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Nitrogen and phosphorus management in wheat (*Triticum aestivum* L.): Impacts on growth, yield and nutrient-use efficiency

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Abstract

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops worldwide and plays a crucial role in maintaining global food and nutritional security. However, increasing population pressure, declining soil fertility, and the limited availability of natural resources have intensified the need for efficient nutrient management practices to sustain wheat production. Among the essential plant nutrients, nitrogen (N) and phosphorus (P) are the two principal macronutrients that regulate crop growth, grain yield, grain quality, and nutrient-use efficiency. Nitrogen is indispensable for chlorophyll biosynthesis, protein synthesis, and photosynthetic activity, whereas phosphorus plays a vital role in energy transfer, root development, and reproductive processes. The balanced application of these nutrients promotes plant growth, biomass accumulation, yield attributes, and grain productivity by enhancing several physiological and biochemical functions. Recent advances in precision nutrient management, conservation agriculture, improved root architecture, and nutrient-use efficiency have provided promising opportunities to enhance fertiliser recovery while reducing environmental impacts. This review discusses the physiological functions of nitrogen and phosphorus, their interaction in regulating wheat growth and productivity, their influence on nutrient-use efficiency and root development, and recent strategies for achieving sustainable nutrient management in wheat production systems.

Keywords: Wheat, nitrogen, phosphorus, nutrient-use efficiency, nitrogen-phosphorus interaction, conservation agriculture, precision nutrient management

Introduction

Wheat (*Triticum aestivum* L.) is one of the most widely cultivated cereal crops and serves as a staple food for a large proportion of the global population. Owing to its high calorific value, considerable protein content, and adaptability to a wide range of agro-climatic conditions, wheat contributes significantly to global food and nutritional security (Mălinaş *et al.*, 2022; Xu *et al.*, 2024) ^[56, 38]. As the global population continues to increase, ensuring sustainable wheat production under the constraints of limited natural resources has become a major challenge for modern agriculture (Xu *et al.*, 2024) ^[56]. In India, wheat is the second most important cereal crop after rice and constitutes a major component of the national food production system. The North Western Plains Zone (NWPZ) contributes a substantial proportion of the country's total wheat production because of its favourable climatic conditions, improved cultivars, and advanced crop management practices (Mohan *et al.*, 2024) ^[40]. Nevertheless, continuous cultivation, deterioration of soil fertility, and imbalanced fertiliser application have emerged as major constraints affecting the long-term sustainability and productivity of wheat cultivation (Godebo *et al.*, 2021; Swapnavahini *et al.*, 2022) ^[19].

Nitrogen and phosphorus are recognised as the two most critical yield-limiting macronutrients in wheat production. Nitrogen is an essential constituent of amino acids, proteins, nucleic acids, enzymes, and chlorophyll, whereas phosphorus plays a fundamental role in ATP synthesis, energy transfer, root growth, and reproductive development (Ali *et al.*, 2020; Mălinaş *et al.*, 2022) ^[1, 38]. Therefore, maintaining an adequate supply of these nutrients is essential for achieving optimum plant growth, biomass accumulation, and grain yield.

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Balanced fertilisation with nitrogen and phosphorus enhances nutrient uptake, physiological efficiency, dry matter production, and yield formation. However, the efficiency of applied fertilisers remains relatively low because substantial quantities of nitrogen are lost through leaching, volatilisation, and denitrification, whereas phosphorus availability is frequently restricted by fixation reactions in the soil (Xu *et al.*, 2024; Hegde *et al.*, 2007)^[56]. Consequently, improving fertiliser-use efficiency through balanced nutrient management, conservation agriculture, and precision nutrient management technologies has become a key priority for achieving sustainable wheat production (Bhattacharya *et al.*, 2023)^[8].

Role of Nitrogen and Phosphorus in Wheat Growth and Development Nitrogen is required in greater quantities than any other essential mineral nutrient and is widely recognised as the primary nutrient governing wheat productivity (Mălinaş *et al.*, 2022; Xu *et al.*, 2024)^[56, 38]. It plays a fundamental role in chlorophyll biosynthesis, protein formation, photosynthesis, and numerous enzymatic reactions that regulate plant metabolism. Wheat plants predominantly absorb nitrogen as nitrate (NO_3^-) and ammonium (NH_4^+), which are subsequently assimilated into amino acids and proteins that support normal growth and development (Li *et al.*, 2023)^[34].

Adequate nitrogen nutrition stimulates vigorous vegetative growth by enhancing leaf expansion, tiller production, and dry matter accumulation. Increased chlorophyll content improves photosynthetic efficiency, resulting in greater biomass production and higher grain yield (Xu *et al.*, 2024)^[56]. Furthermore, nitrogen has a direct influence on grain protein concentration and therefore contributes significantly to both grain quality and overall crop productivity (Mălinaş *et al.*, 2022)^[38].

Phosphorus is another indispensable macronutrient that plays a central role in plant growth and metabolic activities (Ali *et al.*, 2020; Dugassa *et al.*, 2019)^[1, 12]. It forms an essential component of ATP, nucleic acids, and phospholipids and participates in energy transfer, respiration, photosynthesis, and nutrient translocation within the plant. An adequate supply of phosphorus encourages root elongation, branching, and biomass development, thereby improving the plant's capacity to absorb water and nutrients efficiently from the soil (Godebo *et al.*, 2021)^[19].

The availability of phosphorus is particularly critical during the early stages of crop establishment. Sufficient phosphorus nutrition promotes rapid seedling establishment, vigorous root proliferation, and improved early plant vigour, all of which contribute to enhanced crop performance during later developmental stages (Ali *et al.*, 2020)^[1]. Conversely, phosphorus deficiency restricts root development, delays crop maturity, and adversely affects grain formation, ultimately reducing crop productivity.

Numerous investigations have demonstrated that balanced nitrogen and phosphorus fertilisation significantly improves plant height, tiller production, leaf area development, and dry matter accumulation (Ali *et al.*, 2020; Ullah *et al.*, 2018; Dugassa *et al.*, 2019)^[1, 51, 12]. Nitrogen primarily promotes vegetative growth by stimulating cell division and chlorophyll formation, whereas phosphorus supports energy metabolism and facilitates efficient nutrient uptake. Their combined application creates favourable physiological conditions that enhance biomass production and maximise yield potential.

Nitrogen deficiency is commonly characterised by chlorosis of older leaves, poor tillering, weak vegetative growth, and reduced grain yield potential. In contrast, phosphorus deficiency results in inadequate root development, delayed plant growth, and poor

reproductive performance (Mălinaş *et al.*, 2022; Ali *et al.*, 2020)^[1, 38]. Consequently, maintaining an optimum and balanced supply of both nutrients is essential for sustaining healthy crop growth and achieving maximum wheat productivity.

The beneficial effects of nitrogen and phosphorus are not limited to vegetative development but also extend to the reproductive phase of the crop. Adequate nutrient availability promotes spike initiation, grain setting, and grain filling, thereby increasing grain yield and improving the harvest index (Ali *et al.*, 2020; Xu *et al.*, 2024)^[1, 56]. These findings emphasise the importance of integrated nitrogen and phosphorus management for achieving sustainable, resource-efficient, and high-yielding wheat production systems.

Nitrogen × Phosphorus Interaction and Nutrient-Use Efficiency in Wheat

Nitrogen and phosphorus are the two principal macronutrients governing wheat productivity, and their interaction plays a crucial role in regulating plant growth, nutrient acquisition, physiological processes, and grain production (Dugassa *et al.*, 2019; Li *et al.*, 2023)^[12, 34]. Although each nutrient independently contributes to crop performance, their balanced application generally produces superior results because they complement one another in several metabolic and developmental processes (Swapnavahini *et al.*, 2022; Godebo *et al.*, 2021)^[19].

The interaction between nitrogen and phosphorus operates through multiple physiological and biochemical mechanisms. Adequate phosphorus availability promotes root elongation, branching, and biomass development, thereby enhancing the ability of wheat plants to absorb nitrogen from the soil (Ali *et al.*, 2020; Dugassa *et al.*, 2019)^[1, 12]. Conversely, sufficient nitrogen supply stimulates vigorous vegetative growth and increases the crop's demand for phosphorus, thereby improving phosphorus uptake and utilisation (Li *et al.*, 2023)^[34]. Consequently, balanced fertilisation enables more efficient nutrient absorption and utilisation than the application of either nutrient alone.

Root development is one of the primary mechanisms through which phosphorus improves nitrogen utilisation. Well-developed root systems with greater surface area and extensive soil exploration enable plants to absorb larger quantities of nitrogen and other essential nutrients (Ranjan *et al.*, 2019; Godebo *et al.*, 2021)^[45, 19]. In contrast, phosphorus deficiency restricts root growth and limits nitrogen uptake, even when sufficient nitrogen is present in the soil (Li *et al.*, 2023)^[34].

Nitrogen and phosphorus also interact by influencing photosynthesis and biomass production. Nitrogen is essential for chlorophyll formation and the synthesis of photosynthetic enzymes, whereas phosphorus provides the energy required for carbon assimilation and other metabolic activities through ATP production (Mălinaş *et al.*, 2022; Ali *et al.*, 2020)^[1, 38]. The simultaneous availability of both nutrients enhances photosynthetic efficiency, dry matter accumulation, and assimilate production, ultimately leading to increased crop productivity (Li *et al.*, 2023)^[34].

Several studies have reported significant improvements in plant height, tiller production, biomass accumulation, and grain yield when nitrogen and phosphorus are applied together compared with nutrient-deficient or unfertilised conditions (Dugassa *et al.*, 2019; Swapnavahini *et al.*, 2022)^[12]. Balanced nutrient management also promotes spike development, grain setting, grain filling, and overall reproductive efficiency, thereby increasing both grain yield and biological yield (Ali *et al.*, 2020; Godebo *et al.*, 2021)^[1, 19]. These findings clearly demonstrate the

synergistic relationship between nitrogen and phosphorus in wheat production.

In modern agriculture, nutrient-use efficiency has become increasingly important because rising fertiliser costs and environmental concerns require greater crop productivity from every unit of nutrient applied (Mălinaş *et al.*, 2022; Xu *et al.*, 2024) ^[56, 38]. Nutrient-use efficiency refers to the ability of a crop to absorb, transport, assimilate, and utilise nutrients effectively for biomass production and economic yield (Ranjan *et al.*, 2019) ^[45].

Nitrogen-use efficiency (NUE) is generally divided into two major components: nitrogen uptake efficiency and nitrogen utilisation efficiency. Nitrogen uptake efficiency describes the plant's ability to acquire nitrogen from the soil, whereas nitrogen utilisation efficiency reflects its capacity to convert absorbed nitrogen into grain yield (Ranjan *et al.*, 2019; Xu *et al.*, 2024) ^[45, 56]. However, a considerable proportion of applied nitrogen is frequently lost through leaching, volatilisation, and denitrification, resulting in poor fertiliser recovery and increased environmental pollution (Mălinaş *et al.*, 2022; Xu *et al.*, 2024) ^[56, 38].

Similarly, phosphorus-use efficiency remains relatively low because a substantial proportion of applied phosphorus becomes unavailable owing to fixation by calcium, iron, and aluminium compounds present in the soil (Godebo *et al.*, 2021; Dugassa *et al.*, 2019) ^[19, 12]. Consequently, only a limited fraction of applied phosphorus is utilised by the crop during a single growing season. Improving phosphorus-use efficiency therefore depends largely on enhanced root development, greater root proliferation, and efficient nutrient transport mechanisms (Ranjan *et al.*, 2019) ^[45]. Considerable genetic variation in nutrient-use efficiency has been reported among different wheat cultivars. Genotypes possessing deeper and more extensive root systems, greater root biomass, and enhanced nutrient acquisition capacity generally exhibit superior fertiliser recovery and maintain higher productivity under nutrient-limited conditions (Ranjan *et al.*, 2019; Mălinaş *et al.*, 2022) ^[45, 38]. Such variability provides valuable opportunities for breeding nutrient-efficient wheat cultivars capable of producing high yields with reduced fertiliser inputs.

Several agronomic strategies have been developed to improve nutrient-use efficiency in wheat cultivation. Split application of nitrogen according to crop demand enhances fertiliser recovery and minimises nutrient losses (Xu *et al.*, 2024) ^[56]. Likewise, integrated nutrient management involving the combined application of inorganic fertilisers, organic manures, and biofertilisers improves nutrient availability, enhances soil fertility, and increases fertiliser-use efficiency (Gurwinder Singh *et al.*, 2018; Godebo *et al.*, 2021) ^[21, 19].

Conservation agriculture and precision nutrient management have also emerged as effective approaches for improving nutrient-use efficiency. Practices such as residue retention, reduced tillage, site-specific nutrient management, and sensor-based fertiliser recommendations improve synchronisation between nutrient supply and crop demand, thereby minimising nutrient losses and increasing fertiliser recovery (Bhattacharya *et al.*, 2023; Xu *et al.*, 2024) ^[8, 56]. In addition to improving crop productivity, these approaches contribute significantly to long-term environmental sustainability.

Overall, balanced nitrogen and phosphorus management remains fundamental for enhancing nutrient-use efficiency, improving fertiliser recovery, and ensuring sustainable wheat production. Future progress will depend on integrating improved agronomic practices, nutrient-efficient cultivars, and precision nutrient management technologies to maximise productivity while conserving natural resources.

Root Traits, Growth Attributes and Yield Formation in Wheat root systems play a pivotal role in nutrient acquisition and represent one of the most important determinants of growth, productivity, and nutrient-use efficiency in wheat cultivation (Ranjan *et al.*, 2019; Godebo *et al.*, 2021) ^[45, 19]. Since the absorption of water and mineral nutrients begins at the root–soil interface, the architecture and efficiency of the root system largely determine the plant's capacity to utilise available soil resources. Consequently, root-related traits have become important targets in breeding and nutrient management programmes aimed at improving wheat productivity and fertiliser-use efficiency (Li *et al.*, 2023; Mălinaş *et al.*, 2022) ^[34, 38].

Among the various root characteristics, root length, root surface area, root density, and root biomass are the principal factors governing nutrient acquisition. Wheat genotypes possessing extensive and well-developed root systems can explore a larger volume of soil, thereby improving access to water and essential nutrients beyond the immediate rhizosphere (Ranjan *et al.*, 2019) ^[45]. Such root characteristics are particularly advantageous for phosphorus acquisition because phosphorus has limited mobility in most soils. Greater root proliferation and branching therefore enhance phosphorus uptake and improve crop performance under nutrient-deficient conditions (Godebo *et al.*, 2021; Ali *et al.*, 2020) ^[19, 1].

The availability of nitrogen and phosphorus has a profound influence on root development and nutrient absorption. Adequate phosphorus nutrition stimulates root elongation, branching, and biomass accumulation, thereby strengthening the plant's ability to acquire nutrients from the soil (Ali *et al.*, 2020; Dugassa *et al.*, 2019) ^[1, 12]. Likewise, sufficient nitrogen supply supports root metabolic activity and facilitates efficient nutrient transport, resulting in improved nutrient uptake. Consequently, balanced fertilisation promotes the development of an efficient root system capable of sustaining higher crop productivity (Xu *et al.*, 2024) ^[56].

Growth attributes such as plant height, tiller production, leaf area expansion, and dry matter accumulation are highly responsive to nitrogen and phosphorus availability (Ullah *et al.*, 2018; Ali *et al.*, 2020) ^[51, 1]. These parameters are widely recognised as reliable indicators of crop vigour and have a direct influence on the yield potential of wheat. An adequate nutrient supply enhances physiological activity, promotes cell division, and stimulates vegetative development, ultimately resulting in greater biomass accumulation and improved crop performance (Mălinaş *et al.*, 2022; Xu *et al.*, 2024) ^[56, 38].

Plant height is commonly considered an important indicator of crop growth and nutritional status. Nitrogen promotes stem elongation and vegetative development through its role in protein synthesis and chlorophyll formation, whereas phosphorus supports cell division and energy transfer processes that are essential for normal plant growth (Ali *et al.*, 2020; Xu *et al.*, 2024) ^[1, 56]. Several investigations have reported significant increases in plant height following balanced nitrogen and phosphorus fertilisation compared with nutrient-deficient conditions (Dugassa *et al.*, 2019; Ullah *et al.*, 2018) ^[12, 51].

Tillering is another critical growth parameter because the number of productive tillers directly influences spike density and final grain yield. Nitrogen enhances tiller initiation and survival by stimulating vegetative growth and assimilate production, while phosphorus promotes early root development and improves nutrient acquisition (Ali *et al.*, 2020; Ullah *et al.*, 2018) ^[1, 51]. Consequently, balanced fertilisation provides a stronger foundation for increased grain production by improving the development and survival of productive tillers (Dugassa *et al.*, 2019) ^[12].

Leaf area development and dry matter accumulation are closely associated with photosynthetic efficiency and overall crop productivity. Nitrogen promotes chlorophyll synthesis and leaf expansion, thereby improving light interception and carbon assimilation (Xu *et al.*, 2024) ^[56]. Phosphorus, on the other hand, facilitates energy metabolism and the translocation of assimilates, supporting continuous biomass production throughout the crop growth cycle (Ali *et al.*, 2020) ^[1]. As a result, balanced nutrient management significantly enhances dry matter accumulation and overall plant growth (Bhattacharya *et al.*, 2023) ^[8].

The beneficial effects of balanced nitrogen and phosphorus nutrition ultimately contribute to improvements in yield and its associated components. Grain yield in wheat is determined by several yield-contributing traits, including the number of productive tillers, spike length, grains per spike, thousand-grain weight, and harvest index (Dugassa *et al.*, 2019; Xu *et al.*, 2024) ^[12, 56]. The development of these yield components depends largely on an adequate nutrient supply throughout the crop growth period.

Nitrogen contributes to yield formation by enhancing vegetative growth, photosynthetic efficiency, and assimilate production. Improved tiller survival increases the number of productive spikes per unit area, thereby enhancing grain yield (Ullah *et al.*, 2018; Xu *et al.*, 2024) ^[51, 56]. In contrast, phosphorus promotes reproductive development by improving root growth, nutrient uptake, and energy transfer processes (Ali *et al.*, 2020) ^[1]. Adequate phosphorus nutrition supports spike initiation, grain setting, and grain filling, thereby increasing the crop's yield potential.

Several studies have demonstrated that balanced nitrogen and phosphorus fertilisation significantly improves spike length, grains per spike, and thousand-grain weight (Ali *et al.*, 2020; Dugassa *et al.*, 2019) ^[1, 12]. Improved nutrient availability enhances reproductive efficiency and facilitates the effective partitioning of assimilates towards developing grains, resulting in superior grain development and increased grain weight. Collectively, these improvements contribute to higher grain yield and biological yield (Godebo *et al.*, 2021; Swapnavahini *et al.*, 2022) ^[19].

Harvest index, which represents the efficiency with which plants convert total biomass into economic yield, is also influenced by nutrient management. Balanced fertilisation improves source-sink relationships and promotes the efficient translocation of assimilates from vegetative tissues to developing grains (Ali *et al.*, 2020; Xu *et al.*, 2024) ^[1, 56]. Consequently, optimum nutrient management is frequently associated with improvements in harvest index.

Recent studies conducted under intensive wheat production systems have demonstrated that optimised nutrient management can substantially improve productivity and yield stability (Mohan *et al.*, 2024) ^[40]. Modern wheat cultivars grown under balanced fertilisation and favourable environmental conditions have exhibited remarkable yield potential, highlighting the importance of efficient nutrient management in fully exploiting the genetic potential of the crop.

Overall, root traits, growth attributes, and yield formation are closely interconnected processes that are strongly influenced by nitrogen and phosphorus availability. Efficient root systems improve nutrient acquisition, enhanced vegetative growth supports greater biomass production, and balanced nutrient management promotes effective grain development. Therefore, integrated nitrogen and phosphorus management remains essential for maximising wheat productivity, improving nutrient-use efficiency, and ensuring the long-term sustainability of wheat-

based production systems.

Economics, Sustainability and Future Perspectives

Efficient nutrient management is essential not only for enhancing wheat productivity but also for improving farm profitability and ensuring long-term environmental sustainability (Godebo *et al.*, 2021; Bhattacharya *et al.*, 2023) ^[19, 8]. Fertiliser inputs constitute a substantial proportion of the total cost of cultivation; therefore, optimising nitrogen and phosphorus application is crucial for maximising economic returns. Appropriate nutrient management enhances grain yield, improves fertiliser recovery, and increases resource-use efficiency, thereby resulting in higher net returns and improved benefit-cost ratios (Ali *et al.*, 2020; Xu *et al.*, 2024) ^[1, 56].

Nitrogen application has a significant influence on the profitability of wheat cultivation because it is generally regarded as the most yield-limiting nutrient in wheat production systems (Mălinaş *et al.*, 2022; Xu *et al.*, 2024) ^[56, 38]. Adequate nitrogen nutrition promotes biomass accumulation, enhances grain yield, and improves grain quality, thereby increasing gross returns. However, excessive nitrogen application may increase production costs without providing proportional yield benefits, ultimately reducing economic efficiency (Sharma and Solanki, 2025) ^[60]. Consequently, identifying the economically optimum nitrogen dose remains an important objective of nutrient management research.

Similarly, phosphorus application contributes significantly to farm profitability by improving root development, nutrient uptake, and reproductive growth. An adequate phosphorus supply ensures better crop establishment and promotes efficient grain formation, thereby increasing crop productivity and economic returns (Ali *et al.*, 2020; Dugassa *et al.*, 2019) ^[1, 12]. Several studies have demonstrated that the combined application of nitrogen and phosphorus generates higher profitability than the application of either nutrient alone because of their complementary effects on crop growth, yield formation, and nutrient utilisation (Dugassa *et al.*, 2019; Godebo *et al.*, 2021) ^[12, 19].

Integrated nutrient management has emerged as a highly effective approach for simultaneously improving crop productivity and farm income. The combined use of inorganic fertilisers, organic manures, and biofertilisers enhances nutrient availability, improves synchronization between nutrient release and crop demand, and maintains soil fertility, thereby increasing fertiliser-use efficiency and long-term economic sustainability (Gurwinder Singh *et al.*, 2018; Godebo *et al.*, 2021) ^[21, 19]. In addition, these practices reduce dependence on chemical fertilisers while preserving soil health and sustaining crop productivity.

Conservation agriculture has also demonstrated considerable potential for improving both economic viability and environmental sustainability. Practices such as residue retention, reduced tillage, and balanced fertilisation improve soil structure, enhance nutrient cycling, increase water-use efficiency, and reduce cultivation costs (Bhattacharya *et al.*, 2023) ^[8]. Consequently, conservation agriculture contributes to higher profitability while supporting the sustainable management of natural resources in wheat-based production systems.

Environmental sustainability has become a major concern in modern nutrient management because the indiscriminate use of fertilisers can lead to substantial nutrient losses and ecological degradation (Mălinaş *et al.*, 2022; Xu *et al.*, 2024) ^[56, 38]. Nitrogen losses through leaching, volatilisation, and denitrification contribute to groundwater contamination, greenhouse gas emissions, and reduced fertiliser recovery. Likewise, phosphorus

losses through surface runoff accelerate eutrophication and adversely affect aquatic ecosystems (Godebo *et al.*, 2021; Dugassa *et al.*, 2019) ^[19, 12]. Therefore, balanced fertilisation and improved nutrient-use efficiency are essential for reducing the environmental risks associated with intensive agricultural production.

Recent developments in precision nutrient management have created new opportunities for improving both economic and environmental sustainability. Technologies such as site-specific nutrient management, sensor-based fertiliser recommendations, remote sensing, and decision support systems enable accurate nutrient application according to crop requirements. These approaches improve fertiliser-use efficiency, reduce nutrient losses, and promote sustainable crop production (Bhattacharya *et al.*, 2023; Xu *et al.*, 2024) ^[8, 56].

Research gaps and future perspectives

Despite significant advances in nutrient management research, several knowledge gaps remain regarding the efficient utilisation of nitrogen and phosphorus in wheat production systems. Most existing fertiliser recommendations are generalised and often fail to consider genotypespecific nutrient requirements, spatial variability in soil properties, and changing environmental conditions (Ranjan *et al.*, 2019; Li *et al.*, 2023) ^[45, 34]. Therefore, future research should prioritise the development of location-specific and cultivar-specific nutrient management strategies to improve fertiliser-use efficiency.

Greater attention should also be given to understanding root architecture, nutrient transport systems, and the molecular mechanisms governing nutrient acquisition and utilisation. Root characteristics such as root length, root biomass, and root proliferation have shown strong associations with nutrient-use efficiency and should be incorporated into breeding programmes aimed at developing nutrient-efficient wheat cultivars (Ranjan *et al.*, 2019; Li *et al.*, 2023) ^[45, 34].

The integration of precision agriculture, remote sensing, artificial intelligence, and digital decision-support tools offers considerable potential for improving nutrient management in wheat cultivation. These technologies enable real-time assessment of crop nutrient status and facilitate precise fertiliser application under diverse production environments, thereby improving nutrient-use efficiency and crop productivity (Bhattacharya *et al.*, 2023; Xu *et al.*, 2024) ^[8, 56].

Future wheat production systems should also focus on developing climate-resilient nutrient management strategies capable of sustaining productivity under changing climatic conditions. The combined adoption of nutrient-efficient cultivars, conservation agriculture, and integrated nutrient management practices will be essential for ensuring long-term food security while maintaining environmental sustainability.

Conclusion

Nitrogen and phosphorus are the two most essential macronutrients regulating the growth, development, productivity, and nutrient-use efficiency of wheat. Nitrogen is indispensable for chlorophyll biosynthesis, protein synthesis, photosynthesis, and biomass production, whereas phosphorus plays a vital role in energy transfer, root development, nutrient acquisition, and reproductive growth. An adequate and balanced supply of these nutrients promotes plant growth, dry matter accumulation, yield attributes, grain yield, and harvest index by enhancing various physiological and biochemical processes.

The interaction between nitrogen and phosphorus plays a significant role in improving nutrient acquisition, nutrient

utilisation, and overall crop performance. Balanced nutrient management not only increases grain yield and economic returns but also enhances environmental sustainability by improving fertiliser-use efficiency and reducing nutrient losses. Furthermore, root architecture, nutrient uptake mechanisms, and the genetic variability among wheat cultivars substantially influence nutrient-use efficiency and represent promising targets for future crop improvement programmes.

The integration of balanced fertilisation with integrated nutrient management, conservation agriculture, and precision nutrient management technologies offers an effective strategy for enhancing fertiliser-use efficiency while maintaining soil fertility and environmental quality. Future research should focus on developing nutrient-efficient cultivars, improving root system characteristics, formulating genotype-specific fertiliser recommendations, and designing climate-resilient nutrient management strategies. The adoption of these advanced agronomic approaches, together with balanced nutrient management, will be essential for sustaining wheat productivity and ensuring global food security under increasing pressure on natural resources.

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