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Soil Nutrient Dynamics and Agronomic Strategies for Sustainable Wheat Production

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Abstract: *Wheat (*Triticum aestivum *L.) is a cornerstone of global food security, yet sustaining its productivity is increasingly challenged by soil degradation, nutrient imbalances, and climate change. This review synthesizes current knowledge on soil nutrient dynamics and agronomic strategies that underpin sustainable wheat production. Macronutrients (N, P, K), secondary nutrients (S), and micronutrients (Zn, Fe, B, Cu, Mn, Mo, Ni) play critical roles in plant physiology, grain quality, and human nutrition, while soil biology particularly arbuscular mycorrhizal fungi enhances nutrient mobilization and stress resilience. Key constraints such as salinity, acidity, compaction, and organic matter loss undermine soil fertility and yield potential. Integrated nutrient management (INM), organic amendments, biofertilizers, precision fertilization, conservation tillage, crop rotations, and biostimulants offer pathways to improved nutrient use efficiency and environmental sustainability. Emerging technologies, including precision agriculture, remote sensing, IoT-based monitoring, and smart farming, provide opportunities to optimize resource use, while genetic innovations support the development of nutrient-efficient and stress-resilient wheat cultivars. Climate change additionally makes nutrient cycle more complex. Therefore, farmers require policies to adapt the agronomic practices. Remaining of research gaps for long term effects of organic, inorganic, biochar and cost-efficient precision technologies which to addresses these gaps that is important for developing resilient wheat production. This will help to secure world's food supply chain.*

Keywords*: Wheat (Triticum aestivum L.), Soil nutrient dynamics, Integrated nutrient management (INM), Sustainable agriculture, Climate change adaptation, Biofertilizers and organic amendments, Precision agriculture, Micronutrients (Zn, Fe, B, Cu, Mn, Mo, Ni), Soil health and fertility, Smart farming technologies*

Introduction

Wheat is a cereal crop and most of countries use it as staple food. It is very important for the global food security because it is source of protein, and micronutrient to the millions of people. Production growth is become challenge due to several reasons; soil health deterioration and climate change. Nutrient of soil is major concerned for long term sustainable agriculture (Imran and Ortas, 2025). Macronutrients are important for growth of wheat, chlorophyll synthesis, root formation, abiotic and biotic stress tolerance and translocation of energy. These macronutrients including nitrogen (N), phosphorus (P) and potassium (K) (Mussarat et al., 2021; Dai et al., 2013). It is critical to supply these nutrients in balance, they may cause deficiency and toxicity to the crops (Tan et al., 2005). On the other hands, both secondary nutrient (Sulfur) and micronutrients like zinc (Zn) and Iron are also crucial for metabolic and physiological functions and grain quality (Pandey et al., 2020; Ali et al., 2022). Soil microbe; Arbuscular Mycorrhizal Fungi (AMF) help in cycling of nutrients through the enhancement of nutrient efficiency uptake especially, N, P (M Tahat et al., 2020; Ingraffia et al., 2019). However, wheat production capacity decline due to losses in soil fertility, low in organic matter, soil compaction and salinity (Srinivasarao et al., 2021; Alburquerque et al., 2013). To enhance soil fertility and increase yield farmer heavily dependent on chemical fertilizers which further made conditions worse that results in soil degradation and polluted the environment (Kamal et al., 2023). So, wheat production needs a sustainable solution that integrated of soil nutrient management with the agronomic methods. The method of integrated nutrient management (INM) which is combination of organic and inorganic materials which apply in field to increase productivity through the conservation of soil fertility (S. Saha et al., 2018; Zhang et al., 2025). There are different approaches like zero or conservative tillage, cover cropping, crop rotation, use of biofertlizers and precision farming. These things further improve soil health and efficiency use of nutrients (Beres et al., 2020; E. Mohammed et al., 2024). The aim of this paper is to deepen understanding on soil nutrient cycle and agronomic practices for sustainable production of wheat. It evaluates the role of both micro and micro nutrients and also role of other management strategies and technological innovations which help in production of wheat. In addition, it also examines the threats of climate change and relevant policies regarding farmer intervention.

2. Soil Nutrient Dynamics in Wheat Production

Soil nutrient dynamic is important in wheat production and quality. Because nutrients have greater impacts on physiochemical functions like enzyme activations, chlorophyll contents, energy transformation and tolerance of stress. So, it is crucial for wheat growth which require balance amount of macro and micro nutrients and also activities of soil microbes (Mohammed et al., 2024).

2.1 Macronutrients

Nitrogen (N)

Nitrogen is a core component of proteins, amino acids, and chlorophyll, making it indispensable for wheat growth and productivity. Adequate nitrogen supply enhances photosynthetic efficiency, plant vigor, and ultimately yield. Field studies report that nitrogen application substantially increases biological and grain yields, with improved chlorophyll content during the tillering phase (Mussarat et al., 2021). However, imbalanced application whether excessive or insufficient—leads to nutrient inefficiency and environmental losses (Tan et al., 2005). Optimizing nitrogen inputs in relation to soil fertility and water availability improves both yield and nitrogen use efficiency (Z. Li et al., 2022).

Phosphorus (P)

Phosphorus plays a crucial role in root development, energy transfer, and nutrient transport. Its deficiency significantly widens the yield gap, while adequate supply improves wheat productivity. Application of phosphorus fertilizers has been shown to enhance biological and grain yields (Mussarat et al., 2021) and can increase yield by 21.2–38.0% in specific agroecological contexts (Liang et al., 2024). Conversely, low phosphorus availability reduces nutrient uptake and compromises long-term soil health (Dai et al., 2013).

Potassium (K)

Although often less emphasized than N and P, potassium regulates enzyme activation, water balance, and tolerance to abiotic stress. It supports yield quality when N and P are sufficient, but its deficiency results in long-term yield decline (Dai et al., 2013). Therefore, it is important to supply balance nutrients ratios between N, P and K that improve the wheat growth (Mussarat et al., 2021).

2.2 Secondary Nutrients

Sulfur (S)

Sulfur (S) is very important for formation of protein and enzymes in wheat crop. It is secondary essential nutrient which require small amount which improve growth and also increase protein in grain of wheat (Pandey et al., 2020). Sulfur is applied with the other fertilizers that make sure for balance supply of nutrients in wheat crop’s higher productivities (Kihara et al., 2017).

2.3 Micronutrients

Zinc (Zn)

Zinc (Zn) is crucial for enzyme and hormone formation. If Zn is applied in sufficient quantities, it would endurance growth leads to hidden hunger in both human and plants (Ramzan et al., 2020; Velu et al., 2017). Deficiency of Zn in wheat is major problem therefore, foliar sprays of Zn can improve quality of wheat grain (Ali et al., 2022).

Iron (Fe)

Iron (Fe) is the part of plant's chlorophyll. It is function as carrier of oxygen which may drictly impact photosynthesis and energy translocation within the plant cells. Application of Fe as a fertilizer that has potential to increase wheat growth and grain quality (Ali et al., 2022).

Other Micronutrients

Boron (B) is crucial for cell wall process and cell division and copper, nickel, molybdenum, and manganese are necessary for activation of enzymes and metabolic activities. All of above nutrients are important for photosynthesis and protein formation. So, can improve wheat grain yield and quality (Monib et al., 2023; Zewide and Sherefu, 2021).

Table: 1. Plant nutrients and their role in Wheat crop

Nutrient	**Role in Wheat**	**Deficiency Symptoms**	**Yield/Quality Impact**	**Management Strategies (with citations)**
Nitrogen (N)	Essential for proteins, amino acids, chlorophyll; boosts photosynthesis and vigor	Yellowing (chlorosis), poor tillering, stunted growth	Low biomass and grain yield; poor grain protein quality	Balanced N fertilization, split application, integration with organic matter *(Mussarat et al., 2021; Li et al., 2022)*
Phosphorus (P)	Key for root growth, energy transfer, nutrient transport	Poor root development, stunted plants, delayed maturity	Significant yield reduction; weaker plants; poor nutrient uptake	Phosphorus fertilizers, placement near roots, integration with organic inputs *(Liang et al., 2024; Dai et al., 2013)*
Potassium (K)	Regulates enzyme activation, water balance, and stress tolerance	Leaf scorching, weak stems, poor grain filling	Reduced grain size, stress susceptibility, poor quality	Balanced NPK fertilization, foliar sprays, residue management *(Dai et*

				al., 2013; Mussarat et al., 2021)
Sulfur (S)	Required for amino acids, proteins, and enzymes; enhances grain protein	Yellowing of young leaves, poor protein content	Reduced protein and yield, weaker plants	Sulfur-enriched fertilizers, gypsum, integration with INM *(Pandey et al., 2020; Kihara et al., 2017)*
Zinc (Zn)	Activates enzymes, supports hormone synthesis, improves grain nutrition	Stunted growth, leaf chlorosis, poor grain zinc content	Lower yields; "hidden hunger" in humans due to low Zn in grains	Soil/foliar Zn application, biofortification *(Velu et al., 2017; Ali et al., 2022)*
Iron (Fe)	Central to chlorophyll formation, respiration, and energy transfer	Interveinal chlorosis, reduced photosynthesis, poor vigor	Reduced yield and grain Fe content; poor nutritional quality	Soil/foliar Fe supplementation, Fe + Zn integration *(Ali et al., 2022)*
Boron (B)	Supports cell wall formation, reproductive tissue development	Poor seed set, sterility, distorted grains	Lower fertility, poor grain quality and yield	Boron fertilizers, seed treatment, foliar spray *(Monib et al., 2023)*
Copper (Cu)	Important for enzyme activation and lignin synthesis	Dieback of shoots, poor grain filling	Weaker plants, reduced yields, poor stress tolerance	Cu fertilizers, foliar applications *(Zewide & Sherefu, 2021)*

Manganese (Mn)	Cofactor for photosynthesis and nitrogen metabolism enzymes	Interveinal chlorosis, reduced growth	Reduced yield, poor grain quality	Mn fertilizers, foliar sprays, soil application *(Monib et al., 2023)*
Molybdenum (Mo)	Supports nitrogen fixation and enzyme activity	Poor nodulation in legumes, reduced protein content	Lower yield, poor nitrogen efficiency	Mo fertilizers, seed priming *(Monib et al., 2023)*
Nickel (Ni)	Involved in urease enzyme function, nitrogen metabolism	Reduced enzyme activity, impaired N metabolism	Reduced yield and poor nitrogen use efficiency	Micronutrient blends, integrated soil fertility management *(Monib et al., 2023)*

2.4 Soil Biology and Nutrient Cycling

Soil microbes and mutualist fungi are playing crucial role in nutrient absorption and cycling. Fungi like Arbuscular mycorrhizal fungi (AMF) having wide spread root system that increase uptake of nitrogen, phosphorus, zinc and iron (Hetrick et al., 1996; Bucking and Kafle, 2015; Ingraffia et al., 2019) which improve water and abiotic stress tolerance that are environmental problems (Abdel-Fattah and Asrar, 2011; Ganugi et al., 2019). In addition, intercropping system further improve efficiency of AMF which capable to transfer the nutrients between crops like wheat and faba bean. However, there are some factors that effects AMF including different verities of wheat, soil phosphorus contents, climatic conditions and microbial interactions. So it is important to decrease chemical use, improve soil and soil microbiology which contributes in sustainable wheat growth (Hetrick et al., 1996; Thirkell et al., 2019).

3. Soil Constraints and Challenges in Wheat Production

In wheat production, soil stress is main obstacle. Soil stress due to salinity, sodicity, compaction and low organic matter contents and microbial activities. These factors have greater potential to decrease wheat growth (Beres et al., 2020).

3.1 Soil Salinity

In arid and semi-arid regions where low precipitation causes higher salinity problem. The most dominated factor is sodium (Na). Higher concentration of Na ions has antagonist effect on the other nutrients that decrease their absorption such as nitrogen, phosphorus, and potassium. Na also degrade the soil structure and resulted lower water retention and microbial functions (Arshad et al., 2024; El-Sharkawy et al., 2024; Liu et al., 2018; Omara et al., 2022). Salinity stress has adverse effects on seed germination, root growth and reduces the plant biomass and grain yield (Bouras et al., 2023; Guerchi et al., 2024). To tackle salinity problems, there are some management practices; gypsum, biochar, compost, organic manure, which improve structure of soil, water holding capacity and nutrients retention (El-Sharkawy et al., 2024). Chemical fertilizer like phosphorus has some potential to decrease salinity impacts by increasing soil nutrients retentions (Bouras et al., 2023). In addition, inoculation with plant growth promoting rhizobacteria (PGPR) which in improvement of soil nutrient, homeostasis, and osmoregulation (Kumar et al., 2023).

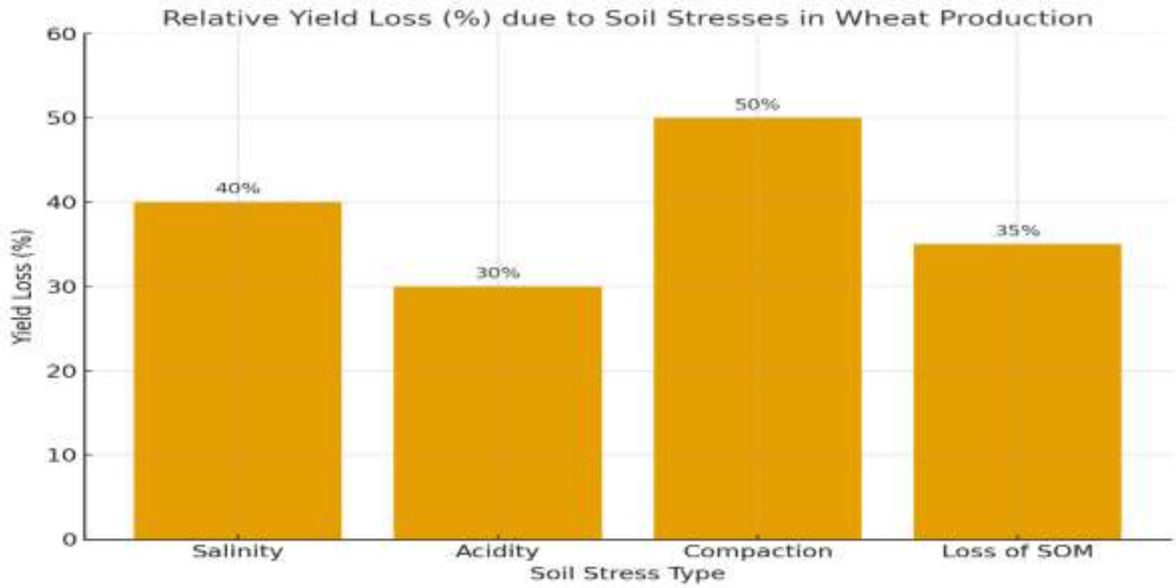
3.2 Soil Alkalinity and Compaction

Soil alkalinity adverse effects on wheat growth because it reduces nutrient absorption and increase the ion toxicity like aluminum (Al) and manganese (Mn). Different amendments strategies to improve soil health like application of bischar that can increase pH of soil and provide nutrients (Alburquerque et al., 2013). Soil compaction is another issue for growth of crops. It is mainly cause by use of heavy machineries that reduce porosity which restrict root growth of crop. In some reports compaction decrease the wheat yield by more than fifty percent (Shaheb et al., 2021). Practices such as subsoiling can mitigate compaction but are energy-intensive and costly. Cover crops like hairy vetch and sunn hemp improve soil aggregation, reduce compaction, and increase soil organic matter, lead to higher wheat yields, particularly under reduced nitrogen application (Blanco-Canqui et al., 2012).

3.3 Loss of Soil Organic Matter

Soil fertility is declining due to reduction in organic matter which impact the wheat production. Soil organic matter is source of plant nutrients. It contains nitrogen, phosphorus and potassium and also helpful in microbial activities, improve soil aggregation and increase the water abosption. Reduction of organic matter has implication for nutrient dynamic, poor soil structure and increase the demand for chemical fertilizers (Panhwar et al., 2018; Spargo et al., 2011; Srinivasarao et al., 2021). Organic matters are crucial for carbon sequestration. If there is low in organic matter content, it would reduce carbon sink into soil. Therefore, increase the impact of climate change (Imran, Amanullah, et al., 2021).

Over reliance on chemical fertilizers instead of of organic matter which adverse consequences of soil health and pollution (Kamal et al., 2023). Hence, to restore the soil organic matter, there should be some management practices including, crop residue, crop rotation, and animal farm manure which is important for sustainable wheat growth.



Graph. 1: Relative Yield Loss Due to Soil Stresses in Wheat Production

4. Agronomic Strategies for Sustainable Wheat Production

Wheat for sustainable production require agronomical practices which improve soil fertility, nutrient use efficiency and decrease the environmental consequences. There are different management methods like integrated nutrient management and precision agricultural technologies.

4.1 Integrated Nutrient Management (INM)

Integrated nutrient management (INM) is a method in which both organic and inorganic materials are used to improve soil fertility for crop yield sustainability. It has been showed in research that INM has reduce nutrient depletion and enhance soil health conditions as compare to over use of inorganic fertilizers (S. Saha et al., 2018). Green manure and crop residues are also source of organic matter which can increase nutrient availability and reduction the chemical fertilizers which helpful for sustainable ecosystem (Zhang et al., 2025).

4.2 Organic Amendments and Biofertilizers

Organic amendments are application of organic matter that includes compost, vermicompost, animal farm manure, poultry manure and crop residues. These amendments improve soil health condition; soil structure, compaction and microbial functions. Vermicompost may increase nitrogen, phosphorus and potassium while decrease absorption of sodium in saline soil (Zaghloul et al., 2024). There is more effective when both organic and inorganic fertilizers are applied that improve wheat yield and also enhance soil fertility (Zhao et al., 2024). On the other hand, bio fertilizer are those fertilizers that contains nitrogen fixation, phosphate solubilizing bacteria, fungi. This improve nutrient efficiency and abiotic stresses. Soil nutrient can also be increase by crop rotation such wheat and maize, because it helps in elevation of microbial activities (A. Ali et al., 2024). Bio fertilizers are ecofriendly as compare to the chemical fertilizers (Bhardwaj et al., 2014; Khan et al., 2024).

4.3 Fertilizer Innovations

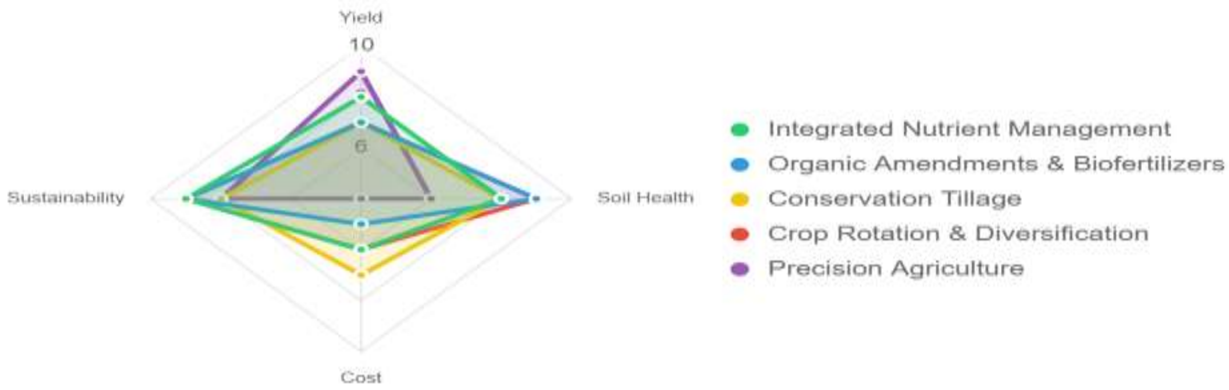
In saline soils balance fertilization is important for soil and crops. When nitrogen and phosphorus applied in combine that has significantly enhance wheat grain yield (Hou et al., 2025). In some new innovations that fertilizers contain different enzymes; urease and nitrification inhibitors. These improve nutrient use efficiency and decline losses, so up to 29 percent grain production reported in contrast to conventional use of urea (Y. A. Mohammed et al., 2016). Another new technique site specific nutrient management is also increasing yield and decrease the fertilizer application input (E. Mohammed et al., 2024; S. Li et al., 2022). In addition, plant growth promoting bacteria like *Azospirillum brasilense* can also increase nutrient uptake efficiency and yield (Galindo et al., 2022).

4.4 Conservation Tillage and Irrigation

Conservation tillage is agronomical practices that minimum application of tillage. In conservation tillage it may be no tillage for improvement of soil structure, conserve soil organic matter, increase soil water retention. In arid region where high temperature, then no tillage application with combine cover cropping or mulching to conserve soil water and increase wheat production (H. Li et al., 2007; Adil et al., 2022). Conservation tillage has higher yield than the conventional tillage (Khorami et al., 2018). Irrigation is also one main factor for wheat or any other crop production. It is necessary, a good efficient irrigation method for arid regions because it would increase water use efficiency and maintain crop yield. (Tahir et al., 2024). So, integration of nitrogen fertilizer with the good irrigation system which further improve wheat production and reduce environmental losses

4.5 Crop Rotation and Diversification

Crop rotation is crucial for soil nutrient cycling and soil microbial activities. When leguminous crops that have characteristics of nitrogen fixation. These crops fix nitrogen from environment into the soil and then crop the nitrogen in symbiotic relation. This reduces over reliance on the chemical fertilizers (Zou et al., 2024). Diversifying cropping system is also beneficial for soil organic matter content and as well for microbes of soil (L. Sun et al., 2023; Yang et al., 2024). Moreover, crop rotation is helpful pest and disease attacks which decrease reliance on pesticides that indirectly significant for ecological sustainability (Shah et al., 2021). Crop rotation and diversification are economical beneficial because higher profit gain from higher production as compared to monoculture cropping system (Volsi et al., 2022). In addition, crop rotation improves soil structure that lead to increase the water and nutrients retention (Baldwin-Kordick et al., 2022).



Graph: 2. Integrated Nutrient Management (INM)

4.6 Biostimulants and Plant Growth-Promoting Rhizobacteria (PGPR)

Biostimulants are substances that stimulate crop growth by improving nutrient retention and their tolerance towards abiotic stress. Biostimulants containing; organic extract and microbial products (Hamid et al., 2021). Plant growth promoting bacteria (PGPR) that increase wheat production capacity by fixing nitrogen, solubilize phosphorus phytohormones and pathogen suppression (Hayat et al., 2012; Jan et al., 2025). When these biostimulants are used in combination with nitrogen fertilzers then there is more production of crop because it increases nutrient uptake and plant biomass (Abbasi et al., 2011;

Nguyen et al., 2018). PGPR is as biostimulants and control pathogen by producing enzyme lytic which reduce use of synthetic chemical fertilizers (Ehinmitan et al., 2024).

4.7 Genetic Improvements for Nutrient Use Efficiency

Using of genetic modified crop that increase the nutrient retention which essential for long tern of sustainable goal. Genetic innovation technology has improved nitrogen use efficiency and salt tolerance by producing different varieties of crop for low nutrient supply (Kenneth et al., 2019; W. Sun et al., 2024). Different wheat varieties are created by biotechnological method (Arif et al., 2025; Hossain et al., 2021). These methods including molecular breeding and CRISPR based editing. These varieties of wheat are more resistant nutrient stress and higher production in yield (Perez-Mndez et al., 2021).

5. Climate Change and Nutrient Dynamics

Climate change is change of weather condition for longer period of time in a particular area. It has been intensified since few decades due to carbon emission into atmosphere which causes global warming (Srivastav et al., 2021). This change in average global temperature has grater implication for agricultural crop like wheat. Climate change threat to wheat production because it changing the nutrient cycle in soil, effects on crop physiological functions. Climate change also induce drought and high heat intensity. Therefore, there should be some agronomic measures to tackle the low production under climatic stress (Nguyen et al., 2018).

5.1 Impacts of Climate Change on Soil Nutrients and Wheat Productivity

Drought Stress

Drought is major challenge for wheat production in arid region. It is low moisture of soil which decline nutrient solubility and retention. Lower water availability causes nutrient imbalance, decrease soil fertility and loss of yield (Srivastav et al., 2021; Tan et al., 2005). It accelerates nitrogen losses which further decline wheat yield (Viancelli & Michelon, 2024).

Heat Stress

High temperatures increase decomposition of organic matter and losses of nutrients which causes greater nutrient losses and decline in soil fertility (Alburquerque et al., 2013). High temperature enhance evaporation and transpiration and nutrient deficiencies (Srivastav et al., 2021).

Waterlogging

Excessive soil moisture from waterlogging causes nutrient leaching and reduces availability of nitrogen and potassium. It also lowers soil aeration, inhibiting microbial activity and nutrient cycling, which negatively impacts wheat growth (Singh & Sidhu, 2014; Teng et al., 2024).

5.2 Adaptive Agronomic Strategies

Conservation agriculture practices such as zero or minimum tillage, residue management, and cover cropping enhance soil health and nutrient retention under climate stress (Singh & Sidhu, 2014). Biochar improves soil nutrient retention, acts as a carbon sink, and sustains yields under variable conditions (Alburquerque et al., 2013; Jan et al., 2025). Fertilizers with slow-release properties and precision farming approaches ensure nutrient supply aligns with crop demand, minimizing losses (Viancelli and Michelon, 2024). Breeding heat- and drought-tolerant wheat varieties through molecular techniques, including CRISPR-Cas, supports resilience under climate variability (arif et al., 2025; Hossain et al., 2021). Genetic diversification using landraces and historical varieties provides valuable resources for stress tolerance (P erez-M ndez et al., 2021). Bio- inoculant are those microbes that are helpful for nutrient uptakes and prevent pest attack during the unfavorable climatic conditions (Campos-Avelar et al., 2023). Smart agriculture technology that can address crop stress during the water and nutrient deficiencies. Including of remote sensing related to soil moisture detectors. So these could benefit the farmers to assess in real time monitoring, irrigation and fertilization (Skendžić et al., 2023; Diacono et al., 2012; Hartono et al., 2024). It depends upon the region. Therefore, specific regions require some specific strategies to tackle the local soil and climatic conditions (Pequeno et al., 2021).

6. Technological Innovations for Sustainable Nutrient Management

In precision farming that has been reshaping nutrient management system for production of crops especially wheat. New technology is being used for growing crops. Including digital tools, soil moisture sensors which are offering new opportunities to improve utilization of resources and decrease ecological impacts.

6.1 Precision Agriculture

Precision agriculture is advancing farming system by providing new technological tools and methods for optimization of nutrients use efficiencies and minimize the production losses.

Precision agriculture enables nutrient application tailored to the spatial and temporal variability of fields. This site-specific approach improves nutrient use efficiency while minimizing losses (Li et al., 2022). In similar way organic material is mixed with the fertilizers that resulted positive yield in wheat crop and also conserved soil fertility (Mohammed et al., 2024). There are several smart farming technological tools that further improved soil fertilizer applications through the real time data analysis. These things improve nutrient management and environmental risks because reduces the nutrients runoff. Wheat crop high yield can be achievable at lower negative impact on ecology if these tools are integrated with agronomic practices (Reza et al., 2025; Jan et al., 2025).

6.2 Remote Sensing and IoT-Based Soil Monitoring

Remote sensors technologies are helpful for farming because they provide early warning and real time data of detection of crop nutrient deficiencies and water stress. High resolution images of drone technology infrared sensors give precision data of crop nutrients status and pest attacks. These technologies are important for fertilizer application in more efficient way (Diacono et al., 2012). The wireless-based sensors are used for real time measurement of soil moisture, temperature, pH and nutrient status in soil and as well as in the environment (Reshma et al., 2020; Hartono et al., 2024). Real time data collections help the farmers make decision about the fertilizer and pesticide and irrigation application at suitable concentrations and time. These systems predicted to decrease the pesticide and fertilizer application by 10 to 20 percent and also by crop yield by similar margin (Ivanovich Vatin et al., 2024). These smart technological tools are not only improving input use efficiency but also decrease the production cost and as well ecological footprints. So farmers can take advantages from these real time data that allows for optimization of wheat crop yield and efficient use of nutrients.

6.3 Smart Farming Innovations

Smart farming is using more advance agriculture technology including reboots, artificial intelligence and drones in fields. Drones are being utilized for purpose of high-resolution images and cover vast area of the field and also drones use sensors for detection of pest attacks and nutrients deficiencies of crop. On other hands reboots are revolutionized the agriculture with accurate fertilizer and pesticide concentration applications which reduces labor cost and ecological effects (Mishra, 2021; P. Saha et al., 2023). The nexus of remote sensors and artificial intelligence which provides precision decision making process for farmers. These technological tool assist farmers for site specific nutrient managements and early warning stress detections. If these new advance tools are used that would enhance the wheat productivity and promote resource use efficiency and climate smart agriculture practices (Skendžić et al., 2023).

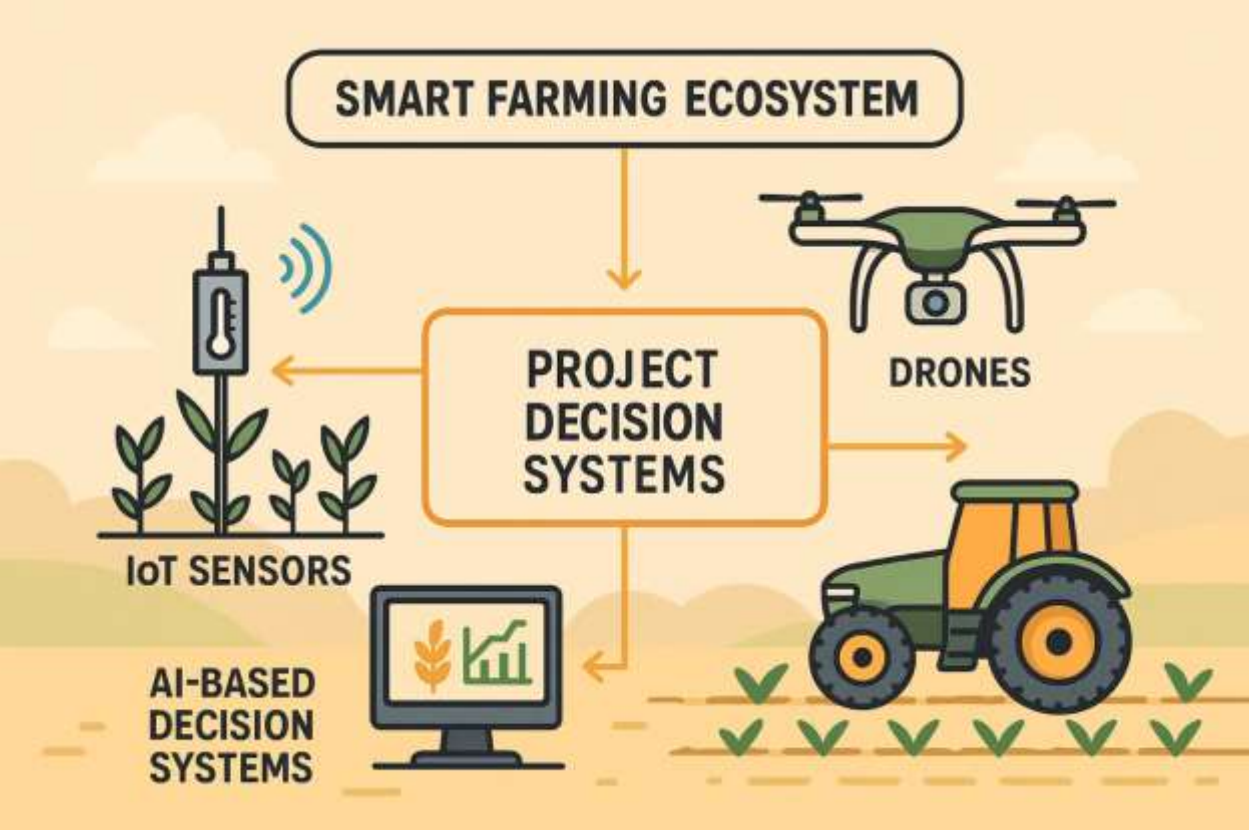


Fig:1. Smart Farming Integrates Advanced Technologies

7. Policy and Farmer-Level Interventions

Wheat production requires sustainable approaches at both policy and farmer levels. Research and technologies proved new advance tools but it depends upon the effectiveness of policies implementation and engagement of farmers.

7.1 Policy-Level Strategies

Policies implementation re very important for sustainable agriculture production. Government promotes eco-friendly farming systems by providing facilities for crop rotation, new certified wheat verities for ensuring stable growth at minimum ecological cost (Rebouh et al., 2023). By providing economic supports for precision farming technological tools is another mile stone step of government. Because this tool would improve fertilizer application and irrigation and also control pest attacks which indirectly reduces the ecological degradations (Gawande et al., 2023; H et al., 2024). Additionally, by investing in smart carbon tracking technology can help the farmers to lower their carbon footprints (Agbelusi et al., 2024). Promote smart agriculture technologies like drones, moisture sensors and reboots. These can further enhance use efficient and growth yield. Policies need partnership between government and private stakeholders to overcome adaptation barriers and make sure broad implementation of the policies (Das, 2024).

7.2 Farmer-Level Strategies

At the farmer stage, vocational training of farmers is one of the best way for adaptation of sustainable practices. Raise awareness programs regarding conservation of agriculture and nutrient efficient use which help farmers to protect soil health condition and decrease carbon emission (Di Bene et al., 2022). Climate smart agriculture adoptability requires efficient irrigation practices, poly cropping system and conservative tillage practices which increase resilience to climate change (Bhanuwanti et al., 2024). Farmers may use carbon farming strategies likes use of compost, covering crop and zero tillage for enhancement soil fertility and decrease the greenhouse gases emissions (Avasiloaiei et al., 2023). At famer level, the use of precision technologies improves nutrient use efficient and pathogen management (Agbelusi et al., 2024; Jan et al., 2025).

8. Research Gaps and Future Directions

Understanding soil nutrient dynamics and agronomic practices for production of wheat. However, there are many gaps that restricted progress for the long-term sustainability. Therefore, address these remaining gaps need interdisciplinary research which link soil science, crop genetic and agronomy.

8.1 Soil Amendments and Biochar Interactions

Plant and microbe's interactions and biochar's role as a nutrient cycling are remained poorly understand. Some studies suggested that concentration of phosphorus in biochar effect the growth of mycorrhiza fungi and uptake of nutrients but it depends upon the characteristics of biochar (Solaiman et al., 2019). In future, the research should identify how various kinds of biochar effects soil properties and microbial symbiosis under different agro ecological conditions.

8.2 Nanotechnology and Soil Health

Nano based fertilizers like zinc oxide nano particles showed potential which enhance wheat growth and nutrient uptake. But it is fully unknown interactions between soil microbes and soil organic matters (Verma et al., 2024).

8.3 Integration of Organic and Inorganic Nutrients

Both organic and inorganic fertilizers are important but optimal ration of application for wheat crops is still undefined. Therefore, it needs research to find out sustainable combination which increase soil fertility efficient use of nutrients for sustainable yield (Hazra et al., 2014; Venkatesh et al., 2017; Lu et al., 2024).

8.4 Crop Rotations and Residue Management

Wheat crop rotation with the pulse which improve soil health and nutrients but their contribution under various management strategies is still not clear (Hazra et al., 2014). In similar ways crop remains increase nutrient retentions but can causes nitrogen unavailable and moisture losses. There is need more research to optimized the crop residue management that lower negative impact and increase the benefits (Kong, 2013; Jan et al., 2025).

8.5 Precision Agriculture and Cost Efficiency

Using precision agriculture technologies for fertilization that improve nutrient uptake, cost effective and small holding farmers remain uncertain. Research required more focus on untreint management zones and development of cheapest and affordable technologies to spread adaptation among those who have limited resources (Ameer et al., 2022; Jan et al., 2025).

Conclusion

In a nutshell sustainable wheat production merely depend on the understanding of soil nutrient dynamics and management practices. The evidence highlights that balanced application of macro-, secondary, and micronutrients, supported by soil biological processes, is indispensable for maintaining productivity and grain quality. However, soil degradation through salinity, acidity, compaction, and organic matter loss continues to threaten long-term fertility. Integrated nutrient management, organic amendments, precision fertilization, conservation tillage, and crop diversification offer viable solutions to enhance nutrient use efficiency while mitigating environmental impacts. Technological innovations such as remote sensing, IoT-based soil monitoring, and smart farming combined with genetic improvements in nutrient-use efficiency, provide powerful tools for future resilience. Yet, unresolved challenges remain regarding the long-term effects of biochar, nanomaterials, and scalable adoption of precision technologies in resource-limited systems. Strengthening farmer capacity, supportive policies, and region-specific adaptive practices will be critical to ensure that wheat production systems remain productive, sustainable, and climate-resilient. Advancing interdisciplinary research that links soil science, agronomy, biotechnology, and digital agriculture will be key to securing global wheat supplies in the face of population growth and climate uncertainty.

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