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Maize nutrient dynamics: growth, yield and sustainable practices: A narrative review

Magdoline Mustafa Ahmed Osman[1,2,3*] – Ronald Kuunya[1,2] – Rania Alrasheed[3,4] – Mohammed M. Hassan[3] – Erastus Wasikoyo[1,2] – Costa Gumisiriya[2,5,6] – Hanan Ibrahim Mudawi[3] – Randa Elsalahi[3] – Ratonyi Tamas[1,2]

[1]Institute of Land Use, Engineering and Precision Farming Technology, Faculty of Agricultural and Food Sciences and Environmental Management, University of Debrecen, 138 Böszörményi street, 4032, Debrecen, Hungary

[2]Kálmán Kerpely Doctoral School, University of Debrecen, 138 Böszörményi Street, 4032 Debrecen, Hungary

[3]Environment, Natural Resources and Desertification Research Institute, National Center for Research, Khartoum, Sudan

[4]Department of Plant Science, McGill University, Macdonald Campus, 21,111 Lakeshore Road, Sainte-Anne-de Bellevue, QC, Canada

[5]Institute of Agrochemistry and Soil Science, Faculty of Agricultural and Food Sciences and Environmental Management, University of Debrecen, 138 Böszörményi street, 4032, Debrecen, Hungary

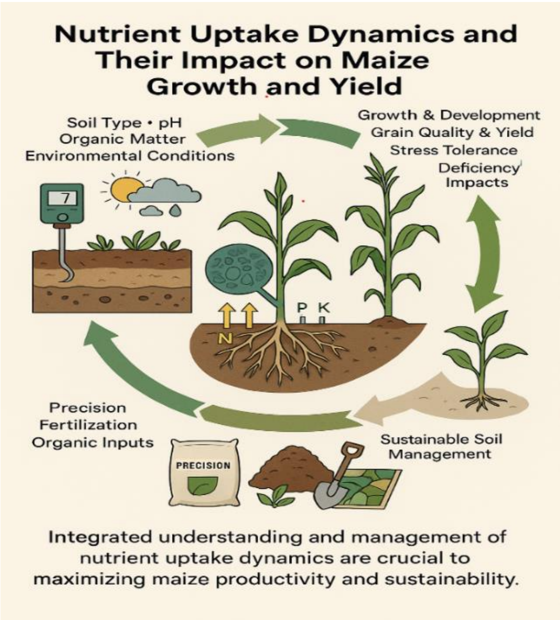
[6]Department of Crop and Animal production, Faculty of Agriculture and Environmental sciences, Mountains of the Moon University, P.O. Box 837, Fort Portal city, Uganda

[*]Correspondence: magdoline.osman@agr.unideb.com

SUMMARY

Nutrient acquisition is the fundamental regulator of maize (Zea mays) growth, development, and yield. The present narrative review intends to integrate existing information on dynamics of nutrient uptake in maize under scrutiny for understanding how the processes affect growth and yield. We focus on the effective absorption and utilization of macronutrients (N, P and K) and micronutrients that promote plant health, grain development, and stress tolerance. Key determinants of nutrient availability (soil type, pH, organic matter, environment) and physiological or yield impacts of deficiency are studied. Strategies to optimize uptake efficiency precision application of fertilizer, organic fertilizers, and sustainable soil management are discussed. Optimizing these dynamics is central to maize productivity, enhancement and sustainable crop production. This review provides valuable insights into optimizing maize nutrition for improved food security and sustainable crop production.

Graphical summary



Source: Authors

Keywords: *Nutrient uptake efficiency; nitrogen-phosphorus-potassium (NPK); sustainable soil management; maize yield; precision fertilization*

INTRODUCTION

Maize (*Zea mays* L.) is a significant cereal crop belonging to the Poaceae family. Maize is multipurpose and extensively use in human food, animal and poultry feed, and in several industrial uses such as starch, dextrose, corn syrup, and corn flakes production (Gul et al., 2021). *Zea mays* is known for its adaptability to diverse soil and climatic conditions, which supports its widespread cultivation. Its ability to absorb nutrients is

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higher than that of other types of agricultural crops, including small-grain cereals and leguminous grains. Maize is cultivated for different purposes, including its use as livestock feed in silage and grain, as well as feed for poultry and swine. Moreover, it is used by human beings in various, such as sweet corn, grain corn, and maize kernels (FAOSTAT, 2020).

Nitrogen, phosphorus, and potassium are essential nutrients needed for the normal growth and development of crops. In the absence of these nutrients, plants face difficulty in absorption of basic elements, resulting in unmet nutrient demands and significant decline in nutrient use efficiency (Li et al., 2019). Nitrogen limitation restricts dry matter accumulation in crops, there by affecting their overall annual yield (Ordóñez et al., 2024). Phosphorus deficiency not only lowers available phosphorus in the soil but also destabilizes soil nutrient balance in general (Thuynsma et al., 2014). P and N exist in a synergistic interaction in the formation of yields. When plants are unable to take up enough phosphorus during sensitive growth phases, the efficiency of nutrient utilization decreases significantly, negatively affecting grain yield formation (Njoroge et al., 2017). The deficient amount of potassium lowers the osmotic pressure in the plant cells, hinders stomatal action and transpiration, restricts photosynthesis, and leads to lower numbers of overall photosynthetic outputs (Sitko et al., 2019).

Nitrogen is one of the necessary nutrients for plant growth. It is a key component of most biological molecules that are needed for photosynthesis and general agricultural production (Sandhu et al., 2021). The higher nitrogen utilization in maize has been associated with peak seedling emergence, improved plant growth, and increased crop yield (Siddiqui et al., 2006). P is a vital nutrient for plant growth and development and a primary factor limiting sustainable maize production (Bindraban et al., 2020). Plant development is influenced by P availability and planting density through changing root morphological characteristics and soil P processes (Gong et al., 2022). In maize farming, the primary process by which phosphorus absorption takes place is the physical extension and growth of the root system (Zhou et al., 2019). In addition to nitrogen and phosphorus, Potassium (K) plays a critical role and an essential macronutrient that performs a central function in plant development and growth, impacting both the quantity and quality of the resultant crops (Fang et al., 2023). It participates in several vital physiological processes such as the maintenance of osmotic balance, regulation of ion concentration, enzyme activation, and facilitating the transport of photosynthetic products (Clarkson and Hanson., 1980).

Additionaly, calcium (Ca) and magnesium (Mg) play a crucial role in maize development and growth (He et al., 2024). Primarily, iron (Fe), zinc (Zn), and manganese (Mn) micronutrients are the structural components of enzymes that participate in a wide range of physiological processes in plants, such as respiration, biosynthesis of chlorophyll, photosynthesis, carbohydrate metabolism, and nitrate assimilation (Kobayashi et al., 2019; Kaur et al., 2022; Thompson, 2022; Lilay et al., 2024).

Recent research has elucidated sophisticated mechanisms of maize nutrient uptake. For example, a field experiment on a large scale conducted in the North China Plain revealed that application of balanced NPK fertilizers greatly enhanced maize yield and nutrient use efficiency, and it emphasized the need for integrated nutrient management strategies (Ju et al., 2004). Similarly, research in Nepal showed that excessive levels of N and K application significantly enhanced hybrid maize grain yield and total dry matter, thereby highlighting the sensitivity of the crop to the availability of nutrients (Paudel et al., 2015).

In this review, we synthesize contemporary understanding of the dynamics of nutrient absorption in maize, evaluating how these processes shape crop development and productivity. Drawing on recent research, we identify practical strategies and key areas of focus for improved nutrient management and sustainable maize production.

MATERIALS AND METHODS

Literature search strategy

This narrative review synthesized current knowledge on maize nutrient uptake dynamics through a systematic literature search. Relevant scientific papers published between 2000 and 2025 were retrieved from the Web of Science Core Collection database. The search used Boolean operators with the main query: (maize OR corn) AND nutrient uptake AND (growth OR biomass OR development) AND (yield OR productivity), limited to English-language publications. An initial screening identified 48,646 documents. After applying relevance criteria, 350 records were shortlisted for detailed review (*Figure 1*). These articles were thoroughly examined, and additional relevant papers identified through cross-referencing were included. This iterative screening process resulted in the exclusion of irrelevant studies, culminating in a final collection of 81 references used in this review.

Data extraction and synthesis

Following title/abstract screening, full texts of 350 articles were read. Study aims, methods, types of nutrients (e.g., N, P, K, micronutrients), growth stages were considered, and experimental conditions (soil type, fertilization treatments, environmental conditions) were extracted as main data. As a narrative review, synthesis was aimed at qualitative analysis, observing patterns, trends, and emerging themes among studies, rather than statistical meta-analysis. Consequently, data were organized in a logical sequence to assess nutrient uptake processes, deficiency effects, and control practices, thereby achieving effective integration of agronomic, physiological, and environmental aspects. This approach enabled a multidisciplinary understanding, combining agronomic, physiological, and environmental perspectives.

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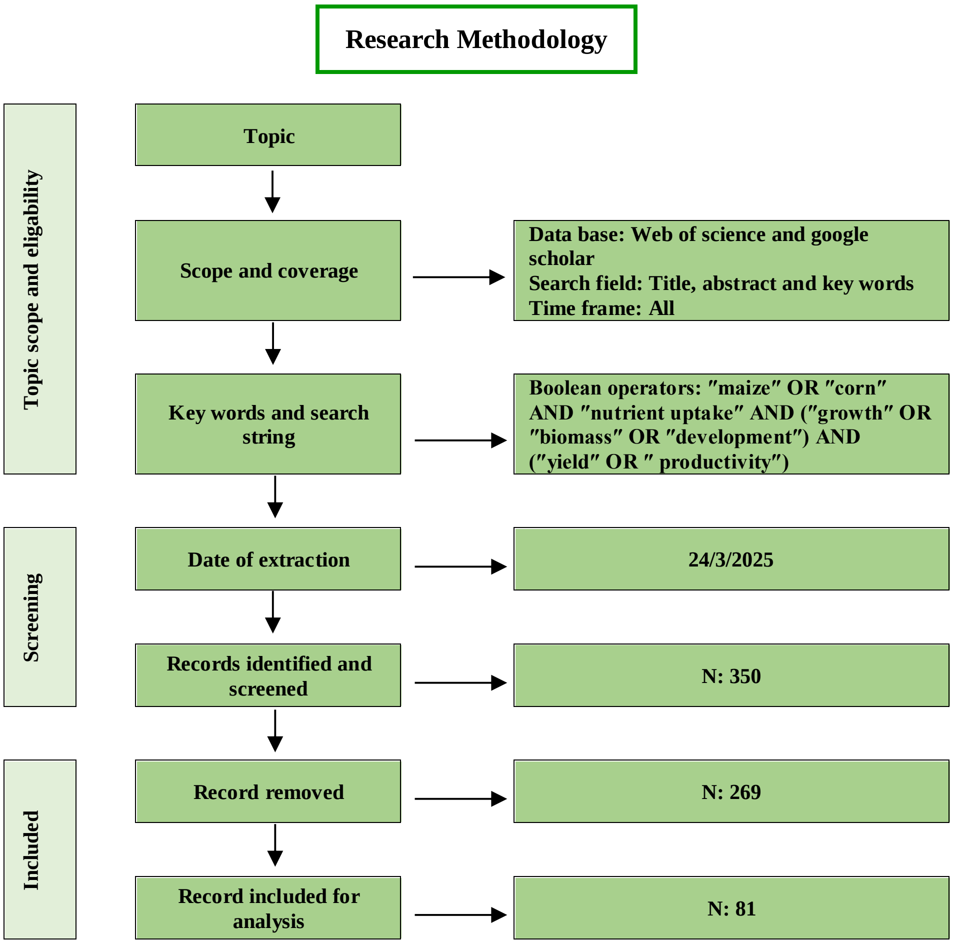
Figure 1. **Summarizing the approach to literature collection and review**



RESULTS AND DISCUSSION

Mechanisms of nutrient absorption in maize

Maize acquires essential nutrients primarily through the root system, where soil exploration and surface absorption mechanisms are quite crucial for growth. However, declining soil water availability significantly impedes the flow of nutrients to roots, detrimentally affecting plant growth (Neina, 2019). Whereas root architecture, growth, and branching enhance foraging capability, the exact mechanisms of nutrient uptake at the root-soil solution interface need to be clarified (Griffiths et al., 2021). Macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) are taken up by root cortical and epidermal cells through specialized transporter proteins. Nitrate (NRTs, NRT1 and NRT2 families) and ammonium (AMTs) transporters regulate nitrogen uptake, whose activity adapts to nitrate levels in soil (Muratore et al., 2021). Similarly, phosphate transporters (PHT1 family) are more highly expressed under low P status for enhanced uptake (Li et al., 2022). The latest advances in transcriptomics and gene editing offer promising strategies for improving overall Nutrient Use Efficiency (NUE) by identifying and altering key regulatory genes (Kumar et al., 2024).

Phosphorus (P) acquisition is particularly difficult as it does not occur naturally in readily available in the soil but tied up in over 170 complex inorganic mineral compounds (Lambers, 2022). Plants take up P largely as inorganic phosphate (Pi), yet Pi tends to be immobilized, limiting its availability and consequently plant growth. To augment the shortage, maize employs several adaptive mechanisms (Guo et al., 2024). Organic acids in root exudates solubilize immobilized P and micronutrients like iron and zinc. Furthermore, symbiotic relationships with mycorrhizal fungi significantly enhance the absorptive functional surface area outside the root system, hence substantially enhancing the uptake of phosphorus, especially in nutrient deficient environments. Such combined physiological and symbiotic mechanisms are crucial in improving the efficiency of phosphorus uptake in maize (Smith et al., 2011).

Plant root cells absorb potassium from soils against a potassium ion (K^+) gradient across the root cell plasma membrane (Maathuis, 2009). Potassium ions are transported into root cells and then pass through the endodermis and enter the xylem parenchyma. The K^+ channels and transporters located on the plasma membrane of parenchyma cells mediate K^+ loading into xylem, by which K^+ ions are transported upward to shoots (Zhang et al., 2023). The functions and nutrient uptake in maize production is shown in *Figure 2*.

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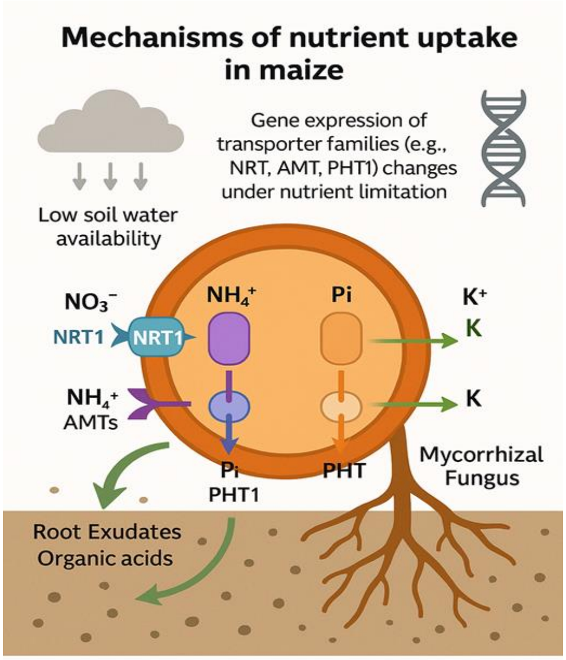
Figure 2. **Mechanisms of nutrient uptake in maize roots under nutrient-limited conditions**



Under nutrient-limited conditions, maize roots employ a variety of morphological, physiological, and molecular mechanisms to enhance nutrient uptake efficiency. These adaptations allow the plant to optimize acquisition of macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), as well as essential micronutrients.

Source: Authors

Essential nutrients for maize growth and yield

Maize yield basically hinges on balanced macronutrient (N, P, K) supply, received chiefly from chemical fertilizers and animal manures, as native soil fertility is generally not sufficient for optimum yields (Bojtor et al., 2022; Batool, 2023; Ullah et al., 2025). Yet, overuse of nutrients is detrimental to toxicity risks, compromised fertility, decreased microbial colonization, and interference with micronutrient uptake (e.g., Zn, Fe, Cu, Mg) (Lisuma et al., 2006). The exact concentration and balance of nutrients are important, for instance, nitrogen is used for vegetative growth and grain yield but needs to be managed carefully to avert environmental degradation through nitrate leaching and greenhouse gas emissions (Batool, 2023).

Phosphorus a common limiting factor participates in root development, flowering, and grain formation (Łukowiak et al., 2016; Batool, 2023), while potassium regulates osmoregulation, enzyme activation, and photosynthesis. Nitrogen and phosphorus also enhance plant water use efficiency, while potassium directly reduces water loss (Manásek et al., 2013). Micronutrients, although needed in limited quantities, are crucial for fundamental physiological processes such as photosynthesis, respiration, protein formation, and reproduction (Martins et al., 2017; Mahdi et al., 2024). The application of foliar spraying technology presents an effective way to increase the uptake of nutrients by plants, especially potassium and magnesium, and circumvent soil limitation (Al-Tamimi and Farhood, 2022). Strategic application of micronutrients like zinc, manganese, sulfur, and molybdenum substantially enhances maize productivity up to 5.99 tons ha^{-1} (Mahdi et al., 2024). Thus, the integrated management strategy involving the use of both macro and micronutrients with precision and balance is the key to unlocking maximum maize growth, yield potential, and resource utilization efficiency while reducing environmental footprint (*Figure 3*).

Determinants affecting nutrient absorption of maize

Maize nutrient uptake is regulated by abiotic and biotic factors including temperature, CO_2, water, light, and soil type that exert direct effects on physiological responses (Ehtaiwesh, 2022). Soil microbiota, specifically arbuscular mycorrhizal fungi (AMF), facilitate the mobilization and transfer of nutrients to their host plants. Concurrently, humic and fulvic acids derived from organic matter function as biostimulants that enhance stress resilience, promote nutrient solubilization, and contribute to root development through the activation of ATPase (Smith and Read, 2008; Canellas et al., 2015; Bender and van der Heijden, 2015).

Ecological agriculture practices like organic amendments (manure or compost), cover cropping, and crop residue retention enhance soil organic carbon (SOC), which raises the soil fertility and nutrient levels (Duan et al., 2022; Fontúrbel et al., 2024; Feng et al., 2023).

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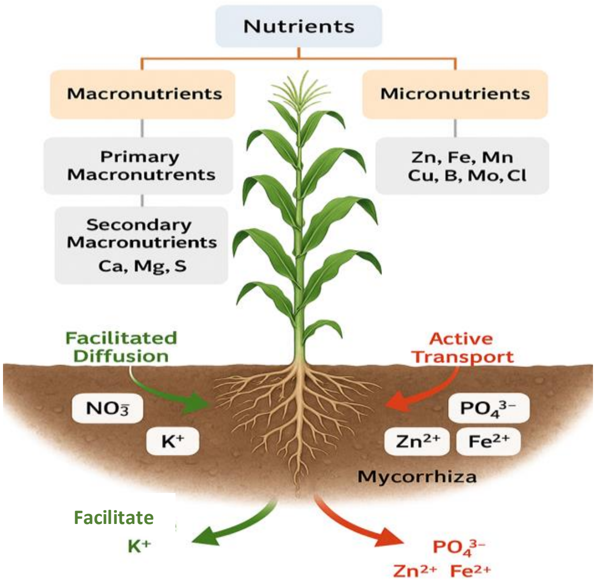
Figure 3. **Nutrient classification and uptake mechanisms in maize**



Macronutrients and micronutrients enter maize roots through facilitated diffusion (e.g., K^+, NO_3^-) or active transport (e.g., PO_4^{3-}, Zn^{2+}, Fe^{2+}), with mycorrhizal fungi enhancing the uptake of immobile nutrients like phosphorus and zinc. Balanced nutrient management is crucial for yield, water use efficiency, and environmental sustainability.
Source: Authors

Effect of nutrient deficiency

Macronutrient (N, P and K) deficiencies stringently restrict maize growth and yield. Nitrogen deficiency reduces dry matter accumulation and yearly yield (Ordóñez et al., 2024), phosphorus limits nutrient and biomass accumulation (Sun et al., 2024), while potassium deficiency reduces stress tolerance (Li et al., 2019), decreases the osmotic pressure in plant cells, impairs stomatal function and transpiration, lowers photosynthetic efficiency, and ultimately decreases the overall production of photosynthetic products (Usandivaras et al., 2018; Sitko et al., 2019). Potassium deficiency reduces yield and stress tolerance; however, it can be effectively managed through soil testing and strategic application at planting and during vegetative growth stages (Batool, 2023) Micronutrient deficiency disorders interfere with yield and crop quality, and human/animal health (Welch, 2003; Mendes et al., 2022). Management of these disorders is through the combined application of organic materials, bio-fertilizers, and micronutrients (Singh et al., 2002) (*Table 1*).

Table 1. **Impact of nutrient deficiency on Maize Production**

Elements	Symptoms	Impact on Maize	Reference (s)
Nitrogen (N)	Chlorosis (yellowing) of older leaves, stunted growth.	Reduce crop yield	Sun et al. (2024); Fageria et al. (2010)
Phosphorus (P)	Purpling of older leaves, poor root growth.	Crop nutrient accumulation and dry matter accumulation	Sun et al. (2024)
Potassium (K)	Marginal leaf scorching, lodging, weak stalks, Browning and curling of leaf tips	Significant reductions in nutrient use efficiency, Decreased photosynthetic rate, water-use efficiency, and grain filling.	Sun et al. (2024); Römheld and Kirkby (2010); Thenveettil et al. (2024)
Magnesium (Mg)	Interveinal chlorosis in older leaves	Reduces carbohydrate formation and translocation	Jezek et al. (2015)
Sulfur (S)	Yellowing of younger leaves	Reduced biomass and chlorophyll content.	Astolfi et al. (2021)
Zinc (Zn)	Short internodes, white bands on leaves, poor cob formation	Disrupts growth, pollination, and kernel development.	Cruz et al. (2010)
Iron (Fe)	Interveinal chlorosis in younger leaves	reduces energy generation and biomass	Marschner (2012) ; Astolfi et al. (2021)
Boron (B)	Deformed tassels and ears	Reduced grain yield	Lordkaew et al.(2010)
Manganese (Mn)	interveinal chlorosis	Decrease crop quality and quantity	Rashed et al. (2019)

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Strategies to enhance nutrient absorption and yield

Organic amendments and overall soil management are necessary to optimize maize uptake of nutrients. Soil testing enables precision fertilization, with the ability to tailor nutrient application to the specific soil profile to optimize efficiency and minimize environmental impact (Dawar et al., 2022). Incorporating organic amendments such as biochar has a beneficial impact on the soil structure, water holding capacity, cation exchange capacity (CEC), concurrently minimizing nutrient leaching and providing necessary nutrients (H, N, O, P, K and C) attributable to its natural porosity and makeup (Arias et al., 2008; Qayyum et al., 2014; Amonette et al., 2009). Likewise, vermicomposting also easily supplies available water-soluble nutrients, which efficiently performs the role of an organic soil conditioner and fertilizer and has been reported to effectively enhance maize plant height, grain yield, and total yield, particularly in conjunction with NPK fertilizers (Lim et al., 2016; Dawar et al., 2022).

Direct delivery of nutrients and agro ecological management practices also maximize uptake and yield. Foliar fertilizer application, such as nano-nutrients and chemicals like potassium silicate, provides direct delivery of nutrients to leaves, enhancing chlorophyll content, photosynthetic potential, and grain yield even during water deficit (Elmer and White, 2016; Rehman et al., 2021). Crop rotation, intercropping (for example, maize with legumes), and cover cropping enhance organic matter, soil structure, and beneficial microbial activity. These practices also enhance nitrogen content and dynamics through better root-microbiome interactions in the rhizosphere, as well as weed control and erosion mitigation (Duchene et al., 2017; Wang et al., 2020)

Genetic improvement and integrated approaches provide long-term solutions. Breeding programs develop nutrient-efficient maize with improved uptake and utilization capacity, resulting in increased yield due to decreased fertilizer application, particularly valuable in low-input systems or infertile soils (Ssemugenze et al., 2025). Lastly, the integration of precision fertilization, organic amendments, foliar nutrition, diversified cropping systems, and improved genetics provides a synergistic solution that maximizes nutrient uptake, raises maize yield, and ensures sustainable production and food security.

Current challenges and future directions

Current issues include fertilizer overuse causing nutrient imbalance, environmental pollution (for example, eutrophication via runoff), and heavy metal pollution that undermines food safety (Roberts, 2008; Boesch, 2001; Yerli et al., 2025). Abiotic stress in the form of salinity and soil acidity also limits uptake (Farooq et al., 2015).

Innovations are targeting the optimization of nutrient-use efficiency (NUE) via mycorrhizal symbiosis for carbon sequestration and the minimization of fertilizer, along with Artificial Intelligence (AI) driven precision agriculture via remote sensing for real time soil and crop monitoring (Batool, 2023). These advances aim to optimize resource use while minimizing ecological impacts.

Maize production faces significant challenges in nutrient management, including inefficient fertilizer use, soil degradation, and environmental pollution (Srivastav et al., 2024). Over use of nitrogen and phosphorus not only increases production costs but also leads to nutrient runoff, contributing to water eutrophication and greenhouse gas emissions (Decrem et al., 2007). To address these issues, innovations aimed at improving nutrient-use efficiency (NUE) are being explored. For instance, the application of mycorrhizal fungi has shown promise in enhancing carbon sequestration and reducing fertilizer requirements by improving nutrient uptake efficiency in crops (Kumar et al., 2020).

Advancements in technology, particularly the integration of artificial intelligence (AI) and remote sensing, are revolutionizing precision agriculture (Javaid et al., 2023). AI driven models analyze data from various sources, including satellite imagery and drone footage, to monitor crop health, predict yields, and optimize fertilizer application (Liu, 2020). Remote sensing technologies provide real time insights into soil conditions and crop status, enabling targeted interventions that enhance productivity while minimizing environmental impact. These technologies collectively contribute to more efficient nutrient management practices, promoting sustainability in maize production (Getahun et al., 2024).

CONCLUSIONS

Maize nutrient uptake optimization is critical for the crop's growth and sustainable yield increase. Physiological, agronomic, and technological integration of balanced fertilization, organic/bio-based amendments, foliar/nano-fertilizers, and nutrient-efficient varieties together greatly improves Nutrient Use Efficiency (NUE). Advances in AI and remote sensing facilitate precision agriculture, permitting real time monitoring and personalized nutrient management with diminished environmental footprints. In spite of ongoing constraints such as soil degradation and climatic variability, integrated, site-specific approaches harnessing these developments can establish resilient maize production systems. Sustained interdisciplinary research is imperative to unlock soil-plant interactions and ensure food security while maintaining environmental integrity.

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