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NUTRIENT STRESS AS A DETERMINANT OF SUSTAINABILITY IN AGRICULTURAL SYSTEMS: A REVIEW

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ABSTRACT

One of the biggest obstacles to global agricultural productivity and sustainability is still nutrient stress. Plant physiological, biochemical, and molecular processes are disrupted by deficiencies, toxicities, and imbalances of vital macro- and micronutrients. This results in decreased growth, yield losses, deteriorating soil health, and decreased nutrient-use efficiency. The mechanisms controlling plant responses to nutrient stress, such as nutrient sensing, signal transduction, hormone regulation, root architecture changes, transporter activity, and interactions with the rhizosphere microbiome, are summarised in this article. The key causes of nutrient stress, including soil degradation, intensive agricultural practices, climate change, nutrient mining, and environmental pollution, are further examined in the review along with their consequences for world food security. The potential of new sustainable management techniques, such as integrated nutrient management, biofertilizers, microbial inoculants, regenerative agriculture, biofortification, and precision nutrient management, to enhance nutrient uptake while reducing environmental effects is assessed. Recent advancements in edge computing, artificial intelligence, machine learning, multispectral and hyperspectral imaging, Internet of Things (IoT)-based monitoring, and remote sensing are also discussed as revolutionary tools for site-specific nutrient management and real-time nutrient stress diagnosis. In order to improve crop resilience, increase nutrient-use efficiency, and support climate-smart sustainable agricultural systems, the integration of multi-omics, high-throughput phenotyping, predictive modelling, and cutting-edge digital agriculture technologies is highlighted in the identification of key knowledge gaps and future research priorities. When taken as a whole, this analysis offers a thorough framework for comprehending nutrient stress and describes creative methods for achieving resilient crop production while maintaining long-term soil health and assuring global food security.

Key words: Nutrient Stress, Sustainable Agriculture, Nutrient Use Efficiency (NUE), Precision Agriculture, Climate Change

Introduction

According to Lopez *et al.*, (2023) and Mishra *et al.*, (2024), nutrient stress refers to the physiological and morphological restrictions imposed on crop productivity caused by the insufficiency or poor bioavailability of essential elements, particularly nitrogen, phosphorus, and potassium. This condition poses an imminent threat to agricultural output and is usually exacerbated by poor soil fertility or nutrient immobilization. It largely restricts biological functions, such as enzyme activity and biomass

accumulation (Abbas *et al.*, 2026). Considering that the current tendency to rely on intensive application of chemical fertilizers to address these problems usually results in negative impacts on the environment, such as eutrophication and soil acidification, addressing this problem is critical for sustainable agriculture (Chen and Liao, 2017 and Poveda and Eugui, 2022). Thus, a deeper insight into how plants perceive and react to fluctuations in nitrogen concentration is necessary to decouple the needs for high-yield and high fertilizing input (Al-

Mohammedi *et al.*, 2025). This review provides an overview of the complex signalling pathways and adaptive physiological responses underlying plant performance under nutrient stress. This paper gives a paradigm for evaluating genetic and agronomical means aimed at enhancing nutrient-use efficiency based on current advances in molecular signalling and eco-physiology (Lambers, 2021; López-Arredondo *et al.*, 2014). The current review specifically focuses on the interaction between external stressors and mineral nutrient insufficiency, with emphasis on the involvement of specialized signal transduction cascades and reactive oxygen species in increasing plant tolerance to stress (Schachtman and Shin, 2006; Wang *et al.*, 2025). This paper also evaluates the possibility of combining advanced breeding goals with precise nutrient management in order to improve resistance of plants to environmental limitations. The current synthesis attempts to emphasize the gaps in the current knowledge of plant-soil dynamics by evaluating the deficiency and toxicity threshold that defines nutrient stress (Pandey *et al.*, 2021). In order to characterize the multi-partite interaction between metabolic pathways and nutrient-stress signaling, which are crucial for the creation of adaptive crops in the era of changing climate, this discussion concludes with a bridge of the above findings to outline future research areas (Briat *et al.*, 2015; Kumar *et al.*, 2021). The assessment of how plants detect suboptimal nutrient availability and coordinate this detection with systemic changes in the resource allocation is important for this approach (Hermans *et al.*, 2006; Kochian and Lucas, 2014). Auxins, cytokinin, and abscisic acid are the examples of phytohormones and root-to-shoot signaling molecules that coordinate development in accordance with changes in nutrients' availability (Al-Mohammedi *et al.*, 2025; Kochian and Lucas, 2014). These regulatory networks play an important role in providing the ability of a plant to sustain productivity under adverse edaphic conditions because of the dynamic repartitioning of resources and architectural remodelling of roots (Abbas *et al.*, 2026; Kochian and Lucas, 2014). Post-translational and transcriptional alterations of specialized membrane transporters that regulate the uptake of vital minerals depending on environmental factors complement these systemic changes (Bamatov *et al.*, 2025; Yu *et al.*, 2024). By combining these molecular pathways with advanced agroecological means, researchers can better understand how soil microbial communities and root-soil exudation patterns minimize the negative physiological effects induced by nutrient-induced redox imbalances (Kumar *et al.*, 2024; Oustric *et al.*, 2021). Moreover, this paper

will evaluate how the specific redox changes induced by nutritional shortage are used to combat oxidative stress. These changes function as the fundamental signals for adaptive gene expression and modification of plant metabolism. Lastly, this study emphasizes the importance of defining root system architecture, such as ideotypes' development, in order to enhance nutrient uptake efficiency under various edaphic conditions by combining research in molecular biology and plant breeding. In order to develop breeding programs capable of making crops resistant to the combined challenges of nutrient deficiency and climate variability, it is important to translate these fundamental discoveries into the practice (Benitez-Alfonso *et al.*, 2023; Khan *et al.*, 2019).

Sustainable Agriculture Context

In order to implement sustainable agriculture, it is necessary to strike a balance between growing need for the world's food security and the necessity to reduce the use of artificial chemical inputs that often aggravate the state of soil (Gojon *et al.*, 2022). Researchers could reduce these ecological costs while maintaining high agricultural yields by prioritizing the development of lower-input plant ideotypes that use endogenous hormonally regulated mechanisms to adapt to different soil profiles (Zhang *et al.*, 2023). This paper comprehensively analyzes the regulatory logic of root system plasticity and the networks controlling homeostatically how plants respond to nutrient changes, which were integrated in this review (Hanikenne *et al.*, 2020). This analysis specifically evaluates how morphological adaptations, such as the changes in the root architecture, are coordinated with the systemic metabolic changes to enhance nutrient acquisition (Giehl *et al.*, 2013; Sebastian *et al.*, 2026). Furthermore, by studying the intersection of phenomics and genomics, this paper will highlight how the species-specific loci and regulatory pathways can be leveraged in order to connect the alleles' diversity with ecosystem-relevant phenotypes. By evaluating these adaptive mechanisms, this review provides the comprehensive framework for the selection of crop genotypes with superior nutrient-use efficiency and performance under limited conditions (Koevoets *et al.*, 2016; York *et al.*, 2013). This synthesis concludes with the methodological integration of functional phenomics and multi-omics approaches in order to identify the genetic markers underpinning resilient root system architecture (Hu *et al.*, 2025; Zenda *et al.*, 2021). Ultimately, this approach intends to clarify how the manipulation of these traits can increase the nutrient uptake in heterogenic soil environments in order to reduce the reliance of agriculture on synthetic fertilizers (Liu *et al.*, 2023; Lynch, 2021). Besides genetic improvements,

the realization of such resilient systems also requires the coupling of these biological insights with high-fidelity modelling of rhizosphere processes and microbially-mediated nutrient cycling (Lynch *et al.*, 2023). This multifaceted approach helps to move from the descriptive studies of nutrient stress to predictive frameworks that can optimize nutrient capture in diverse agricultural landscapes (Licaj *et al.*, 2025; Lynch and Brown, 2012). Accordingly, this review is structured so as to first categorize the fundamental mechanisms of nutrient stress in agricultural systems and then evaluate the efficacy of emerging biotechnological interventions (Nadeem *et al.*, 2023). Specifically, it will delineate the biochemical pathways regulating nitrogen and phosphorus uptake that are the primary limiting factors for global crop productivity (Li *et al.*, 2015). Nutrient stress defined as the insufficient bioavailability of essential mineral elements like nitrogen and phosphorus is the primary restriction for crop productivity, especially in the agricultural systems affected by soil degradation and resource instability caused by climate change (Al-Mohammed *et al.*, 2025; Gojon *et al.*, 2022). Considering the urgent necessity to decrease the dependence on synthetic fertilizer input, it is important to understand the complex regulatory networks that control plant responses from morphological root remodelling and transporter modulation to symbiosis establishment (Giehl *et al.*, 2013; Kumar *et al.*, 2024). By studying these adaptive mechanisms and how they help the plant metabolism, this section will delineate the physiological strategies underlying plant resilience and thus provide the framework for identification and development of high-efficiency crop ideotypes capable of maintaining yield stability under sub-optimal edaphic conditions (Lynch, 2021; Nadeem *et al.*, 2023; Zhang *et al.*, 2023).

Types and Classification

Nutrient stress in agricultural systems is fundamentally categorized into deficiency, toxicity, and imbalance, depending on the bioavailability and physiological impact of essential elements in relation to plant needs (Farhan *et al.*, 2024). Deficiency occurs when the concentrations drop under the critical threshold needed for the metabolic function, while toxicity means that the excessive accumulation of a nutrient causes cell damages and competitive inhibition of other ions (Fageria *et al.*, 2008). In turn, nutrient imbalance is the consequence of the stoichiometric dysregulation of essential elements, which can happen even when absolute concentrations are sufficient enough, thus disturbing metabolic and signalling cross-talk (DeLoose *et al.*, 2023). The severity levels of these stress states are officially classified by

the degree of yield reduction and the extent of the related transcriptomic reprogramming, where the combined nutrient starvation usually provokes the antagonistic responses different from those in single stress conditions. In order to operationalize this classification, research must introduce the diagnostic criteria that integrate the soil test-based nutrient bioavailability with the quantitative physiological biomarkers (Oldroyd and Leyser, 2020). For example, the metrics like nutrient nutrition indices or critical concentration curves provide the quantitative framework for the assessment of real crop nutritional status in comparison with theoretical physiological demands, thus allowing a more objective classification of the stress severity (Oldroyd and Leyser, 2020). This systematic categorization allows for the differentiation of the environmental abiotic stress from intrinsic genetic limitations, thus providing a foundation for the targeted interventions in breeding programs (Sathee *et al.*, 2022). Besides, the differentiation of these stress categories requires the evaluation of the interaction between edaphic factors like pH and salinity, which can exacerbate toxicities and interfere with the nutrient uptake pathway. For example, alkaline soil conditions usually diminish the bioavailability of essential micronutrients through precipitation, thus causing secondary deficiencies even when the total soil concentrations are sufficient (Al-Mohammed *et al.*, 2025; Gojon *et al.*, 2022). In turn, high salinity levels cause the osmotic stress and the competitive ion exclusion, thus complicating the diagnosis by mimicking or masking nutrient-specific symptoms. Consequently, a robust multivariable diagnostic approach is necessary to decouple these complex edaphic confounders from intrinsic genetic nutrient-use limitations (Gojon *et al.*, 2022; Oldroyd and Leyser, 2020).

Macronutrient Deficiency

The limitation in the availability of nitrogen, phosphorus, and potassium is the major constraint to global food production as these elements are indispensable for primary metabolic processes, structural integrity and osmotic regulation (Andjelkovic, 2018; Bang *et al.*, 2020). The plants deficient in nitrogen usually show chlorosis in old leaves due to the systemic remobilization, while phosphorus limitation heavily influences the root architectural development and the energy transfer through ATP-dependent pathways (Lazarević *et al.*, 2022). In contrast, potassium deficiency causes the impairment of the stomatal conductance and enzymatic activation, thus causing the reduction in turgor pressure and the susceptibility to lodging (Muhammad *et al.*, 2025). While the deficiencies in nitrogen and phosphorus limit biomass accumulation and grain yield through metabolic and

reproductive development (Tossi *et al.*, 2022), potassium deficiencies are characterized by more acute qualitative changes, such as the reduction of grain quality and starch synthesis. Such constraints are prevalent in the intensive cereal production systems of Asia and Africa, where the continuous cultivation led to soil depletion. Besides, besides these geographic hot spots, acidic soils, which occupy over 40% of global agricultural land, often limit the phytoavailability of phosphorus and potassium while exacerbating the aluminium toxicity (White *et al.*, 2013). Conversely, the magnesium and sulphur limitations are increasingly recognized for the crucial role of these elements in the chlorophyll synthesis and protein structures, respectively, but their field-scale deficiency is often confused by the excessive application of NPK fertilizers (Osmolovskaya *et al.*, 2020; Schjoerring *et al.*, 2018). For example, magnesium deficiency usually presents itself through interveinal chlorosis in old leaves before moving to necrosis, while sulphur limitation is manifested as a generalized chlorosis of young foliage due to its lower phloem mobility (Ahmed *et al.*, 2023; Akýnoglú, 2025). Calcium deficiencies largely influence the cell wall stability and meristematic integrity, manifesting themselves as the localized tissue necrosis or blossom-end rot in sensitive fruit and vegetable crops (Kalaji *et al.*, 2017). These secondary macronutrient limitations usually operate in a complex hierarchical way, where the inadequate supply of calcium causes the disruption of the root system architecture and hinders the nitrogen uptake, regardless of the external availability of this element (Andjelkovic, 2018; Tossi *et al.*, 2022). Such interdependencies underline the stoichiometric constraints in plant physiology, where the essential elements' ratios like the ratio of calcium-to-magnesium and potassium-to-calcium must be preserved in order to maintain enzymatic functionality and signalling cross-talk (Andjelkovic, 2018; DeLoose *et al.*, 2023). When these ratios are skewed, even abundant primary nutrients may become unavailable or physiologically inaccessible, thus demonstrating that the sustainable management strategies must be based on balanced nutrition rather than the simple supplementation of single nutrients (Fageria *et al.*, 2008).

Micronutrient Deficiency

Micronutrient deficiencies, such as iron, zinc, manganese, copper, boron, molybdenum, and chlorine deficiencies, are known to result in “hidden hunger” where the yield limiting physiological disturbances happen well before the appearance of any visible morphological symptoms (Kihara *et al.*, 2017). This condition is especially common in soils where high pH or carbonates severely limit the solubility and root uptake of elements like iron

and zinc (Adal and Mulat, 2024). Additionally, while the specific visual signs like chlorosis, necrosis, or stunted growth can be the indicators, these signs usually appear at the advanced stages of depletion and conceal the underlying metabolic inefficiency (Abbas *et al.*, 2021; Ghimirey *et al.*, 2024). For example, latent deficiencies often result in the increased susceptibility to the colonization by pathogens and pests, since the suboptimal concentrations of one micronutrient can cause the excessive accumulation of antagonistic elements, such as iron and manganese during the copper deficiency (Rácz and Radocz, 2020). Besides these threshold-dependent visible markers, transient shortages of trace elements remain undetected in diverse soil types due to the restrictive rooting systems or insufficient seedbed consolidation that impedes nutrient contact regardless of their abundance (Jones *et al.*, 2013). This general lack of micronutrient availability is exacerbated by edaphic factors like soil parent material, organic matter contents, and complex interaction of competing anions that cause the chemical precipitation (Dimkpa and Bindraban, 2016). In this context, the zinc deficiency has become a pervasive global limitation, especially in alkaline and calcareous soils, where its solubility is tightly regulated by electrochemical soil changes (Rashid and Ryan, 2004). Similarly, iron availability is often limited in the calcareous soils, thus requiring precise management in order to prevent the metabolic disruptions (Szerement *et al.*, 2021). The limitations in manganese and copper often impair photosynthetic electron transport and enzymatic activation, while boron and molybdenum deficiencies disrupt cell wall synthesis and nitrogen fixation, respectively (Pathak and Nidhi, 2025). Additionally, the geochemistry of these elements, including the role of chlorine in osmotic regulation and the specific soil-plant transfer mechanisms that depend on redox potential, shows that bioavailability is basically governed by the soil pH, mineralogy and organic matter contents (Galic *et al.*, 2025). Moreover, the effectiveness of plant uptake is further complicated by the species-specific acquisition strategies like phyto-siderophores in graminaceous monocots and the proton-mediated acidification in dicotyledonous species to increase the iron solubility (Stassen *et al.*, 2020; Vigani *et al.*, 2013). These specialized mechanisms activated in response to the nutrient deficiency condition show that plants are capable of changing the rhizosphere in order to mobilize poorly soluble mineral fractions (Murgia *et al.*, 2021; Velez Bermudez and Schmidt, 2022). However, the effectiveness of these strategies is often limited by edaphic factors, especially in alkaline or calcareous soils,

where high pH severely affects the solubility of iron and zinc, thus possibly overwhelming these adaptive responses (Velez Bermudez and Schmidt, 2022; Schenkeveld *et al.*, 2014). Similarly, the competitive interactions between minerals in the rhizosphere, where the high concentrations of calcium and bicarbonate ions impede the formation of stable metal-ligand complexes, can also render these acquisition strategies less effective, thus increasing the risk of latent nutritional deficiencies (Schenkeveld, Schindlegger, *et al.*, 2014). Consequently, even with these evolutionary adaptations, plants remain vulnerable to “hidden hunger” in case of adverse soil conditions and nutrient imbalances that prevent the nutrient uptake, thus demonstrating the complex interdependence of plant physiology and soil chemistry (Mimmo *et al.*, 2018; Rengel, 2015). This stresses the necessity to distinguish between the total soil concentrations and the actual bioavailability that is governed by complex chemical interactions including the antagonistic ion uptake and shared transporter pathways (Bindraban *et al.*, 2015; Dwivedi *et al.*, 2023).

Nutrient Toxicity

Nutrient toxicity occurs when the accumulation of specific ions, whether essential micronutrients or non-essential heavy metals exceeds the threshold for homeostatic regulation, leading to biochemical interference and cellular damage. This stress often manifests as aluminium, salinity, or heavy metal toxicity, where excessive cationic activity disrupts soil solution equilibria and root membrane integrity (Tibbett *et al.*, 2021). In acidic environments, high aluminium concentrations provoke root tip damage and inhibit cell division, while salinity stress induces osmotic imbalance and ion toxicity, triggering cytotoxic effects that exceed the plant's capacity for vascular sequestration (Pandey *et al.*, 2021; Roorkiwal *et al.*, 2021). Simultaneously, the prevalence of heavy metals such as cadmium or lead often induces oxidative stress by stimulating the uncontrolled generation of reactive oxygen species, a process further aggravated by the antagonistic uptake mechanisms that displace essential elements from functional enzymatic sites (Saleem *et al.*, 2022). Such competitive inhibition frequently extends beyond localized enzymatic disruption, precipitating broader nutrient imbalances where the hyper-accumulation of non-essential metals actively suppresses the uptake and translocation of vital micronutrients (Bindraban *et al.*, 2015; Pandey *et al.*, 2021). This interference effectively decouples soil availability from physiological acquisition, as the influx of toxic ions overrides standard transport pathways designed for essential mineral homeostasis, thereby exacerbating

systemic metabolic distress and limiting overall vegetative vigour (Ghimirey *et al.*, 2024).

Sources and Causes

The sources of nutrient stress in agricultural landscapes are represented by both anthropogenic activities and inherent pedological characteristics of soils. Among anthropogenic factors, it should be mentioned the uncontrolled application of artificial fertilizers and nanoparticulate agrochemicals, which might cause toxicity by reducing the optimal concentrations of mineral substances (Coskun *et al.*, 2025; Ghorbani *et al.*, 2024). Besides, the poor irrigation and drainage result in accumulation of saline substances such as chlorides and sulphates (Hussain *et al.*, 2022; Sahin *et al.*, 2024). At the same time, the intentional acidification of the soil induced by intensive nitrogen fertilization and industrial pollution leads to mobilization of aluminium and manganese that alter the rhizosphere geochemistry (Huang *et al.*, 2023). The natural factors that are connected with the weathering of the parent material and dramatic climate phenomena fluctuate the parameters of soil pH and redox potential, which either immobilize nutrients or make them available (Aloo *et al.*, 2023; Anand *et al.*, 2023). The environmental stressors, such as extreme heat and drought, increase the geochemical variations in the soil, thus disrupting ion homeostasis and producing reactive oxygen species within plants (Manzoor *et al.*, 2022). The anthropogenic effects are frequently combined with heavy metal contamination caused by the use of sewage sludge-based biosolids and contaminated water for irrigation (Rashid *et al.*, 2023). Heavy metal contamination is especially dangerous since it means that persistent elements enter the soil, bypassing the plant uptake regulation and causing the competitive inhibition of essential microelements such as zinc and iron (Akram *et al.*, 2025; Almotairy, 2024). In addition to chemical factors, the excessive waterlogging causes the additional nutrient losses due to leaching and soil acidification (Mackinnon and Stone, 2022). At last, in the case of tropical regions with high rainfall, the natural pedogenic processes with emphasis on leaching lead to creation of the bases unsaturated zone, thus restraining crop growth. Within heavily weathered soil landscapes, the process of downward water flux causes the leaching of exchangeable bases (e.g. calcium, magnesium) and results in the acidification of the soil that triggers the mobilization of phytotoxic aluminium ions (Huang *et al.*, 2023). Such a pedological restriction is often exacerbated by poor agricultural management, when the lack of replacement of base ions during intensive cultivation destroys the nutrient cycles.

Table 1: Classification of nutrient stress, major causes, plant responses, agricultural impacts, and representative references

Nutrient stress type	Major causes	Major plant responses	Agricultural consequences	References
Macronutrient deficiency (N, P, K, Ca, Mg, S)	Low soil fertility, nutrient mining, continuous cropping, leaching, soil acidity	Chlorosis, reduced photosynthesis, altered root architecture, reduced biomass, impaired enzyme activity	Yield reduction, poor grain quality, reduced nutrient-use efficiency	Fageria <i>et al.</i> , (2008); Andjelkovic (2018); Lazarevic <i>et al.</i> , (2022); Tossi <i>et al.</i> , (2022); Muhammad <i>et al.</i> , (2025)
Micronutrient deficiency (Fe, Zn, Mn, Cu, B, Mo, Cl)	High soil pH, calcareous soils, low organic matter, nutrient antagonism	Hidden hunger, impaired enzyme function, reduced chlorophyll synthesis, poor reproductive growth	Decline in crop nutritional quality and human micronutrient deficiency	Dimkpa and Bindraban (2016); Vigani <i>et al.</i> , (2013); Murgia <i>et al.</i> , (2021); Rengel (2015)
Nutrient toxicity	Soil acidification, salinity, excessive fertilization, heavy metal contamination	Oxidative stress, membrane damage, root inhibition, ROS accumulation	Growth suppression, poor nutrient uptake, reduced productivity	Pandey <i>et al.</i> , (2021); Tibbett <i>et al.</i> , (2021); Saleem <i>et al.</i> , (2022); Roorkiwal <i>et al.</i> , (2021)
Nutrient imbalance	Excess application of individual nutrients, improper fertilizer management	Disturbed nutrient homeostasis, metabolic dysfunction, altered ion transport	Lower fertilizer efficiency and environmental pollution	De Loose <i>et al.</i> , (2023); Oldroyd and Leyser (2020); Gojon <i>et al.</i> , (2022)

Soil Degradation Factors

The degradation of soil quality is caused by the improper agricultural practices (over-tillage, monoculture and deforestation), which lead to depletion of organic matter and the disruption of the soil structure (T and Rajeswari, 2025). These soil alterations make soil susceptible to erosion and nutrient mining, as the unstable aggregate structure makes the surface of the soil easy for erosion (Obade and Gaya, 2021; Srivastava *et al.*, 2017). In addition, the persistent usage of synthetic fertilizers may produce the nutrient imbalance, which will overload the buffering capacity of the soil and reduce the rate of microbial mineralization, thus decreasing the cycling speed of nutrients (Belay, 2024; Him *et al.*, 2026; Le *et al.*, 2021). Monoculture additionally reduces the soil nutrient levels, as it exhausts the soil reserves and facilitates the spread of pathogens specific for particular crops (Khan *et al.*, 2023). The absence of organic matter replenishment due to insufficient incorporation of plant residues limits the possibility of buffering chemical changes (Kuzuyakov and Zamanian, 2019). As a result, the structural and chemical degradation of soil becomes evident in form of the nutrient depletion, which, combined with erosion and sedimentation, reduces the global agricultural yields (Lal, 2015). The erosion rates on agricultural lands, which are much higher than in the natural soil formation process, actively strip nutrient-rich topsoil, thus destroying its productivity (Ramankutty *et al.*, 2018). The reduction of biological activity of soil, which is revealed by decrease in organic carbon pools, reduces the soil's capability to

provide the process of mineralization (Abshiba *et al.*, 2025; Soto *et al.*, 2020). Such a decline is exacerbated by the growing nutrient removal–use gap, which means that export of nutrients through the plant biomass outpaces their replenishment (Jones *et al.*, 2013; Medinets *et al.*, 2025). Such a phenomenon, known as nutrient mining, is exacerbated by the irrational usage of primary and secondary nutrients; namely, intensive nitrogen fertilization may often exceed the soil's buffering capacity (Wallace, 1994; Zhang *et al.*, 2016). Such chemical oversaturation may produce persistent nutrient imbalance, which causes the soil acidification and competitive inhibition of the uptake of micronutrients (Kannan *et al.*, 2024; Ullah *et al.*, 2023). As a result, the combination of chemical and structural decline reduces the restorative capacity of soil matrix due to the deficiency of biological and chemical buffers for the maintenance of the nutrient cycle and mineralization (Kibblewhite *et al.*, 2007; Mulvaney *et al.*, 2009). This decline is aggravated by the decoupling of biological return pathway, when the temporal and spatial movement of harvest residues disrupts feedback loops necessary for maintaining soil organic matter and nutrients (Hansen, 2026). The current situation with soil degradation is quite alarming since the majority of soil resources are considered to be poor or very poor (Khan *et al.*, 2023; T and Rajeswari, 2025). Such a trend represents the pervasive threat to global food security due to decreasing capability of soils to provide essential ecosystem services such as nutrient cycling, water retention and maintenance of microbial biodiversity (Lal,

2015). With the world population reaching 9.5 billion in 2050, the need of 70% increase in agricultural production emerges, which is undermined by soil degradation and land degradation as a result (Lal, 2015). The regions with already poor soils and lack of technology for restoration are particularly vulnerable to this threat, hence the importance of science-based interventions to address this problem (Le *et al.*, 2021; T and Rajeswari, 2025).

Climate Change Influence

The climate change serves as the factor that multiplies the soil degradation effects, as the changes in precipitation pattern increase the rate of nutrient leaching and water deficit that hinders nutrient availability for roots (Saleem *et al.*, 2024; Xing *et al.*, 2025). The excessive rainfall increases the process of nutrient leaching beyond the rhizosphere, while temperature-induced water deficit reduces the microbial mineralization rates, thus decoupling the nutrient supply and plant demands (Bibi and Rahman, 2023; Sakrabani, 2024). Temperature stress directly affects the physiology of plants by affecting metabolic rates and reducing transpiration-driven mass flow needed for nutrients uptake. The prolonged drought additionally reduces the availability of nutrients in the soil solution due to limited diffusion of nutrients, thus reducing the bioavailability of phosphorus and potassium despite the presence of nutrient stocks. The hydro-climatic instabilities are additionally exacerbated by accelerated decomposition of soil organic matter under rising temperatures, which causes the quick release of carbon from microbes while disturbing the nutrient sequestration (Amundson *et al.*, 2015; Gama, 2023). Such a combination of environmental and anthropogenic factors, including land use intensification and climate variability, shows that the global soils are facing the planetary boundaries now. The increase in climate volatility together with rapid growth of population and economy (Montanarella *et al.*, 2016; Rust *et al.*, 2022) require urgent changes in soil management to prevent degradation of about 33% of the global arable lands (Timilsina *et al.*, 2025). To deal with such instabilities, one should incorporate the principles of adaptive management, including deployment of stress-resistant genotypes and improvements in the cropping systems in order to ensure the nutrient bioavailability under environmental volatility (Lal, 2015; T and Rajeswari, 2025). In addition, the implementation of 4R nutrient stewardship, which includes proper selection of the source, rate, time and place, allows for optimizing nutrient utilization and minimizing losses in spite of erratic precipitation regime (Kannan *et al.*, 2024). Alongside with this, the regenerative practices such as organic amendment and maintenance of continuous

vegetative cover strengthen the soil structure and microbial resilience to buffer the thermal and moisture stresses that may affect nutrient supply (Gama, 2023; Xing *et al.*, 2025).

Agricultural Practices

The transition from conventional monoculture-based systems to integrated management systems is necessary to avoid the extraction-driven nutrient mining in intensive agriculture (Babarao *et al.*, 2026; Rashmi *et al.*, 2024). The conventional systems include the focus on yield maximization using the synthetics, while the integrated systems include the usage of crop diversification and nutrient management according to particular sites to restore the soil organic matter and optimize biological cycle (Kumar, 2026; T *et al.*, 2025). The monocultures enhance the nutrient depletion zones by applying uniform root architecture that exploits the same soil layers and leads to exhaustion of particular elements. Meanwhile, the regenerative practices such as crop rotation and intercropping diversify the nutrient uptake pattern and stimulate the microbial activity, thus enriching the soil biodiversity and restoring the disrupted ecological balance caused by intensive extraction (Asante *et al.*, 2025; Joshi *et al.*, 2026). In addition, the excessive fertilization in intensive system often ignores the balance of plant requirements, thus causing nutrient runoff and soil degradation in the long run (Yimer and Tarnawa, 2025). The systemic focus on high-input monocultures ignores

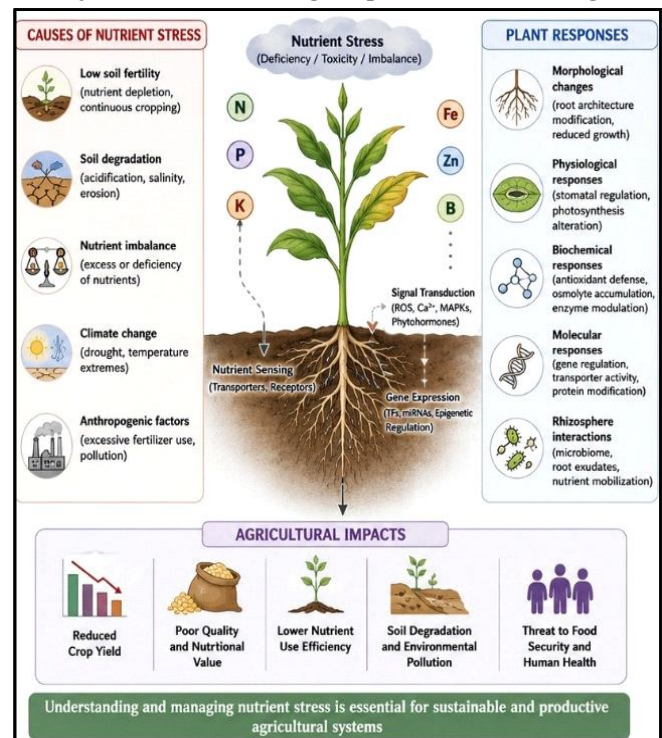


Fig. 1: Overview of nutrient stress in plants: Causes, Signaling, Physiological Responses and Impacts.

the important synchrony between microbial mineralization rates and nutrient fluxes.

Impact on Crop Productivity

The empirical research shows that the abiotic factors, particularly the nutrient–climate interactions, generate yield gaps, which usually surpass 30–50% in major cereals, thus threatening the nutritional security in economically vulnerable regions (Penuelas *et al.*, 2023; Singh *et al.*, 2025). The combination of nutrient scarcity with the other abiotic stressors, including salinity and extreme temperature changes, produces synergistic negative effect on crop physiology, thus reducing the effectiveness of fertilization regimes. Such a stress environment requires the transition to the precision nutrient management that uses remote sensing and machine learning to optimize the nutrient application and mitigate the effects of the fluctuations of soil condition (Paramesh *et al.*, 2023). The yield stagnation, combined with the growth of global population, demonstrates that the threshold has been reached when the inability of restoring the intrinsic soil fertility threatens the long-term food security (Selim, 2020). As a result, the decrease of soil nutrient availability not only affects the stability of global food supply but also causes the deficiencies in human population, which is dependent on the depleted cropping systems (Joshi *et al.*, 2026; Mamassi *et al.*, 2023). To solve such a problem, it is necessary to develop the mineral-efficient crops to increase the uptake of nutrients and to implement integrated soil fertility management to increase the global food and nutrition security. In addition, it is necessary to adjust the spatial imbalances in the fertilizer consumption in order to avoid stoichiometric mismatch that would constrain the yield potential in particular regions (McKenzie and Williams, 2015). With more than 2.0 billion people affected by the deficiencies caused by “hidden hunger,” the persistence of the depleted agricultural outputs represents the serious threat for global nutrition security (Joshi *et al.*, 2026). Such systemic degradation of dietary quality, combined with the increasing climate-driven stresses, which impede the nutrient assimilation in plants, requires the urgent transition to the integrated management system that will restore the soil mineral levels along with crop productivity (Babarao *et al.*, 2026).

Yield Reduction Effects

The abiotic stressors, in particular, the nutrient limitations, are associated with the yield losses from 50% to 80% in different cropping systems (García-García *et al.*, 2020). Such losses impose the great economic burden on the smallholder farmers, as they lose profits and

become indebted due to the necessity of escalating the usage of synthetic inputs in order to compensate for the depleted soil fertility (Dimkpa and Bindraban, 2016; Snapp *et al.*, 2023). For instance, in India, decades of intensive rice-wheat cropping system led to marked depletion of zinc soil levels, thus contributing to yield stagnation and deterioration of crop nutrient profile (Dimkpa and Bindraban, 2016). In sub-Saharan Africa, the region where 75% of arable lands experience significant fertility depletion, such nutrient shortages directly affect food insecurity and vulnerability to the mineral-related diseases (Adal and Mulat, 2024). In addition to direct yield impacts, the physiological interaction between the nutrient stress and such factors as phosphorus immobilization and salt-induced cation antagonism reduces the bioavailability of such essential elements as zinc and iron (Bindraban *et al.*, 2020; Ebbisa, 2022). Such an interaction creates the negative feedback loop, in which the climate-induced changes in soil moisture and pH levels further reduce the micronutrient availability and limit the production of nutritionally rich crops. The yield stagnation limits the income of smallholders, thus preventing investments in the soil restoration practices or good quality inputs that would increase yield (Dimkpa and Bindraban, 2016). As a result, the resource-poor households get locked into intensive and nutrient-depleting monocultures, causing the vicious circle of soil degradation and agricultural instability (Dimkpa and Bindraban, 2016; Snapp *et al.*, 2023).

Soil Health Decline

The persistent depletion of soil organic matter (SOM) serves as the main driver of long-term soil fertility decline, as the reduced level of carbon stocks weakens the soil structure and nutrient-retention capabilities (Hayat *et al.*, 2025). Such a process is facilitated by continuous monoculture and insufficient recycling of organic matter, accelerating the erosion of productive capacity (Mango *et al.*, 2017). In addition, the depletion of soil microbial diversity due to the continuous synthetic fertilizer application and the absence of biological substrates distorts the nutrient-cycling processes and nitrogen-fixing associations (Upadhyay *et al.*, 2023). The loss of mycorrhizal associations and beneficial rhizobacteria prevents the mineralization of organic nutrients in soil, thus requiring the usage of increasing amounts of synthetics to maintain the yields (Sagnon *et al.*, 2024). Such microbial shift increases the rapid oxidation of soil organic carbon, thus embedding the cycle of degradation that decreases the chemical and physical resilience of the agroecosystem. At the same time, the reduction of microbial activity impedes the immobilization of nitrogen and phosphorus, leading to the nutrient leaching and

impossibility of carbon sequestration in soil (Drinkwater and Snapp, 2022; Dwivedi *et al.*, 2013). The wide-scale conversion of the arable land, which may affect up to 65% of cultivated lands in particular regions, demonstrates the urgent need of adopting regenerative soil management practices to reverse this trend. To achieve regenerative outcomes, one should address the depletion of soil organic matter, which is recognized as the basic prerequisite for the soil health maintenance (Joshi *et al.*, 2026). The increase of carbon stocks increases cation exchange capacity and water retention, thus improving root-soil interaction and increasing nutrient availability (Joshi *et al.*, 2026). In addition, the increase of SOM supports the diversity of microbial communities, including arbuscular mycorrhizal fungi and rhizobacteria, which are necessary for nitrogen mineralization and phosphorus solubilization (Joshi *et al.*, 2026; Sagnon *et al.*, 2024). Thus, through the systematic restoration of such biological and chemical processes, farmers may become independent from “fertilizer treadmill” and create more resilient agroecosystems that will be able to buffer the nutrient scarcity and climate stresses (Babarao *et al.*, 2026; Drinkwater and Snapp, 2022).

Plant Physiological Responses

In order to survive under limiting nutrient conditions, plants evolve complex adaptation mechanisms starting from root architecture changes for efficient foraging in poor soil layers (Matson *et al.*, 1997 and Singh *et al.*, 2024). Indeed, increased lateral root branching and modified ratio of root vs shoot biomass become a flexible response of species aimed at efficient exploitation of nutrient-rich patches within the heterogeneous rhizosphere (Xing *et al.*, 2025). Besides these morphological changes, plants activate high-affinity transport systems responsible for phosphorus mobilization from legacy storage and simultaneously increase root exudation of organic acids to increase mineral nutrient solubility. Moreover, plants establish symbiosis with arbuscular mycorrhizal fungi that increases the effective surface area of roots and thus improves nutrient (phosphorus) uptake (Ogwu *et al.*, 2026). At the same time, many species experience internal physiological changes, such as increased remobilization of nutrients from senescing leaves to younger plant tissues and maintenance of large internal nutrient pools to overcome transient deficiencies (Bindraban *et al.*, 2015). Additionally, crops in limited nutrient environment can optimize these interactions by modifying their root exudates, for instance, secreting more carboxylates and phosphatases to activate legacy nutrient sources (Zhang *et al.*, 2022). Thus, physiological trade-offs indicate the priority of nutrients acquisition over biomass formation

and enable plants to retain the ability to perform basic metabolic processes in suboptimal fertility. Moreover, the production of Phyto siderophores by gramineous species represents a specific avoidance mechanism for iron and zinc acquisition, enabling chelation of these metals in the soils where they are chemically immobilized (Ebbisa, 2022; Palmer and Guerinot, 2009; Zuo and Zhang, 2008). This chelation-based mechanism includes the secretion of mugineic acid-family compounds into the rhizosphere that allows these plants to bypass bioavailability bottleneck in the constrained soil environments (Ebbisa, 2022; Hanikenne *et al.*, 2020).

Morphological Adaptations

Plants evolve a set of root architecture adaptations, including increased production of root hairs and increased root surface area, aimed at maximizing nutrient interception and acquisition for relatively immobile nutrients. In the case of phosphorus deficiency, morphological plasticity is accompanied by the development of cluster roots that accumulate carboxylates to solubilize mineral-bound phosphates (Etesami *et al.*, 2021 and Lopez *et al.*, 2023). Additionally, plants develop chlorotic patterns in their mature leaves due to nutrient redistribution from old leaves to young tissues in order to maintain photosynthesis capacity under nutrient deficiency. Apart from these physiological adaptations, plants activate phenological adaptations such as accelerated flowering or prolonged vegetation periods in order to synchronize their nutrient acquisition with ephemeral availability of soil nutrients (Oldroyd and Leyser, 2020). Such modifications incur great carbon costs, since root exudation and respiration consume a significant proportion of total plant assimilates (Sallaku *et al.*, 2022). As a result, breeding programs now focus on creating “Topsoil Foraging” ideotypes, which emphasize these energetically costly root phenotypes for maximizing phosphorus acquisition and decreasing metabolic costs of soil exploration. In addition, specific morphological traits such as increased cortical aerenchyma and increased amount of root hairs are important to increase nitrogen acquisition efficiency of plants and to make them more resistant to abiotic stresses such as soil acidity and compactness (Lynch, 2019). These root phenotypes allow plants to form rhizosheath, which creates a special chemically active environment around the root tips to optimize resource mining (Addesso *et al.*, 2023). This special layer of soil tightly connected with root systems due to interactions between root hairs, mucilage secretion, and microbiome activity helps to retain moisture and absorb nutrients (Huang *et al.*, 2025 and Li *et al.*, 2024). Within the rhizosheath, accumulated root

exudates modify rhizosphere chemistry by altering pH and mobilizing phosphorus and other micronutrients (Addesso *et al.*, 2023 and Li *et al.*, 2024).

Sustainable Management Strategies

The problem of nutrient deficiency can be addressed by the shift from synthetic inputs to integrated management schemes aimed at soil health and biological nutrient cycling (Koevoets *et al.*, 2016). Cover cropping, green manure use and precise nutrient application can significantly increase soil organic matter and thus ensure long-term nutrient availability and minimize metabolic costs of nutrient acquisition (Lynch *et al.*, 2021 and Satheesh and James, 2026). Nevertheless, the efficiency of such management strategies is strongly dependent on matching crop phenotype with edaphic constraints of specific sites, which can be observed in superior performance of ‘steep, cheap and deep’ ideotypes for nitrogen leaching deep soils compared to ‘topsoil foraging’ phenotypes specialized for phosphorus-limited tropical environments (Lynch, 2019). Although these specialized strategies show great promise, their scaling is limited by the intrinsic complexity of soil heterogeneity mapping and optimization of crop selection based on site conditions (Xing *et al.*, 2025). In addition, using of intercropping systems consisting of different root types and exudate profiles can help to achieve efficient rhizosphere development (Huang *et al.*, 2025). Intercropping can help to form synergies between different root systems and rhizosphere microbiome that can help to mobilize co-limiting nutrients and reduce dependence on external synthetic fertilizer application (Ebbisa, 2022; Zuo and Zhang, 2008). The efficiency of such intervention is critically dependent on proper combination of root traits to optimize spatial and temporal interactions. This fact implies the need for evidence-based crop selection that takes into account site-specific characteristics, which is complicated by the complexity of soil-root interactions. Addressing this problem requires the integration of high-throughput phenotypic monitoring and prediction for optimal crop selection based on specific edaphic constraints.

Biofortification Approaches

The use of microbial inoculants and biofertilizers allows to change rhizosphere conditions and thus mobilize mineral-bound phosphorus via the action of secreted microbial metabolites. These beneficial microbial associations such as mycorrhizal fungi not only increase the effective surface area but also allow plants to mine legacy phosphorus deposits that were otherwise unavailable for the host plant (Pavinato *et al.*, 2020). Meanwhile, compost and green manure application allows

to increase soil organic matter and thus to support the activity of these microbial communities (An *et al.*, 2023). Compost supplies soil with stable carbon and helps to increase soil structure and long-term nutrient retention, whereas green manures introduce a pulse of available nitrogen and carbon that stimulates intense microbial colonization and changes in rhizosphere pH to mobilize minerals (Honvault *et al.*, 2020). Comparison between these two interventions shows that green manures mainly increase the availability of nitrogen through rapid decomposition, whereas compost provides a more long-lasting increase in soil physical properties and phosphorus availability. The effectiveness of these interventions is strongly dependent on the interaction of microbial inoculants, chemical properties of soil and specific traits of crop species to increase nutrient use efficiency (Bargaz *et al.*, 2018). In addition, using molecular methods such as functional gene analysis allows to understand changes in microbial community structure after applying these interventions and thus helps in acceleration of soil restoration process. Using high-throughput metagenomics and transcriptomics, researchers can move beyond simple taxonomy and reveal functional potential of these communities by analyzing key pathways such as nitrogen fixation and phosphorus mineralization involved in ecosystem restoration (Bargaz *et al.*, 2018 and Xing *et al.*, 2025). This more detailed analysis allows to apply biofertilizers based on the real-time information about microbial colonization of root zone and their interaction with native microbiome under variable field conditions. Thus, the correlation of functional gene activity with nutrient uptake is an important benchmark for validation of biofortification interventions.

Integrated Nutrient Management

This approach centres on the synergistic combination of organic amendments, biofertilizers, and strategic synthetic inputs to balance immediate crop demands with long-term soil health (Weng, 2026). By adopting the 4R nutrient stewardship principles, Right source, Right rate, Right time, and Right place farmers can systematically minimize nutrient losses while maximizing input use efficiency (Batool, 2024). Aligning these practices with site-specific diagnostics—such as soil testing and crop demand modelling, ensures that the integration of mineral fertilizers with organic bio-stimulants promotes nutrient uptake while reducing the environmental footprint of excess leaching (Ali *et al.*, 2025 and Shahzad *et al.*, 2025). Furthermore, the application of PGPR-based biofertilizers within this integrated framework enhances nutrient bioavailability through nitrogen fixation and phosphate solubilization, effectively mitigating the

suppressive effects of intensive chemical fertilization on soil microbial diversity (Badiyal *et al.*, 2024; Shaaban *et al.*, 2025). To bridge the gap between theoretical potential and field-level implementation, modern multi-omics approaches are increasingly deployed to characterize complex plant-microbe symbioses, ensuring that bioformulations are specifically tailored to the unique metabolic demands of varying pedoclimatic conditions. Such precision-driven applications can be further augmented by encapsulating microbial agents within nanoparticles, which shields the inoculants from adverse field conditions and promotes a sustained, targeted delivery of bioactive compounds. Beyond these technological enhancements, overcoming adoption barriers requires addressing the scalability of these complex inputs, as farmers often face significant logistical and economic challenges when integrating multi-component bio-based systems into traditional management routines (Ait-El-Mokhtar *et al.*, 2025; Hakim *et al.*, 2021). These logistical challenges are further exacerbated by the short shelf-life of certain microbial inoculants and the lack of standardization across varied agro-ecosystems, necessitating the development of localized production infrastructures to ensure consistent performance. Simultaneously, bridging the knowledge gap through targeted farmer training and supportive regulatory frameworks is essential to facilitate the transition from experimental application to widespread, reliable adoption of these integrated strategies (Shaaban *et al.*, 2025 and Shahzad *et al.*, 2025).

Precision Agriculture Tools

The implementation of sensor-based deficiency diagnosis enables the real-time identification of nutrient stress, allowing for the deployment of variable rate technology to apply inputs precisely where needed (Ibanez *et al.*, 2023). By integrating these diagnostic sensors with decision support systems, producers can translate high-resolution spectral data into automated management protocols, thereby optimizing the synchronization between nutrient application and dynamic plant demand (Li *et al.*, 2025). These systems utilize advanced machine learning algorithms to process multispectral imagery and ground-truth soil sensor inputs, minimizing the uncertainty inherent in traditional blanket application methods. Furthermore, remote sensing technologies such as drone-based multispectral mapping allow for the high-resolution spatial monitoring of physiological distress signals, enabling the site-specific allocation of biocontrol agents and nutrient formulations to optimize recovery (Ayaz *et al.*, 2024). The integration of these diagnostic data streams into robust decision support systems is essential for scaling precision

nutrient management, as it reduces reliance on manual assessments and provides actionable insights for complex, site-specific interventions (Birgovan *et al.*, 2025; Verma *et al.*, 2024). However, the scalability of these precision systems remains constrained by the technical gap between sensor-based hardware processing capacity and the algorithmic requirements needed for real-time, field-edge nutrient application. Bridging this divide requires advancing edge-computing architectures that facilitate on-device processing of sensor data, thereby minimizing latency in variable rate application commands (Danesh, 2025; Khan, 2026). Furthermore, fostering cross-disciplinary collaboration between agronomists, data scientists, and agricultural engineers is essential to standardize these protocols and ensure that such high-tech interventions remain economically viable for producers (Danesh, 2025; Li *et al.*, 2025). By integrating diverse expertise, practitioners can simplify decision support interfaces, thereby mitigating the technical and operational complexities that often hinder the widespread adoption of variable rate technologies and remote sensing platforms in real-world farming environments (Birgovan *et al.*, 2025).

Future Research Directions

To catalyse the next generation of resilient agricultural systems, research should prioritize the development of model lightweighting and transfer learning, which facilitate the broader deployment of intelligent management systems across heterogeneous cultivars and environments (Hu *et al.*, 2025). Furthermore, investigating the hybridization of remote sensing indices, such as combining early-stage NDWI with mid-to-late growth stage markers is critical for establishing a continuous, longitudinal monitoring framework capable of detecting nutrient deficiencies before they induce irreversible physiological damage (Cohen *et al.*, 2025). Additionally, future efforts must focus on multi-sensor fusion and the integration of high-throughput phenotyping data to enhance the generalizability of predictive models under real-world, variable field conditions (Patra and Sahoo, 2025; Shi *et al.*, 2020). To support the operational scaling of these technologies, research should emphasize the economic feasibility of site-specific management through multi-location and multi-season validation protocols (Ramteke *et al.*, 2026). Moreover, prioritizing the coupling of mechanistic crop growth models with deep learning architectures offers a transformative pathway for achieving scalable, fine-scale yield estimation under diverse environmental stressors (Han *et al.*, 2024). Furthermore, integrative approaches should leverage edge-computing frameworks to enable localized, real-time

nutrient decision-making, significantly reducing reliance on cloud-based latency while maintaining model accuracy through collaborative task scheduling (Yu *et al.*, 2025; Dhanaraj *et al.*, 2025). Finally, policy frameworks must incentivize the development of centralized knowledge bases that curate long-term longitudinal data on nutrient transport and microbial-plant interactions to train more robust, site-specific machine learning models (Corti *et al.*, 2021; Zhang *et al.*, 2021). Complementing these technical advancements, policymakers should prioritize initiatives that bridge the digital divide and foster public-private partnerships, ensuring that precision agriculture tools remain equitable and accessible to smallholder farmers (Akintuyi, 2024). Establishing comprehensive regulatory governance frameworks is equally critical to ensure data sovereignty, ethical AI deployment, and the creation of international interoperability standards for agricultural technologies. Establishing comprehensive regulatory governance frameworks is equally critical to ensure data sovereignty, ethical AI deployment, and the creation of international interoperability standards for agricultural technologies. Furthermore, future investigations must fully exploit underutilized image features, such as texture, structure, and spatial distribution to enhance the precision of plant nutritional status recognition (Shi *et al.*, 2020). Unlike traditional spectral indices that primarily capture biochemical reflectance, these structural descriptors provide essential insights into canopy architecture and physiological vigour, which often deteriorate in response to prolonged nutrient imbalances. By integrating these multi-dimensional datasets through advanced deep learning frameworks, such as convolutional neural networks capable of capturing hierarchical spatial dependencies, investigators can further mitigate the confounding effects of environmental heterogeneity and ensure more robust, generalizable diagnostic performance across diverse field conditions (Patra and Sahoo, 2025).

Knowledge Gaps Identified

Current academic literature reveals a critical scarcity in large-scale, annotated image datasets that specifically account for the high variability of nutrient-stressed crops under diverse field conditions, limiting the training efficacy of modern deep learning models (You *et al.*, 2023). Moreover, there is an urgent need to standardize reporting practices regarding crop phenology and environmental metadata within these datasets, as inconsistent documentation currently restricts the cross-study utility of existing vegetation indices (Castilho *et al.*, 2024). Additionally, existing research lacks robust bias detection and mitigation methodologies, which are necessary to

prevent diagnostic errors that could disproportionately affect specific crop varieties or geographical regions (Shafay *et al.*, 2025). Furthermore, the industry must transition from static, single-point assessment models toward dynamic, explainable AI architectures that provide actionable insights and transparency for end-users (Ngugi *et al.*, 2024). Additionally, shifting research focus toward the detection of micronutrient deficiencies remains a priority, as current diagnostic models disproportionately emphasize macronutrient limitations (Gallegos *et al.*, 2024). Finally, there is an underexplored need to investigate how soil-microbiome interactions influence nutrient uptake, as current vision-based diagnostic tools often overlook below-ground biological drivers of observable stress (Sudhakar and Priya, 2023). Furthermore, longitudinal studies are essential to evaluate how seasonal climatic volatility modulates these plant-microbe feedback loops, thereby ensuring that predictive frameworks remain resilient amidst shifting environmental conditions (Muhammad *et al.*, 2025). Moreover, a significant research gap persists regarding the application of three-dimensional (3D) convolutional neural networks, as current reliance on two-dimensional imaging frequently fails to adequately capture the nuanced architectural responses to nutrient stress, such as shifts in leaf orientation or vertical canopy stratification, which are essential for robust diagnostics in high-density or structurally complex agricultural environments. Furthermore, future efforts should prioritize the development of multi-modal, sensor-integrated frameworks that combine RGB imagery with multispectral and environmental data to overcome current limitations in data dimensionality (Orka *et al.*, 2023). Integrating hyperspectral data into these pipelines offers a promising avenue to identify metabolic stressors long before they manifest as visual symptoms. Hyperspectral imagery provides rich spectral signatures that reveal biochemical fluctuations, such as alterations in photosynthetic pigments or water content, which act as early indicators of nutritional imbalance (Muhammad *et al.*, 2025). However, the high-dimensional nature of these datasets necessitates sophisticated data fusion techniques and dimensionality reduction strategies to avoid computational bottlenecks and ensure operational feasibility in real-time edge environments (Han *et al.*, 2024; Orka *et al.*, 2023). Future efforts must prioritize the synergistic integration of these spectral inputs with LiDAR and thermal data, leveraging advanced deep learning frameworks to map complex spatiotemporal stress dynamics with unprecedented resolution and diagnostic robustness (Muhammad *et al.*, 2025).

Emerging Technologies

The development of plant-inspired miniature machines equipped with real-time nutrient sensors represents a transformative leap in precision agrotechnology, enabling direct, non-destructive monitoring of soil-plant nutrient dynamics (Giovannetti *et al.*, 2023). These autonomous systems leverage edge computing architectures and lightweight model compression techniques to facilitate immediate on-site data processing and real-time decision-making (Upadhyay *et al.*, 2025). Moreover, deploying Generative Adversarial Networks to synthesize comprehensive training datasets allows these autonomous systems to uphold diagnostic robustness amidst the inherent variability of illumination and environmental conditions encountered in diverse agricultural fields (You *et al.*, 2023). Furthermore, the adoption of snapshot spectral imaging systems integrated onto autonomous aerial or ground platforms will significantly enhance data acquisition efficiency by bypassing the constraints of traditional line-scan sensors (Mishra *et al.*, 2020). By integrating these sensors with multispectral and hyperspectral imaging, stakeholders can achieve a comprehensive understanding of crop conditions and improve site-specific resource management (Atanasov, 2023). Furthermore, the widespread adoption of such technologies requires the establishment of standardized measurement and preprocessing protocols to ensure cross-platform data interoperability and long-term diagnostic reliability. Simultaneously, the integration of CRISPR-based biosensors into these autonomous platforms offers a frontier for the direct detection of molecular-level nutrient fluctuations, enabling unprecedented sensitivity in early-stage diagnosis (Gentile *et al.*, 2022). To fully realize these systems, research must focus on optimizing embedded chip performance and lightweight network architectures to overcome current limitations in real-time edge processing (Zhang *et al.*, 2022). Furthermore, the progression toward machine learning-based robotic platforms is critical to optimize nutrient-use efficiency, moving beyond simplified canopy colour assumptions to capture the complex interplay between initial crop status and forward-looking environmental variables. By synthesizing baseline physiological data with high-resolution spatiotemporal metrics, these systems can distinguish between transient nutrient deficiencies and stressors driven by factors like soil compaction or water availability, which frequently confound traditional optical assessments (Pearson *et al.*, 2022). Such integration facilitates the development of predictive models that anticipate crop requirements throughout the growth cycle, enabling precision

intervention rather than reactive, single-point management (Abdalla *et al.*, 2020). Consequently, shifting from descriptive imaging to causal, process-based diagnostic frameworks represents an essential evolution for enabling site-specific, adaptive agricultural management that sustains yield stability under unpredictable climatic regimes (Abdalla *et al.*, 2020 and Pearson *et al.*, 2022).

Conclusion

Achieving this paradigm shift necessitates transdisciplinary collaboration to harmonize autonomous robotics, sophisticated data fusion, and biotechnological innovations into cohesive, self-optimizing ecosystems (Atefi *et al.*, 2021 and Shinwari *et al.*, 2026). By leveraging the synergy between real-time IoT monitoring and data-driven machine learning models, these systems can significantly enhance resource-use efficiency and mitigate the environmental impacts of nutrient management (Khoddamzadeh *et al.*, 2026 and Zhang *et al.*, 2025). Ultimately, the transition toward autonomous, high-resolution diagnostic platforms remains pivotal for securing global food productivity by enabling precise, variable-rate nutrient applications tailored to fluctuating environmental stressors (Jaiswal *et al.*, 2025 and Sharma and Shivandu, 2024). Moreover, the shift toward these proactive, sensor-integrated infrastructures is essential to overcome the limitations of traditional, manual diagnostic methods that are increasingly incapable of addressing modern agricultural demands (Batool *et al.*, 2026; Cohen *et al.*, 2026). Ultimately, this technological evolution will foster a transition from reactive farming to predictive, site-specific management, effectively closing the persistent yield gaps seen in modern production systems (Colaço *et al.*, 2024). Expanding the geographic scope of these integrated analytical frameworks to include diverse climatic and soil conditions will be essential to establish generalized, scalable strategies for global agricultural resilience (Akanbi *et al.*, 2024; Shuai *et al.*, 2023).

Furthermore, by bridging the divide between plant science, engineering, and data analytics, such holistic approaches will be instrumental in minimizing synthetic input overuse while simultaneously bolstering crop productivity under the constraints of a changing climate. These integrated frameworks represent a necessary evolution toward adaptive, self-optimizing agricultural systems that harmonize food security with rigorous ecological stewardship (Shinwari *et al.*, 2026). By enabling site-specific, data-driven management of nutrient applications, such innovations will substantially enhance resource-use efficiency and reduce environmental footprints, ultimately fostering a sustainable pathway to

address the escalating complexities of modern food production (Khoddamzadeh *et al.*, 2026 and Zhang *et al.*, 2025). Future research must prioritize the development of robust, cost-effective sensor arrays to facilitate the widespread democratization of these diagnostic tools across varied agricultural landscapes (Sharma and Shivandu, 2024). Such initiatives are essential for lowering adoption barriers and ensuring that high-fidelity monitoring becomes accessible to resource-limited producers, ultimately bridging the technological divide and bolstering agricultural resilience on a global scale (Shinwari *et al.*, 2026).

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