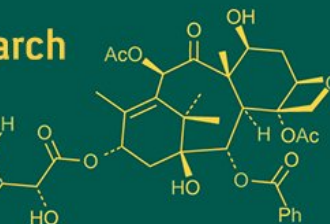
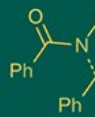


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Integrated nutrient management in wheat (*Triticum aestivum* L.): A review of agronomic performance, soil health, and economic implications

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Abstract

Integrated nutrient management (INM) has become the main method to maintain wheat production because soil organic matter levels decrease and nutrient levels become unbalanced and micronutrients become unavailable and fertilizer effectiveness decreases. This review provides a synthesis of recent research from 2018 to 2025 which demonstrates how farmers can use mineral fertilizers and farmyard manure and vermicompost and zinc sulfate and biofertilizers to increase wheat growth and yield and soil quality and economic returns. The literature shows that using only chemical fertilizers results in temporary productivity increases which lead to long-term soil damage across physical and chemical and biological properties. The use of INM technology results in better nutrient matching through improved root development and microbial activity and increased soil carbon content and better access to essential trace elements. The most effective results from multiple studies occur when farmers use reduced fertilizer applications together with organic manures and microbial inoculants on soils that need zinc and have low organic carbon content. Integrated nutrient strategies from rice-wheat systems show evidence that they improve carbon sequestration and energy efficiency and system resilience when compared to using only fertilizers. The review demonstrates that integrated nutrient management functions as a complete system-based framework which enables farmers to maintain wheat production and soil health and farm financial viability during periods of growing agricultural environmental pressures.

Keywords: Integrated nutrient management, wheat, farmyard manure, vermicompost, zinc sulphate, Azotobacter, soil organic carbon, nutrient-use efficiency, soil health

Introduction

Wheat (*Triticum aestivum* L.) represents a key cereal crop which people worldwide depend on for their essential food needs because the crop can grow in various environments and creates substantial food production results which provide essential calories and proteins for human consumption. Wheat serves as a vital component in India's rabi cropping system because it plays a critical role in maintaining food security throughout different Indian agricultural regions. The current process of maintaining wheat production at its previous levels has become extremely challenging because agricultural growth with high-yielding cultivars and mineral fertilizer usage has reached its limits due to decreasing soil quality problems and nutrient distribution issues and diminished efficiency of production elements (Sharma & Tomar, 2025; Walia *et al.*, 2024) ^[22, 27]. Wheat systems which use intensive methods face a persistent problem because they depend too much on mineral NPK fertilizers while they do not replenish their organic matter content. These agricultural methods increase immediate crop yields. However, they decrease the capacity of soil to hold together and the activity of microorganisms and the ability of soil to keep moisture and the capacity of soil to store nutrients. The conditions create more severe cases of hidden micronutrient deficiencies which affect secondary elements and micronutrients, specifically zinc which scientists identify as a factor that limits cereal crop production (Ali *et al.*, 2022; Gupta *et al.*, 2022) ^[6, 11]. Research in north Indian rice-wheat regions indicates that fertilizer-only systems do not sustain soil organic carbon and nutrient-use efficiency and balanced nutrient changes throughout extended periods (Rani *et al.*, 2023; Walia *et al.*, 2024) ^[23].

The practice of integrated nutrient management (INM) has become an environmental sustainability method which improves crop nutrient management. The main principle of INM uses inorganic fertilizers and organic nutrients and beneficial microorganisms to provide balanced nutrient distribution which increases resource efficiency and protects soil productivity over time (Meena *et al.*, 2024; Yadav *et al.*, 2025) ^[21, 10]. The decomposition of farmyard manure (FYM) and vermicompost results in carbon release which creates better soil conditions and better microbial environments while providing nutrients in a slow process (Patel *et al.*, 2022; Singh & Kumar, 2021) ^[12, 16]. The biofertilizer *Azotobacter* enhances root development while it allows plants to access nutrients from their surroundings and zinc sulphate provides essential micronutrients which support metabolic processes for chlorophyll production and enzyme function and grain development (Khan *et al.*, 2023; Singh *et al.*, 2024) ^[14, 8]. This research is unique since the findings pertain to the wheat

production system that encounters difficulties arising due to variations in soil characteristics and landscape complexity and nutrient deficiencies in Uttarakhand (Sharma & Tomar, 2025) ^[27].

The study represents a true review synthesis in contrast with the previous manuscript that used a thesis format for presentation. The study encompasses the existing literature on INM in wheat via four research domains that include plant growth, physiology, yields, and nutrient use efficiencies as well as soil health and nutrient cycling and sustainability aspects of INM.

The importance of INM now extends beyond its ability to increase crop production. Recent research demonstrates that integrated nutrient management practices lead to higher soil carbon storage rates and lower greenhouse gas emissions and better nutrient efficiency and stronger protection for cereal crops grown in high-intensity farming systems (Rani *et al.*, 2023; Walia *et al.*, 2024) ^[22, 23].

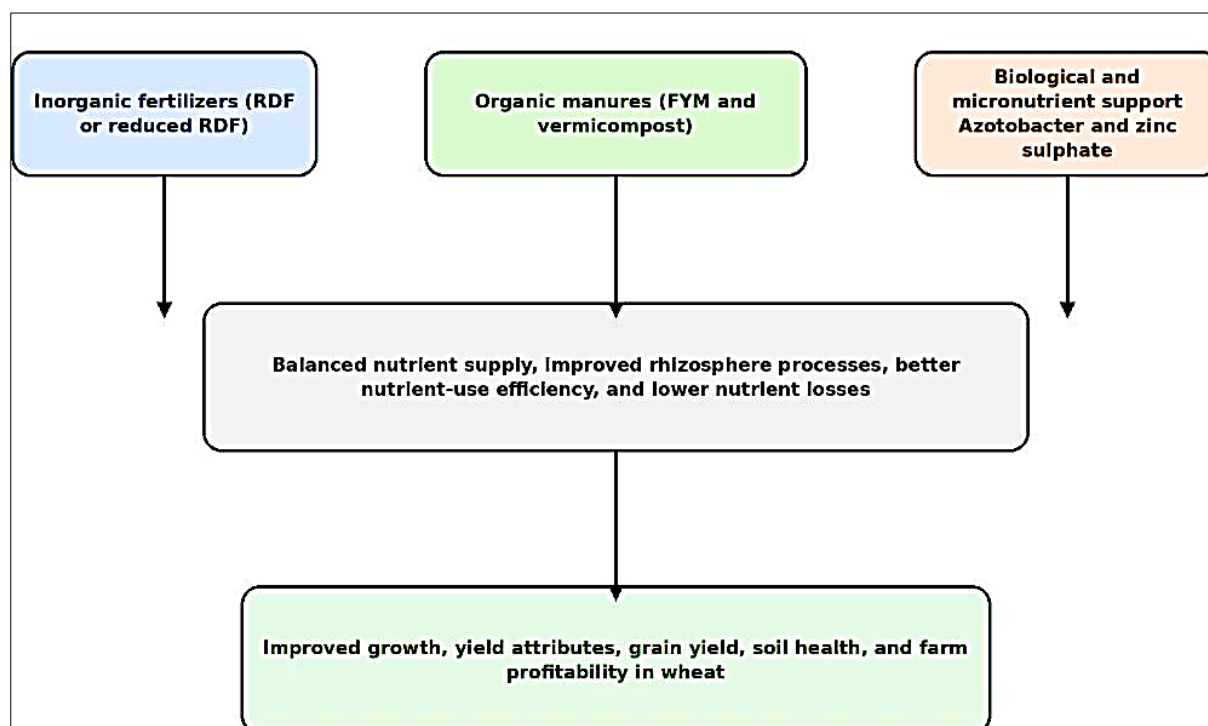


Fig 1: Conceptual framework of integrated nutrient management in wheat, showing the convergence of inorganic fertilizers, organic manures, and biological or micronutrient support toward improved productivity and soil health.

1. Concept and agronomic basis of INM

The INM agronomic system establishes its basic principles because modern agricultural methods need multiple nutrient sources to maintain soil health and crop growth. Mineral fertilizers deliver nutrients that plants can absorb immediately but their effectiveness decreases because of material losses through volatilization and leaching and fixation and incorrect timing with plant needs. Organic manures provide nutrient release through a gradual process which enhances cation exchange capacity and water retention ability of soils while they build up carbon storage over time. Biofertilizers create higher biological activity in the rhizosphere which allows plants to access both native and applied nutrients through their enhanced nutrient transformation abilities.

The complete understanding of wheat response to these components requires knowledge about both applied nutrient quantities and their application schedule and complementary nutrient sources and soil biological processes. Studies from Indian cereal systems indicate that integrated nutrient strategies improve both agronomic efficiency and partial factor

productivity relative to sole inorganic fertilization (Das & Rout, 2021; Kumar *et al.*, 2023) ^[9, 3]. The evidence from long-term field studies demonstrates that integrated nutrient management practices lead to reduced environmental impact through enhanced soil carbon levels and decreased greenhouse gas emissions (Rani *et al.*, 2023; Walia *et al.*, 2024) ^[22, 23].

2. Effects on crop growth and physiological development

Research studies demonstrate that INM leads to improved vegetative growth in wheat because it enables better plant establishment and results in increased tiller density and larger leaf area and more robust root development and higher dry matter production (Choudhary *et al.*, 2022; Patel *et al.*, 2022) ^[12, 2]. The observed plant responses result from better nutrient release synchronization with crop requirements and improved rhizosphere conditions and increased photosynthetic ability. Researchers found through their recent investigations that the combination of recommended or reduced fertilizer doses with FYM or vermicompost produces better plant growth results than control and fertilizer treatments. The application of

vermicompost delivers quick benefits to crops because the material contains a narrow C:N ratio and humified organic fractions and nutrients that plants can use immediately (Singh & Kumar, 2021; Singh *et al.*, 2024) ^[14, 16]. FYM provides stronger benefits to soil physical properties and residual fertility because it maintains its positive effects over time. The combination of these two substances with *Azotobacter* results in two benefits for plants through the delivery of plant growth-promoting substances together with biologically mediated nitrogen contribution (Kumar *et al.*, 2023; Sharma *et al.*, 2023) ^[13, 9].

Zinc performs a crucial function that needs particular attention. Zinc deficiency hinders the functions of enzymes while obstructing the creation of chlorophyll and the process of carbohydrate metabolism and the development of reproductive organs. The addition of zinc to INM packages benefits plant growth through two major outcomes which include increased chlorophyll content and improved leaf growth and biomass accumulation and general plant health under conditions of soil zinc deficiency or marginal deficiency (Ali *et al.*, 2022; Gupta *et al.*, 2022) ^[6, 1]. Research in wheat cultivation shows that soils which need zinc respond positively to growth increases when $ZnSO_4$ is used with DIM including reduced RDF and organic materials (Khan *et al.*, 2023; Singh *et al.*, 2024) ^[14, 8].

3. Yield attributes, grain yield, and nutrient-use efficiency

The practice of integrated nutrient management will lead to improved growth results which will produce higher crop yields. Integrated nutrient treatments lead to measurable increases in spike length and grains per spike and test weight

and grain yield and straw yield and biological yield according to research findings. The observed responses result from improved source-sink relationships together with better nutrient absorption during reproductive periods and sustained nutrient supply which enhances grain filling processes. The studies demonstrate that using organic materials as partial replacements for chemical fertilizers maintains crop productivity while improving nutrient utilization efficiency. The combination of 75% or 100% RDF with FYM and vermicompost and zinc sulphate and biofertilizers results in better performance than using RDF only (Choudhary *et al.*, 2022; Meena *et al.*, 2024; Verma *et al.*, 2024) ^[18, 2, 10]. The reproductive traits benefit from short-duration assessments while the long-term trials show progress through better soil nutrients and enhanced nutrient buffering capacity. The evidence from long-term studies supports this conclusion. The 36-year rice-wheat research from Bihar showed that integrated organic-inorganic treatments lead to increased wheat grain yield and N P K agricultural efficiency and soil organic carbon sequestration while decreasing greenhouse gas emissions when compared to the inorganic RDF treatment. The system-level value of integration shows through the treatment which combines 50% RDF with 50% FYM N to achieve the biggest SOC accumulation and a 24.7% wheat yield advantage over RDF across both crops. The 34-year Punjab study demonstrated strong positive relationships between wheat yield and soil organic carbon and available nitrogen and available phosphorus under integrated nutrient regimes which showed that soil quality restoration directly affected yield stability (Walia *et al.*, 2024) ^[22].

Table 1. Synthesis of representative findings on INM effects in wheat

Study window	Nutrient combination	Primary response domain	Key inference
2018-2022	RDF + $ZnSO_4$	Growth, chlorophyll content, nutrient uptake, grain yield	Zinc application is consistently beneficial in Zn-deficient soils and improves physiological efficiency and reproductive development.
2021-2024	75% RDF + FYM or vermicompost	Plant height, tillering, dry matter, post-harvest fertility	Partial fertilizer substitution with organics can sustain growth and improve soil properties relative to sole chemical fertilization.
2023-2025	RDF + <i>Azotobacter</i>	Establishment, effective tillers, nutrient-use efficiency	Biofertilizer support improves early root function and enhances crop responsiveness to applied nutrients.
2022-2025	RDF + vermicompost/FYM + $ZnSO_4$ + biofertilizer	Yield attributes, grain yield, microbial activity, economics	Multi-component integration generally produces the most balanced agronomic and soil-health gains.
Long-term evidence	Organic-inorganic integration in rice-wheat systems	SOC sequestration, nutrient-use efficiency, grain yield, emission intensity	INM improves system sustainability by enhancing carbon storage, fertilizer efficiency, and yield resilience over time.

4. Impacts on soil health and nutrient transformations.

The strongest long-term justification for INM lies in its effect on soil health. Studies consistently show that integrated treatments improve soil organic carbon, available nitrogen, phosphorus, potassium, and micronutrients, while also moderating soil bulk density and enhancing water-holding capacity (Choudhary *et al.*, 2022; Tripathi *et al.*, 2022; Walia *et al.*, 2024) ^[22, 17, 2]. Organic applications provide substrates of carbon, which activate microbial activities, enhance aggregate stability, and make the soil more efficient in nutrient retention and recycling.

Long-term experiments yield significant insights. The 34-year experiment in Punjab found that treatment methods involving integration of FYM, green manure, or cut straw from wheat plants with mineral fertilizer greatly enhanced soil organic carbon content and availability of nitrogen and phosphorus compared with control treatments and treatments with lower

fertilizer application. Additionally, the above experiment demonstrated better microbial community and accumulation of micronutrients including iron and zinc with integrated treatments. According to Rani *et al.*, FYM-based INM increased SOC content, carbon pool index, carbon sequestration rate, and reduced soil bulk density compared with fertilization alone in the long-term experiment in Bihar (2023).

Such evidence suggests that INM is beneficial not only in terms of enhancement of the plant-available nutrient reservoir but also in regard to enhancing nutrient transformation via the improvement of physical and biological properties of soil. Organic inputs increase porosity and aggregation and reduce compactness, improving root exploration of the soil. Enhanced microbial activity leads to mineralization, immobilization, chelation, and exchange of nutrients. Thus, the efficiency of soil as a growing medium improves significantly.

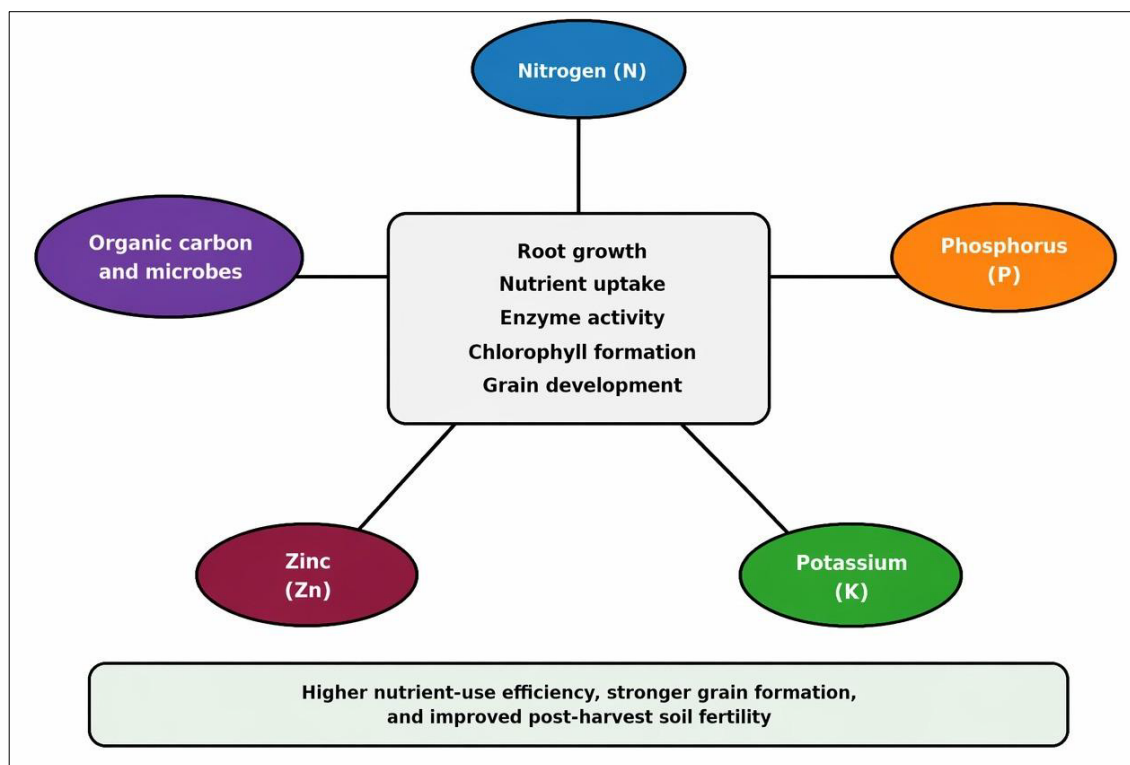


Fig 2: Pathways for nutrient interactions through integrated nutrient management, where N, P, K, Zn, and microbial action stimulated by organic carbon collectively contribute to nutrient uptake, grain development, and post-harvest soil fertility.

5. Micronutrient dimension, especially zinc

In terms of wheat nutrition, micronutrient management appears to be another important issue that deserves more attention in the future. One particular micronutrient that has been observed to limit yield in intensively grown cereals is zinc (Ali *et al.*, 2022; Gupta *et al.*, 2022) [6, 1]. Often, the addition of macronutrients is not enough for achieving optimal results if there is zinc deficiency causing problems in root growth, metabolism, and grain formation.

Based on this review, zinc should ideally be used as a part of an integrated nutrition plan rather than as a separate treatment. The availability of zinc can be enhanced by adding organic fertilizers, as this impacts chelation reactions, root development, and the micro-environment of the rhizosphere. Increased microbiological activity can potentially help with mobilizing micronutrients. Thus, a combination of RDF, organic manure, zinc sulphate, and biofertilizers is likely to demonstrate better results compared to NPK+Zn (Khan *et al.*, 2023; Singh *et al.*, 2024) [14, 8]. This becomes relevant in relation to wheat growing in zinc-deficient alluvial and foothill soils. Therefore, INM can be considered as a solution for optimizing macronutrient content and improving micronutrient functions in soils.

Economics of integrated nutrient management

Economic efficiency becomes an essential factor in determining adoption of agricultural innovation. According to the findings from literature analysis, INM tends to enhance economic gains in terms of net returns and benefit-cost ratio because of enhanced nutrient-use efficiency and increased crop productivity. However, profitability depends on the costs associated with locally available sources of organic matter (Yadav *et al.*, 2025; Vitale *et al.*, 2020) [19, 21]. An interesting trend from field experiments revealed in this review is the fact that the highest yields do not necessarily correlate with the highest profitability when

dependent on a relatively large amount of applied fertilizers externally supplied. Integrated methods based on 75% or even 100% of recommended dose of fertilizers along with FYM, vermicompost, or biofertilizers have been shown to demonstrate superior or equal economic efficiency owing to improved nutrient-use efficiency and increased residual impact on soil fertility (Patel *et al.*, 2022; Verma *et al.*, 2024) [18, 12]. Moreover, long-term research findings suggest that economic efficiency needs to be evaluated in several consecutive seasons as well. This is due to the fact that INM maintains soil fertility. Economic viability of INM can differ among regions depending on the cost of locally available organic material. When there is availability for seed inoculation and microurishments, adding Zn and biofertilizers may enhance yields without causing much increase in cost. Hence, an economic approach should consider appropriate local fertilizer packages and not a standard formula.

Environmental and sustainability implications

Recent publications increasingly put INM into the context of sustainable intensification as an overall discourse. The sustainability of cereal crop production systems involves the dual task of sustaining agricultural outputs while minimizing environmental harm. Chemical fertilizers alone can lead to nutrient depletion, less carbon in soils, and greenhouse gas emission intensity. In addition to analyzing the productive potential of INM, the environmental co-benefits of integrated nutrient systems are increasingly considered.

Based on long-term research on rice-wheat systems, the use of organic and mineral fertilizers leads to increases in carbon storage in soils and lower emission intensity compared to systems using chemicals alone. Such effects can be attributed to better soil quality, additional carbon from organic sources, and efficient nutrient cycling.

Although the degree of environmental benefit depends on climate, management, and the source of organic inputs, research results point toward a more environmentally

sustainable path compared to solely mineral-based approaches (Rani *et al.*, 2023; Walia *et al.*, 2024) [22, 23].

Table 2: Comparative interpretation of major nutrient sources used in INM for wheat

Input	Primary contribution	Major strength	Main limitation
Mineral fertilizers	Readily available N, P, K	Rapid crop response and precise dose control	Low residual effect; possible imbalance and nutrient loss
FYM	Organic matter and broad nutrient support	Strong effect on soil structure, carbon build-up, and residual fertility	Bulky; variable nutrient content; slower release
Vermicompost	Readily mineralizable organic nutrients	Faster nutrient release; good effect on early growth and microbial activity	Often costlier and less available in bulk
Azotobacter	Biological stimulation and N support	Improved root vigor, establishment, and nutrient-use efficiency	Response depends on soil and inoculum quality
ZnSO ₄	Micronutrient correction	Corrects Zn deficiency and supports enzymatic and reproductive functions	Most effective only where Zn is limiting

Discussion

However, there are enough arguments in the reviewed literature to state that the wheat nutrient management issue should be regarded as a systems challenge, rather than a mere problem of fertilizer dose determination. INM superiority is not related to any individual element of this concept, but instead results from the interactions between mineral fertilizers, organic sources of nutrients, microbial activity, and micronutrients balance.

The second general conclusion of importance for the present research is that the positive effects of INM are particularly evident during system-level analysis of crop production, rather than in single-season yield evaluation. Even though solely based on chemical fertilizers, the crop growth could

sometimes compete with integrated approaches in terms of yield; however, other factors such as soil organic carbon content, microbial activity, and nutrients utilization rate make INM superior.

From the research findings, it is evident that partially replacing mineral fertilizers with organic manure and other biological components is also agriculturally advisable. This is significant in areas where there is an increase in the cost of fertilizers or soil depletion and/or micronutrient deficiencies. Nevertheless, INM must not be perceived as a universal approach such as the percentage replacement rate for all farmers. Its effectiveness is largely dependent on soil fertility, the quality of organic inputs, and the level of skill available.

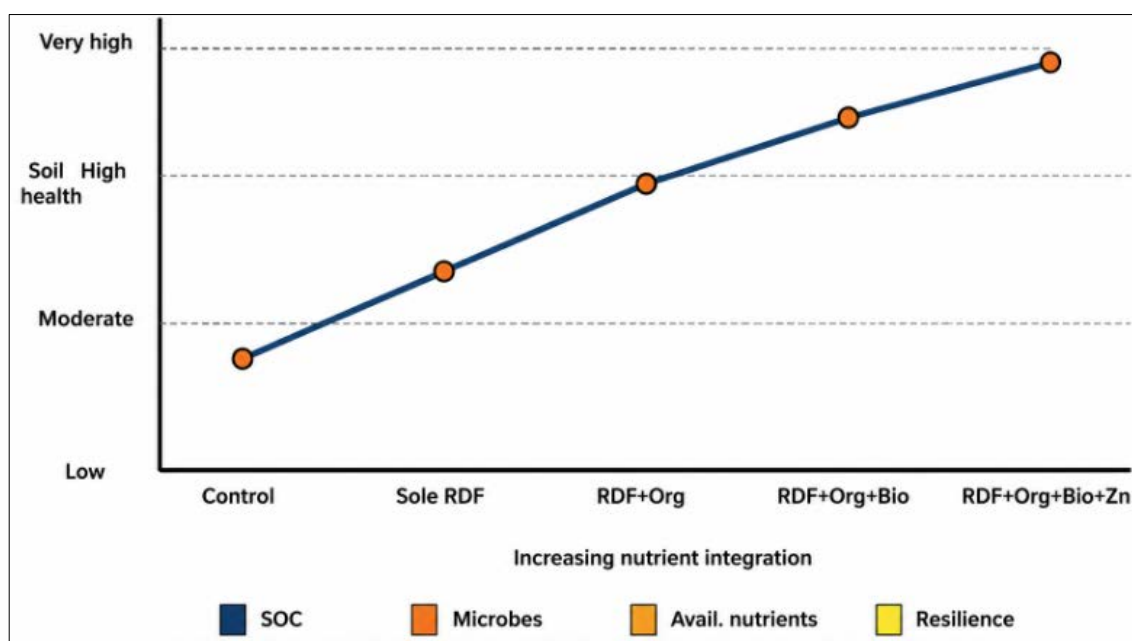


Fig 3: Trend indicating progressive improvement in soil health status with increase in integration of mineral fertilizers, organic manures, biofertilizer and zinc with wheat production systems.

Conclusion

Integrated nutrient management stands out as a promising approach towards maintaining wheat productivity and improving soil health through intensive farming. From the discussion of literature, it is evident that integration of mineral fertilizer, FYM/vermicompost, zinc sulphate, and biofertilizers offers better performance in terms of vegetative characteristics, yield attributes, grain yield, SOC content, nutrient status, and profitability compared to the

application of chemical fertilizers alone. Further evidence from long-term practices has shown the benefits of INM in increasing nutrient use efficiency, soil carbon sequestration, and resilience of the system. Thus, INM can be viewed as a crop-soil systems approach.

Future Scope

Further research should concentrate on site-specific optimization, long-term verification for wheat-based

systems of Uttarakhand, integrating the effects of micronutrients and biofertilizers on grain quality parameters, and process indicators such as soil enzyme activity, shifts in microbial functionality, and nutrient use efficiency.

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