	Better leaf expansion due to improved soil moisture and nutrients	Quick leaf growth under high nitrogen availability	Highest leaf area index	Integrated treatments improved photosynthetic area and crop vigor	Sharma <i>et al.</i> (2024) ^[32]
Chlorophyll	Increased through humic	Increased through	Highest SPAD	Combined nutrient application	Lamlom <i>et al.</i>

Content	substances and microbial activity	nitrogen availability	values	improved chlorophyll stability	(2023) ^[19]
Root Growth	Enhanced root proliferation and soil aggregation	Limited long-term improvement in soil structure	Deep and extensive root growth	Organic amendments improved the rooting environment	Dhaliwal <i>et al.</i> (2023) ^[6]
Dry Matter Accumulation	Gradual biomass increase	Rapid early biomass accumulation	Maximum dry matter accumulation	Integrated fertilization improved nutrient uptake and biomass production	Kajal <i>et al.</i> (2024); Mishra <i>et al.</i> (2024) ^[14, 21]

5. Comparative Effects on Yield Attributes

5.1 Spike Length and Grains per Spike

Spike length and spike grain number are characteristics of wheat yield that help to determine wheat productivity at the end of the crop. Comparative studies show that on applying an integrated dose of organic and inorganic fertilizers, the spike length and the grains per spike produced were significantly high as compared to that of chemical fertilizers and organic manures individually. Inorganic fertilizers, particularly N and P, cause rapid nutrient availability, which favours spike initiation and reproductive growth. But, the use of organic nutrient sources like farmyard manure (FYM), vermi compost, and compost can boost soil structure, microbial activities, and slow nutrient release for ensuring spike formation throughout the development of the crop. The results of the recent studies have shown that vermicompost (VC) with 125% of the recommended dose of fertilizers (RDF) gave the best spike length and grains per spike in irrigated wheat (Yadav *et al.*, 2023) ^[41]. In the same way, the integrated nutrient management (75% NPK in combination with FYM and vermicompost) recorded a more positive response for the spike length and grain number as compared to sole inorganic fertilization (Singh, 2019) ^[35].

5.2 Test Weight and Grain Filling

Test weight is a measure of grain size, grain density, and efficiency of grain filling, all of which are closely related to nutrient availability at the reproductive stage. Balanced feeding (organic-inorganic nutrients) is beneficial for assimilate translocation and grain development, and hence test weight. Nitrogen is important for protein synthesis and grain formation, and phosphorus and potassium are important for transferring energy and accumulating carbohydrates in developing grains. Organic amendments also provide better micronutrient availability and soil

moisture holding capacity, which promote good grain filling in fields. Sheoran *et al.* (2017) ^[34] showed that the integrated nutrient management practices had a significant effect on 1000-grain weight and grain filling compared to inorganic nutrient application. Biofertilizers and organic manures also help to increase physiological efficiency and nutrient uptake, resulting in better grain quality and increased grain weight (Lamlom *et al.*, 2023) ^[19].

5.3 Grain Yield, Straw Yield, and Harvest Index

In wheat production systems, the ultimate measures of the efficiency of fertilizers are grain yield, straw yield, and harvest index. Integrated application of organic and inorganic fertilizers has always been found to yield higher grain and straw production as compared to the separate nutrient application in comparative studies. Chemical fertilizers provide the crop with nutrients in the short term, while organic manures help to build soil fertility, retention of nutrients, and soil productivity. Integrated nutrient management in this case, therefore, has a synergistic effect that increases biomass production and allocates assimilates to grain. Singh (2019) ^[35] reported that the grain yield and straw yield under 75% NPK, along with FYM and vermicompost, significantly improved over recommended NPK alone under a wheat-based crop system. Similarly, long-term fertilization trials showed that the combination of organic manures and inorganic fertilizers has more beneficial effects on harvest index, nutrient use efficiency, and wheat yields compared to chemical fertilization alone (Sheoran *et al.*, 2017) ^[34]. The enhanced nutrient availability and increased soil biological properties of the integrated treatments are also expected to improve the sustainable yield in wheat cultivation and increase the economic benefits (Chandra *et al.*, 2022) ^[4].

Table 2: Comparative Effects of Organic and Inorganic Fertilizers on Yield Attributes of Wheat

Yield Attribute	Organic Fertilizers	Inorganic Fertilizers	Integrated Organic + Inorganic Fertilizers	Major Findings	References
Spike Length	Moderate increase due to gradual nutrient release	Rapid improvement through readily available nutrients	Highest spike length recorded	Vermicompost + RDF significantly improved spike length	Yadav <i>et al.</i> (2023); Singh (2019) ^[35, 41]
Grains per Spike	Improved through enhanced soil fertility	Increased due to better nutrient supply	Maximum grains per spike observed	Integrated nutrient management enhanced reproductive growth	Yadav <i>et al.</i> (2023); Sheoran <i>et al.</i> (2017) ^[34, 41]
Test Weight	Better grain development under improved soil health	Higher grain weight under balanced NPK	Highest 1000-grain weight achieved	Combined nutrient application improved grain filling	Sheoran <i>et al.</i> (2017); Lamlom <i>et al.</i> (2023) ^[19, 34]
Grain Filling	Sustained nutrient availability supports grain development	Rapid nutrient availability during the reproductive stage	Superior grain filling efficiency	Organic amendments improved nutrient translocation	Lamlom <i>et al.</i> (2023) ^[19]
Grain Yield	Moderate yield increase	High grain yield due to quick nutrient uptake	Maximum grain yield obtained	75-125% RDF + vermicompost/FYM gave the highest yield	Singh (2019); Yadav <i>et al.</i> (2023) ^[35, 41]
Straw Yield	Improved biomass production	Increased vegetative growth	The highest straw yield was observed	Integrated fertilization enhanced biomass accumulation	Singh (2019); Chandra <i>et al.</i> (2022)

					[4, 35]
Harvest Index	Moderate improvement	Higher harvest index than the control	Maximum harvest index achieved	Better assimilate partitioning under INM	Sheoran <i>et al.</i> (2017); Yadav <i>et al.</i> (2023) [34, 41]

6. Impact on Soil Health and Nutrient Dynamics

The use of wheat nutrition is greatly affected by soil health, and nutrient dynamics depend on the kind and proportion of fertilizers used for wheat cultivation. In many instances, the over-dependency of chemicals leads to an imbalance of nutrients, soil acidification, reduction in organic matter, and loss of soil organisms. On the other hand, the use of integrated nutrient management strategies (INM) in wheat-based cropping system like use of organic manures, biofertilizers, and inorganic fertilizers, contributes to the maintenance of soil fertility and nutrient cycling. Farmyard manure (FYM), compost, and vermicompost are important sources of organic nutrients that help to enhance the status of soil organic carbon, aggregation, porosity, and water holding capacity. Long-term experiments have demonstrated that using a balanced fertilization program with organic amendments can lead to a higher soil organic carbon level and better availability of nutrients, including nitrogen, phosphorus, potassium, sulfur, and micronutrients. The long-term experiment in the Indo-Gangetic Plains showed that integrated nutrient management had significant soil health benefits in terms of soil health indicators and soil nutrient transformations compared to sole chemical fertilizer management (Walia *et al.*, 2024) [40].

Organic carbon is regarded as one of the main measures of soil fertility as it controls the soil's ability to retain nutrients, soil structural stability, and microbial activity. The application of FYM, GM, and CR increases the carbon sequestration and prevents nutrient losses by leaching and volatilization of the soil. Wheat cultivation practices were employed for recent investigations, which showed that treatments with vermicompost and recommended doses of nitrogen significantly improved soil organic carbon, available potassium, and nutrient uptake rates as compared to the conventional fertiliser practices (Kumar & Kumar, 2025) [16]. Organic amendments also help to increase the microbial biomass carbon, enzyme activities, and beneficial soil microorganisms that are important in decomposition, mineralization, and nutrient availability. Acceleration of microbial activities brings about higher fixation of nitrogen, solubilization of phosphorus, and degradation of organic matter, which makes nutrients readily available to wheat plants. Research results showed that soil enzymatic activity and microbial activity were enhanced in an organic farming system, and the productivity of wheat was maintained under the integrated nutrient management system (Sharma *et al.*, 2024) [32].

Adequate nutrient supply and nutrient-use efficiency are greatly influenced by fertilizer application. Inorganic fertilizers are often low in nutrient-use efficiency due to losses in run-off, leaching, denitrification, and volatilization, and can be a quick source of nutrients if applied in isolation. Integrated nutrient management systems allow a better synchronisation of nutrient release and crop uptake and thus enhance the uptake efficiency and reduce environmental losses. Wheat studies showed that using 75-100% of recommended dose of fertilizers (RDF) with vermicompost, FYM and biofertilizers improved the uptake of N, P, K, and nutrient use efficiency significantly when compared to

chemical fertilizers used alone (Maskey *et al.*, 2024) [20]. Precision nutrient management techniques also contribute to improved fertilizer use efficiency by ensuring nutrients are applied at the right time and in the right quantities based on the crop's stage of development and soil nutrient levels. Recent studies also demonstrated that precision nutrient management under a zero-till wheat system resulted in better soil organic carbon management, which led to increased soil enzymatic activity, reduced N2O emissions, and improved nutrient-use efficiency (Sadhukhan *et al.*, 2024) [29].

7. Integrated Nutrient Management (INM) Approaches
7.1 Combined Use of Organic and Inorganic Fertilizers

Integrated Nutrient Management (INM) is a sustainable management system where organic manure, inorganic fertilizers, crop residues, green manures, and biofertilizers are used together to maintain soil fertility and improve the productivity of a crop. Wheat cultivation practices involving INM are designed to provide balanced nutrient supplies and reduce negative impacts from too much chemical fertilizer. Soil physical and biological properties will be enhanced by the use of organic nutrient sources like farmyard manure (FYM), compost, vermicompost, and green manure, while inorganic fertilizers will provide readily available nutrients for immediate crop uptake. The complementary action of these nutrient sources leads to better nutrient availability, root growth, microbial activity, and nutrient-use efficiency for wheat cropping systems. Recent experiments have shown that the plant growth, grain yield, and nutrient uptake were significantly improved under integrated application of 75-100% recommended dose of fertilizers (RDF) with FYM or vermicompost than inorganic fertilizers alone (Yadav *et al.*, 2024; Tabassum *et al.*, 2024) [37, 42].

Figure 3. The concept of integrated nutrient management is represented in this diagram by the combined use of organic manure, crop residues, green manure, biofertilizers, and inorganic fertilizers, enhancing the soil fertility, nutrient availability, and microbial activity. A combination of these nutrient sources improves the nutrient availability, organic matter, sustainable plant growth, and long-term soil health.

7.2 Benefits of Integrated Fertilization in Sustainable Wheat Production

Integrated fertilization is key to sustainable wheat production, contributing to a healthy soil, a productive soil, and to resource use efficiency. Organic amendments help to increase SOM, aggregate, water holding capacity, and microbial biomass, and chemical fertilizers provide a quick nutrient release at the most critical growth stages. The nutrients combined result in conditions that are conducive to better photosynthesis, tillering, spike formation, and grain filling. It has been demonstrated that INM practices have resulted in significantly higher wheat grain yield, straw yield, harvest index, and uptake of nutrients compared to the sole use of chemical fertilizers. Enzymatic activities and nutrient transformations are also improved under an integrated fertilization system, which is crucial for soil fertility under an intensive crop production system (Walia *et*

al., 2024)^[40]. In addition, farmers can benefit from better economic returns as integrated nutrient management can cut their reliance on expensive chemical fertilizers. In recent years, it has been recognized that balanced application of

organic and inorganic fertilizers is a key to ensuring nutrient-use efficiency and maintaining wheat production under the changing climate (Farouk *et al.*, 2024)^[8].

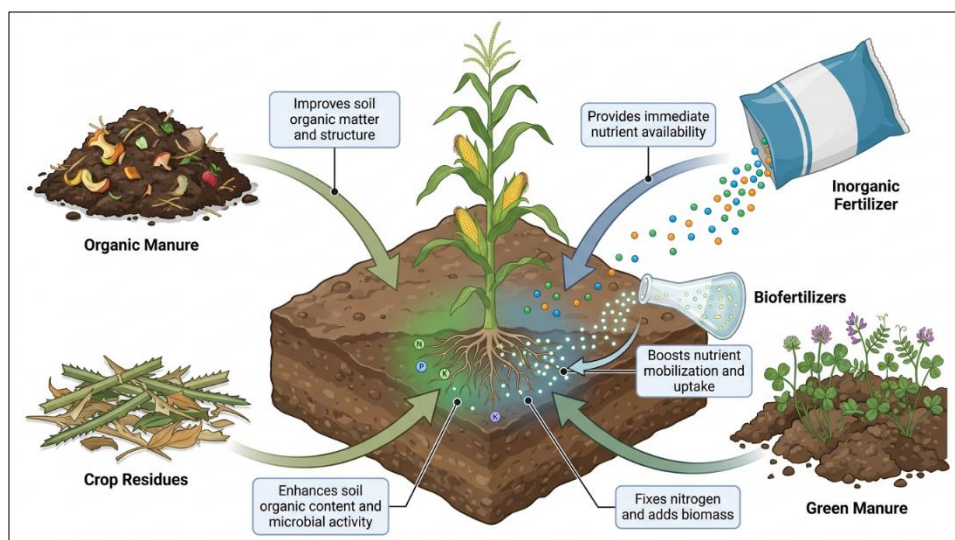


Fig 3: Integrated nutrients improve sustainable soil fertility.

7.3 Long-Term Productivity and Environmental Sustainability: Long-term experiments have shown that the application of INM practices is very effective in maintaining wheat yield and enhancing environmental quality. Soil organic matter is depleted, soil is degraded, and a nutrient imbalance may occur when chemical fertilizers are continuously applied to the soil without other measures. Conversely, the use of integrated organic manures and fertilizers leads to an increase in carbon sequestration, nutrient cycling, and wheat-based cropping systems' resilience. According to a 36-year-long-term study, soil organic carbon accumulation, wheat productivity, and environmental sustainability were significantly higher

compared to conventional fertilization practices when subjected to application of 50% RDF along with FYM (Ranjan *et al.*, 2023)^[25]. Likewise, carbon footprints and energy-use efficiency of maize-wheat rotation were lowered by using conservation agriculture-based integrated crop management systems (Barman *et al.*, 2024). Use of INM also helps in the reduction of greenhouse gases and pollution in the environment due to high consumption of chemical fertilizers. Incorporating residues for longer and adopting balanced P management further enhanced soil health and wheat productivity in rice-wheat systems (Gupta *et al.*, 2024)^[1, 9].

Table 3: Major Benefits of Integrated Nutrient Management in Wheat Production

Parameter	Sole Organic Fertilizers	Sole Inorganic Fertilizers	Integrated Nutrient Management (INM)	Major Outcomes	References
Nutrient Supply	Slow and gradual nutrient release	Rapid nutrient availability	Balanced and synchronized nutrient release	Improved nutrient-use efficiency	Yadav <i>et al.</i> (2024); Tabassum <i>et al.</i> (2024) ^[37, 42]
Soil Organic Carbon	Significantly improved	Often declines under long-term use	Highest soil carbon accumulation	Better soil fertility and carbon sequestration	Ranjan <i>et al.</i> (2023); Walia <i>et al.</i> (2024) ^[25, 40]
Microbial Activity	Enhanced microbial biomass	Limited improvement in soil biology	Maximum microbial and enzymatic activity	Improved nutrient cycling	Walia <i>et al.</i> (2024) ^[40]
Grain Yield	Moderate increase	High short-term yield	Highest and sustainable yield	Better productivity and profitability	Farouk <i>et al.</i> (2024); Tabassum <i>et al.</i> (2024) ^[8, 37]
Nutrient Use Efficiency	Moderate	Lower due to nutrient losses	Highest nutrient-use efficiency	Reduced nutrient leaching and volatilization	Yadav <i>et al.</i> (2024) ^[42]
Soil Health	Improved structure and aggregation	Risk of soil degradation	Best soil physical and biological properties	Sustainable soil fertility	Gupta <i>et al.</i> (2024) ^[9]
Environmental Impact	Eco-friendly but slower response	Higher risk of pollution and GHG emissions	Reduced environmental footprint	Improved sustainability and reduced emissions	Barman <i>et al.</i> (2024); Ranjan <i>et al.</i> (2023) ^[1, 25]
Long-Term Productivity	Sustainable but lower immediate yield	Productivity decline over time	Sustained long-term productivity	Enhanced resilience of wheat systems	Chander <i>et al.</i> (2023) ^[3]

8. Economic Analysis of Fertilizer Application

Fertiliser application analysis in wheat is vital to assess profitability, sustainability, and the feasibility of various

nutrient management practices for wheat farmers. Organic and inorganic fertilizers have a strong impact on production cost, crop production, net returns, and benefit-cost (B: C)

ratio. Inorganic fertilizers like muriate of potash, DAP, and urea will ensure the quick availability of nutrients and will usually yield higher short-term grain production and immediate economic returns. The high cost of fertilizers and reliance on chemical fertilizers, however, have posed issues regarding the profitability and sustainability of soils. Organic fertilizers such as Farmyard Manure (FYM), Vermicompost, Compost, and Biofertilizers are beneficial in improving soil fertility and soil quality, but these are labor-intensive, transport-intensive, slow-release, and have relatively less immediate returns. The study has revealed that the use of integrated nutrient management (INM) of organic and inorganic fertilizers has a more balanced approach as it stabilizes the yield, lowers the input costs in the long term, and improves soil productivity (Kumar & Mishra, 2025)^[17].

The results of a comparative economic assessment show that in most cases integrated fertilization results in higher gross return and better resource-use efficiency as compared to sole fertilization. According to a recent field study conducted on wheat, the highest grain yield along with the maximum net monetary return was ₹86,710 ha⁻¹ while conventional fertilizer treatments were NPK @ 150:75:60 kg ha⁻¹ plus FYM, biofertilizers (Azotobacter and phosphate-solubilising bacteria), and sulphur (S) (Kumar & Mishra, 2025)^[17]. The integrated nutrient management is more effective in using nutrients because it is able to synchronize nutrient release and nutrient demand by the crop, reducing nutrient losses through leaching, runoff, and volatilization. Better nutrient use means less excess fertilizers are needed, and better economic returns are generated per unit of nutrient input. Long-term experiments under rice-wheat cropping systems also showed that the combined application of FYM and the recommended dose of fertilizers significantly increased the productivity of wheat, farm profit, and soil fertility over the sole chemical fertilizer application (Chander *et al.*, 2023)^[3]. Besides resource-use efficiency, there are other factors that affect the economic aspects of fertilizer use in the field. A higher productivity combined with better water-use efficiency, energy-use efficiency, and nutrient recovery efficiency using integrated nutrient management practices. According to the studies under the maize-wheat and rice-wheat systems, it was observed that the integrated nutrient management under drip irrigation and conservation agriculture resulted in higher net income and benefit-cost ratio and lower water and fertilizer consumption (Sairam *et al.*, 2026; Jat *et al.*, 2023)^[13, 30]. Moreover, the integrated crop management system, which includes the use of crop residues and balanced fertilizer, improved the farm economy by 19-22% over the conventional crop management system (Jat *et al.*, 2022)^[12].

9. Environmental Implications

Although the indiscriminate and continuous application of chemical fertilizers has been greatly significant in achieving increased productivity of the crops in modern agriculture, they have been identified as serious environmental and soil health problems. Excessive nitrogen application in the form of nitrogenous fertilizers like urea and ammonium-based fertilizers is frequently associated with nutrient imbalance, acidification of soil, contamination of groundwater, eutrophication, and emission of greenhouse gases like nitrous oxide. Excessive long-term application of chemical

fertilizers may also lead to lower soil microbial diversity, poor soil structure, and soil organic matter, which will impact sustainable crop production. But recent studies indicated that high fertilizer use had an adverse effect on the farmland ecosystems and declined soil productivity over time despite a short-term yield benefit (He *et al.*, 2024).

In an intensive wheat-based cropping system, continuous application of chemical fertilizer has led to soil degradation being a major challenge. Too much (and too little organic fertiliser) will lead to nutrient mining and a decrease in soil fertility with time, caused by imbalanced fertilisation practices. Long-term use of chemical fertilizers is often associated with loss of soil organic carbon, reduced soil aggregation, and decline in soil biological properties. A recent study based on India's Soil Health Card data suggested that the soil health in India is very much degraded with intensive use of fertilizers, as large fractions of the Indian soils are deficient in N and organic carbon. In the wheat systems, long-term experiments showed that microbial activity and nutrient transformations were reduced under sole chemical fertilization, while integrated nutrient management increased soil fertility and microbial enzyme activity (Sheoran *et al.*, 2024)^[33]. Too much chemical fertilizer application can also cause an imbalance of nutrients, which would cause a reduction in fertilizer-use efficiency due to high nutrient losses in leaching, run-off, denitrification, and volatilization. These nutrient losses not only drive up production expenses but also result in environmental pollution and consequently reduced ecosystem stability.

Use of organic inputs like farmyard manure (FYM), compost, vermicompost, crop residues, green manures, and biofertilizers is found to be playing an important role in promoting sustainable and eco-friendly agriculture. Organic amendments increase the soil organic carbon, microbial diversity, nutrient cycling, and soil physical properties, which restores soil fertility and ecological balance. It has been demonstrated that using some of the chemical fertilizers with organic fertilizers can greatly lead to the improvement of soil quality and the richness of soil microbes in the wheat field, as well as to carbon sequestration (He *et al.*, 2024). Organic nutrient sources also help to decrease nitrate buildup, nutrient loss, and enhance soil water holding capacity and nutrient availability. In dryland wheat systems, blending organic and inorganic fertilizers has been shown to enhance carbon sequestration and diversity of bacterial communities, which was found to be beneficial for the long-term environmental sustainability (Song *et al.*, 2024)^[36].

The use of organic farming practices, such as integrated nutrient management, is gaining prominence as a solution to promote both productivity and environmental preservation. Use of FYM as well as balanced doses of fertilizer over the years enhances the fertility, microbial activity, and nutrient transformation processes of the soil in addition to reducing environmental degradation (Sheoran *et al.*, 2024)^[34]. Organic farming methods also contribute to the decrease of GHG, biodiversity, and resilience of agricultural systems in the face of climate change. Thus, proper application of fertilization, in which both organic and inorganic fertilizers are used, is essential to ensure soil health and continuity of productivity of the crops and environment-friendly agriculture.

10. Recent Advances and Future Prospects

Wheat production is being revolutionized by recent technological developments in nutrient management to produce more and more productive, efficient, and environmentally friendly crops. Precision nutrient management (PNM) is an emerging technology that uses the nutrient needs of the crop, soil nutrient status, and field spatial nutrient variability to optimize nutrient use. Site-specific nutrient management in wheat is becoming more common with the advent of new tools like Global Positioning System (GPS), Geographic Information Systems (GIS), remote sensing, Leaf Color Chart (LCC), GreenSeeker sensors, Soil-Plant Analysis Development (SPAD) meters, and Nutrient Expert decision-support systems. These technologies can enhance the nitrogen-use efficiency, minimise nutrient losses from fertilizers used, and increase crop productivity without polluting the environment. Recent studies have shown that results from precision nutrient management application under a zero-tillage system resulted in significantly higher wheat production, nutrient-use efficiency, soil enzymatic activity, and lower N₂O emissions under rice-wheat system (Sadhukhan *et al.*, 2024) ^[29]. Advanced precision nitrogen management strategies also help to increase the efficiency of fertilizer use by implementing split application, in situ monitoring of nutrients, and variable rate nitrogen application, which can help in sustainable intensification of wheat production systems (Kumar *et al.*, 2025) ^[16].

Nano-fertilizers and bio-based sources of nutrients are becoming increasingly popular as alternatives to conventional nutrient sources for sustainable wheat production. Engineered nanomaterials engineered to deliver nutrients efficiently via controlled release, targeted delivery, and improved nutrient uptake are called nano-fertilizers. Nano-fertilizers can lower nutrient losses due to volatilization or leaching, and have better nutrient-use efficiency in various environmental conditions than conventional fertilizers. Zinc oxide nanoparticles, nano-urea, nano-phosphorus, and hydroxyapatite nanoparticles were found to have potential towards enhancing the growth and yield of wheat, tolerance against abiotic stress, and uptake of nutrients in wheat plants (Nazir *et al.*, 2024). Tripathi *et al.* (2025) ^[22, 39] recently reported that application of nano-urea resulted in increased NUE, profitability, and environmental friendliness in wheat cultivation in various agro-climatic regions of India. Additionally, nano-fertilizers can also play a part in sustainable agriculture by limiting over-dependence on the use of chemical fertilizers and decreasing greenhouse gas emissions. There have been comprehensive evaluation which has highlighted that the use of nano-fertilizers can significantly boost the productivity of wheat and help reduce environmental degradation and maintain soil health (Channab *et al.*, 2024) ^[5]. In addition to nano-fertilizers, other nutrient sources of biological origin, like biofertilizers, microbial inoculants, and organic amendments, are also increasingly being incorporated into nutrient management systems to promote soil microbial activity, nutrient mobilization, and ecological sustainability.

The management of nutrients with consideration of climate change (climate-smart nutrient management) is becoming an increasingly important issue to ensure wheat productivity in future changing climatic conditions. Climate change-induced stresses like increasing temperature, variation in

rainfall, drought, and increased carbon dioxide levels in the atmosphere have a great impact on nutrient dynamics and fertilizer-use efficiency in wheat systems. Balanced fertilization, integrated nutrient management, conservation agriculture, slow-release fertilizers, nitrification inhibitors, and precision nutrient application are some of the principles of climate-smart approaches that enhance resilience and minimize environmental impact. Nitrification and urease inhibitors were found to significantly lower the gaseous losses and thus increase the N-use efficiency of wheat under high CO₂ and high temperature conditions (Chakrabarti *et al.*, 2024) ^[2]. Implementing conservation agriculture and precision nutrient management further increases soil organic carbon, water-use efficiency, and crop health and resilience to climate variability. All of these methods not only help to boost productivity, but also to minimize GHG emissions and nutrient losses, making wheat production more sustainable in future climate scenarios. Hence, the use of precision agriculture, nano-fertilizer technologies, and climate-smart nutrient management practices could be a potential way forward for resilient, environmentally friendly, and sustainable wheat production systems.

11. Conclusion

The nutrient source x crop response experiment is quite effective in highlighting the importance of both organic and inorganic fertilizer sources for enhancing wheat (*Triticum aestivum* L.) productivity, soil fertility, and nutrient dynamics. Inorganic fertilizers offer a quick nutrient supply, which encourages rapid plant growth, increased tillering, better chlorophyll formation, and higher grain production, but the overuse and misuse of inorganic fertilizers can result in nutrient imbalances, environmental pollution, and soil degradation. Organic fertilizers like farmyard manure, compost, vermicompost, green manure, and biofertilizers are comparatively slower in their nutrient release but help in increasing the soil organic carbon, microbial activity, soil structure, nutrient retention, and soil long-term health. Comparative studies showed that Integrated nutrient management (INM) (combination of organic and inorganic nutrient sources) is the most suitable practice for sustainable wheat production as it has the most beneficial effects in terms of nutrient-use efficiency, yield, soil biological activity, and environmental sustainability. Together, INM practices enhance economic returns, minimize nutrient losses, and boost the climate resilience of wheat systems under a changing climate. So, balanced fertilization, precision nutrient management, residue recycling, and increased organic nutrient sources, along with recommended doses of chemical fertilizers, should be emphasized in a sustainable wheat production system. Climate-smart and integrated nutrient management will be crucial to ensure the sustainability of food production, the sustainability of natural resources, soil fertility, and productivity in the long-term.

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