



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; 9(1): 860-866
Received: 16-10-2025
Accepted: 22-11-2025

Deshmukh Sarita Babarao
Ph.D. Scholar, Department of Agronomy,
College of Agriculture, Kerala Agricultural
University, Thiruvananthapuram, Kerala,
India

Harshavardhan Mohan Totawar
Ph.D. Scholar, Department of Vegetable
Science, College of Agriculture, Vellayani,
Kerala Agricultural University,
Thiruvananthapuram, Kerala, India

Laxmi PS
Ph.D. Scholar, Department of Postharvest
Management, College of Agriculture,
Vellanikkara, Kerala Agricultural University,
Thrissur, Kerala, India

Yogesh V Wayal
Ph.D. Scholar, Department of Genetics and
Plant Breeding, College of Agriculture,
Vellayani, Kerala Agricultural University,
Thiruvananthapuram, Kerala, India

V Siva Teja
Ph.D. Scholar, Department of Floriculture and
Landscaping, College of Agriculture,
Vellanikkara, Kerala Agricultural University,
Thrissur, Kerala, India

Choudhari Balaji Keshavrao
Ph.D. Scholar, Department of Agronomy,
College of Agriculture, Vellayani, Kerala
Agricultural University, Thiruvananthapuram,
Kerala, India

Jagmal P Khatana
M.Sc. Scholar, Department of Agronomy,
Chimanbhai Patel College of Agriculture,
Sardarkrushinagar Dantiwada Agricultural
University, Sardarkrushinagar, Banaskantha,
Gujarat, India

Sruthi T
Ph.D. Scholar, Department of Genetics and
Plant Breeding, College of Agriculture,
Vellayani, Kerala Agricultural University,
Thiruvananthapuram, Kerala, India

N Sravya
Ph.D. Scholar, Department of Agronomy,
College of Agriculture, Vellayani, Kerala
Agricultural University, Thiruvananthapuram,
Kerala, India

Khushal B Muradi
Ph.D. Scholar, Department of Vegetable
Science, College of Agriculture, Vellanikkara,
Kerala Agricultural University, Thrissur,
Kerala, India

Corresponding Author:
Choudhari Balaji Keshavrao
Ph.D. Scholar, Department of Agronomy,
College of Agriculture, Vellayani, Kerala
Agricultural University, Thiruvananthapuram,
Kerala, India

Nutrient management strategies under climate extremes: Implications for sustainable and climate-resilient agriculture

Deshmukh Sarita Babarao, Harshavardhan Mohan Totawar, Laxmi PS, Yogesh V Wayal, V Siva Teja, Choudhari Balaji Keshavrao, Jagmal P Khatana, Sruthi T, N Sravya and Khushal B Muradi

DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i11.4812>

Abstract

Climate change is intensifying the frequency and severity of climate extremes such as heat waves, droughts, floods, erratic rainfall, and cold stress, posing serious threats to agricultural productivity and soil nutrient sustainability. These extremes disrupt soil-plant-nutrient interactions by altering nutrient cycling, microbial activity, nutrient availability, and plant uptake mechanisms, ultimately reducing fertilizer use efficiency and crop yields while increasing nutrient losses and greenhouse gas emissions. Conventional blanket fertilizer recommendations and excessive reliance on inorganic fertilizers have proven inadequate under such variable and stress-prone conditions, leading to soil degradation, micronutrient deficiencies, eutrophication, and enhanced nitrous oxide emissions.

This review synthesizes current knowledge on nutrient dynamics under climate extremes, highlighting changes in carbon-nitrogen-phosphorus interactions, soil biological processes, and micronutrient availability. It critically evaluates the vulnerability of traditional nutrient management practices and emphasizes the need for climate-resilient approaches. Key strategies discussed include integrated nutrient management, precision nutrient management, optimized nutrient timing and placement, climate-smart fertilizers, and crop-based adaptations such as diversification, legume inclusion, cover cropping, and development of nutrient-efficient and stress-tolerant varieties. The review further examines nutrient management interventions tailored to major climate extremes drought, flooding, and heat stress and their role in mitigating greenhouse gas emissions while enhancing soil carbon sequestration.

Finally, the review underscores the importance of region-specific, socio-economically viable, and policy-supported nutrient management frameworks. Addressing existing knowledge gaps through interdisciplinary research and emerging technologies is essential for achieving sustainable, climate-resilient agriculture that balances productivity, environmental protection, and long-term food security.

Keywords: Climate change, Climate extremes, Nutrient management, Integrated nutrient management, Precision agriculture, Soil nutrient dynamics, Nutrient use efficiency, Soil-plant interactions, Climate-smart agriculture, Greenhouse gas emissions, Soil carbon sequestration, Sustainable agriculture, Crop resilience, Fertilizer management

Introduction

Background: Climate Change and Increasing Frequency of Climate Extremes

Climate change poses significant challenges to global food security by disrupting agricultural systems through increased temperatures, altered precipitation patterns, and extreme weather events (Yimer *et al.*, 2025) ^[45]. Rising temperatures, altered precipitation patterns, and increasingly frequent extreme weather events severely degrade soil structure, reduce fertility, and disrupt biodiversity, accelerating soil erosion and nutrient depletion (Rashmi *et al.*, 2024) ^[35]. Without transformative adaptation strategies, climate change is projected to reduce global crop yields and increase food insecurity, while rising greenhouse gas emissions further exacerbate the crisis (Kabato *et al.*, 2025) ^[12].

Importance of Nutrient Management in Sustainable Agriculture

Traditional nutrient management practices, often reliant on excessive chemical fertilizer use, contribute to nutrient losses, soil degradation, and greenhouse gas emissions (Yimer *et al.*, 2025) ^[45]. Integrated Nutrient Management (INM) is a critical strategy in sustainable agriculture to maximize the utilization of organic and inorganic nutrient sources to sustain soil fertility, increase crop productivity, and minimize environmental degradation (Yadav *et al.*, 2025) ^[13]. Over four decades, reduced use of organic manure and injudicious use of inorganic fertilizer led to declining trends of organic carbon and pose serious global warming threats to the environment (Kannan *et al.*, 2015) ^[14].

Linkages Between Nutrient Dynamics, Crop Productivity, and Climate Resilience

Climate change highlights multifaceted impacts on soil nutrient cycles, microbial activity, crop physiology, and crop yield, with elevated temperatures and CO₂ levels significantly affecting nutrient availability and uptake (Yimer *et al.*, 2025) ^[45]. The availability, acquisition and translocation of phosphorus are influenced by fluctuation of temperatures, pH, drought and elevated carbon dioxide, with both lower and higher soil temperatures reducing uptake and translocation (Maharajan *et al.*, 2021) ^[23]. Changing climate highly influences crop phenology, physiology, root morphology and uptake mechanism, making it inevitable to understand climate change mediated changes in soil nutrient availability and plant nutrient uptake in different ecosystems (Kannan *et al.*, 2015) ^[14].

Knowledge Gaps and Rationale for the Review

In the past two decades, decreasing trends of nutrient utilization efficiency and deficiency of micronutrients rendered land barren under changing climate, but direct impact of climate change on nutrient availability and uptake mechanism has not been understood (Kannan *et al.*, 2015) ^[14]. Future research is needed on chemical, molecular, microbiological and physiological aspects to improve understanding on how temperature, pH, drought and elevated CO₂ affect the availability, acquisition and transport of nutrients by plants (Maharajan *et al.*, 2021) ^[23]. There is an urgent need for better nutrient management strategies to secure nutrient supply and ensure long-term protection of soil fertility while avoiding environmental impacts (Maharajan *et al.*, 2021) ^[23].

Objectives and Scope of the Review

The scope encompasses systematic analysis of nutrient management strategies under climate change, evaluating climate change's impacts on soil nutrient cycles, microbial activity, crop physiology, and yield (Yimer *et al.*, 2025) ^[45]. The review aims to explore innovative strategies to enhance soil resilience, with focus on conservation agriculture, cover cropping, and integrated nutrient management to mitigate adverse effects of climate change and preserve vital ecosystem services (Rashmi *et al.*, 2024) ^[35]. The objective includes examining climate-smart agriculture as a key strategy for enhancing crop productivity, building climate resilience, and reducing greenhouse gas emissions while emphasizing strategic interventions for large-scale implementation (Kabato *et al.*, 2025) ^[12].

Climate Extremes Affecting Agricultural Nutrient Management

Types of Climate Extremes

Heat Waves and Rising Temperatures: Heat waves and

elevated temperatures severely disrupt nutrient management systems. (Vogel *et al.*, 2019) ^[43] found that temperature-related extremes show stronger associations with yield anomalies than precipitation factors across major crops globally. (Maharajan *et al.*, 2021) ^[23] specifically notes that both lower and higher soil temperatures reduce phosphorus uptake and translocation, directly affecting plant nutrition. Rising temperatures also accelerate soil organic matter decomposition, altering nutrient availability patterns.

Droughts and Prolonged Dry Spells

Drought conditions create multiple nutrient management challenges. (Sivakumar *et al.*, 2020) ^[40] identifies droughts as potentially disastrous extreme events for agriculture in developing countries. (Ashokan *et al.*, 2024) ^[1] explains that drought stress is among the abiotic factors causing 51-82% reductions in crop productivity. (Maharajan *et al.*, 2021) ^[23] notes that drought conditions affect phosphorus availability, acquisition, and translocation by plants, disrupting essential nutrient processes.

Floods and Waterlogging

Flooding and waterlogging events cause immediate and long-term nutrient disruptions. (Sivakumar *et al.*, 2020) ^[40] categorizes flash floods among the extreme events with direct physical damage to crops and indirect effects on production capacity. (Ashokan *et al.*, 2024) ^[1] identifies waterlogging stress as a major abiotic factor reducing crop productivity, while waterlogged conditions typically lead to anaerobic soil conditions that alter nutrient transformation processes.

Erratic Rainfall and Extreme Precipitation

Events Irregular precipitation patterns fundamentally disrupt nutrient cycling. (Vogel *et al.*, 2019) ^[43] found that while temperature extremes had stronger effects, precipitation-related factors still significantly influenced crop yield anomalies. (Yimer *et al.*, 2025) ^[45] emphasizes that altered precipitation patterns are among the key climate change factors disrupting agricultural nutrient dynamics and threatening environmental sustainability.

Cold Stress and Frost

Events Cold stress and frost create region-specific nutrient management challenges. (Sivakumar *et al.*, 2020) ^[40] includes cold waves and winter storms among extreme events affecting agriculture. (Ashokan *et al.*, 2024) ^[1] identifies temperature variations, including cold stress, as having overwhelming impacts on crop growth and productivity, while (Maharajan *et al.*, 2021) ^[23] notes that lower soil temperatures specifically reduce phosphorus uptake and translocation.

Impacts of Climate Extremes on Soil-Plant-Nutrient Systems Alterations in Nutrient Cycling and Transformation

Climate extremes fundamentally alter how nutrients cycle through soil-plant systems. (Yimer *et al.*, 2025) ^[45] highlights that climate change disrupts soil nutrient cycles and microbial activity, which are essential for nutrient transformation processes. (Rashmi *et al.*, 2024) ^[35] explains that altered precipitation patterns and extreme weather events disrupt nutrient cycling processes, while temperature changes affect the rate of organic matter decomposition and nutrient release.

Effects on Nutrient Availability and Uptake: Climate extremes directly impact how plants access and absorb nutrients.

(Maharajan *et al.*, 2021) ^[23] provides specific evidence that temperature fluctuations, pH changes, and drought conditions all influence phosphorus availability, acquisition, and translocation. (Ashokan *et al.*, 2024) ^[1] notes that abiotic stresses increase reactive oxygen species levels and affect physiological processes, ultimately reducing nutrient uptake efficiency and plant growth.

Nutrient Losses Through Multiple Pathways

Climate extremes accelerate nutrient losses through various mechanisms. (Yimer *et al.*, 2025) ^[45] identifies that traditional practices contribute to nutrient losses, which are exacerbated under climate change conditions. (Rashmi *et al.*, 2024) ^[35] specifically mentions that extreme weather events accelerate soil erosion and nutrient depletion, while (Nasiro *et al.*, 2024) ^[30] emphasizes that inefficient nutrient use leads to problems like nitrate leaching and nitrous oxide emissions, which are worsened by climate variability.

Soil Nutrient Dynamics under Climate Extremes

Carbon-Nitrogen-Phosphorus Interactions Under Climate Extremes

Changes in mineralization and immobilization

Climate extremes fundamentally disrupt the coupled cycling of carbon, nitrogen, and phosphorus in soils. (Mooshammer *et al.*, 2017) ^[28] demonstrated that temperature disturbances like freeze-thaw and heat events cause a decoupling of these nutrient cycles, with carbon and nitrogen processes initially accelerating while phosphorus cycling becomes down-regulated. This decoupling represents a critical shift from the normally synchronized nutrient transformations that maintain ecosystem stability.

Regarding mineralization and immobilization processes, (Mooshammer *et al.*, 2017) ^[28] found that while carbon and nitrogen mineralization rates initially increased following temperature extremes, they recovered relatively quickly. However, phosphorus mineralization showed prolonged suppression and much slower recovery rates, indicating that extreme events can create lasting imbalances in nutrient availability that persist well beyond the initial disturbance period.

Soil organic matter stability under extreme conditions

Soil organic matter stability becomes compromised under extreme conditions as (Singh *et al.*, 2021) ^[39] explains that climate change affects soil microbial community composition and metabolic activities, which are fundamental controllers of organic matter decomposition and nutrient storage. (Powlson *et al.*, 2015) ^[35] emphasizes that soil organic matter represents a large reservoir of nutrients that are released through microbial action, making its stability crucial for sustained nutrient supply.

Micronutrient Availability and Deficiency Risks

Climate-induced changes in micronutrient solubility

Climate-induced changes significantly alter micronutrient solubility and availability in soils. (Soares *et al.*, 2019) ^[41] documents that climate change factors, particularly elevated CO₂, temperature changes, and altered precipitation patterns, directly influence the soil availability of essential micronutrients including iron, potassium, and other minerals. These changes occur through modifications in soil pH, moisture content, and microbial activity that control nutrient solubility.

Impacts on crop nutrition and quality

The impacts on crop nutrition and quality are substantial, as (Soares *et al.*, 2019) ^[41] demonstrates that climate change affects the accumulation of minerals and proteins in crop plants, with elevated CO₂ being the primary driver of most reported nutritional changes. (Pilbeam *et al.*, 2015) ^[33] notes that understanding these climate-nutrient interactions is crucial for crop breeding programs aimed at maintaining nutritional quality under changing conditions.

Soil Biological Processes

Response of soil microbes and enzymes to extremes

Soil microbes and enzymes show complex responses to climate extremes that vary depending on the type and intensity of stress. (Singh *et al.*, 2021) ^[39] explains that microbial communities, which are the mainspring for key processes like decomposition and mineralization, experience altered composition and physiological activities under climate change drivers including increased temperatures and changed precipitation patterns. (Mooshammer *et al.*, 2017) ^[28] found that extracellular enzyme activities respond differently to stress compared to intracellular microbial processes, with enzyme responses being more dependent on resource nutrient content.

Implications for nutrient use efficiency

The implications for nutrient use efficiency are significant, as (Medhi *et al.*, 2021) ^[24] notes that soil microbiota are both originators and extenuators of greenhouse gases while simultaneously controlling nutrient transformations. (Hamel *et al.*, 2004) ^[9] emphasizes that nitrogen losses from soil are reduced in systems where nitrogen release corresponds to plant demand, but climate extremes can disrupt this synchronization. The research suggests that maintaining microbial diversity and function is essential for preserving nutrient use efficiency under changing climate conditions.

Vulnerability of Conventional Nutrient Management Practices

Limitations of Blanket Fertilizer Recommendations

Conventional nutrient management relies heavily on one-size-fits-all fertilizer recommendations that fail to account for site-specific conditions and temporal variability. (Liu *et al.*, 2025) ^[20] demonstrates that blanket fertilization methods show inferior efficiency compared to precision approaches. (Miao *et al.*, 2011) ^[25] emphasizes that crop yield responses to nitrogen fertilization vary significantly year-to-year due to weather conditions and indigenous nutrient supply, making prescriptive approaches inadequate for optimal nutrient management.

Reduced Fertilizer Use Efficiency under extremes

Current fertilizer use efficiency is alarmingly low across major cropping systems. (Miao *et al.*, 2011) ^[25] reports nitrogen-uptake efficiency of only 28.3%, 28.2%, and 26.1% for rice, wheat, and maize respectively, with intensive agricultural regions experiencing less than 20% efficiency. (Nakachew *et al.*, 2024) ^[29] found that farmers in sub-Saharan Africa receive only \$0.50 in increased productivity for every dollar spent on fertilizer due to these inefficiencies.

Environmental Consequences: GHG emissions, eutrophication, soil degradation

Conventional practices generate severe environmental impacts through multiple pathways. (Wu *et al.*, 2015) ^[44] documents substantial reactive nitrogen losses and greenhouse gas emissions under traditional management systems. (Miao *et al.*,

2011)^[25] identifies over-application of nitrogen fertilizers as causing significant soil acidification, decreasing soil pH by 0.13 to 2.20 units, alongside surface and groundwater pollution. (Shah *et al.*, 2024)^[38] further confirms that non-adherence to recommended practices, coupled with residue burning, adversely affects soil health and water quality, with multiple fertilizers and pesticides detected in groundwater systems.

Climate-Resilient Nutrient Management Strategies **Integrated Nutrient Management (INM)**

Integrated Nutrient Management (INM) represents a comprehensive approach that synergistically combines organic and inorganic nutrient sources to optimize soil fertility and crop productivity. This strategy emphasizes the balanced use of chemical fertilizers alongside organic materials such as crop residues, compost, and green manures (Yadav *et al.*, 2025)^[13]. The integration helps restore soil health, enhance nutrient use efficiency, and provide sustained nutrient release while reducing dependence on chemical fertilizers alone (Kushwah *et al.*, 2023). INM also incorporates beneficial microbial inoculants like *Rhizobium*, *Azospirillum*, and phosphate-solubilizing bacteria to enhance biological nitrogen fixation and nutrient availability (Yadav *et al.*, 2025)^[13].

Precision Nutrient Management

Precision Nutrient Management focuses on site-specific nutrient application using advanced technologies and data-driven approaches. This strategy employs sensors, decision support tools, and digital agriculture platforms to optimize nutrient delivery based on real-time crop needs and soil conditions (Nasiro *et al.*, 2024)^[30]. The approach follows the “4 Rs” principle - Right rate, Right source, Right application method, and Right timing - to ensure nutrients are applied when and where they are most beneficial (Nasiro *et al.*, 2024)^[30]. Variable rate fertilizer application and tools like optical sensors enable real-time nitrogen application adjustments during the growing season, supporting cost-effective and environmentally sustainable practices (Nasiro *et al.*, 2024)^[30].

Nutrient Timing, Placement, and Form

Nutrient Timing, Placement, and Form strategies optimize how, when, and where nutrients are delivered to crops. Split application strategies help synchronize nutrient supply with plant uptake patterns, reducing losses and improving efficiency (Kannan *et al.*, 2015)^[14]. Deep placement techniques and controlled-release fertilizers ensure nutrients are positioned optimally in the soil profile and released gradually to match crop demand (Nimanka *et al.*, 2023)^[32]. Under stress conditions, foliar nutrition provides an alternative pathway for nutrient delivery when root uptake may be compromised, offering flexibility in nutrient management during adverse weather events (Kannan *et al.*, 2015)^[14].

Climate-Smart Fertilizers

Climate-Smart Fertilizers encompass innovative fertilizer technologies designed to enhance nutrient efficiency while reducing environmental impact under changing climate conditions. Slow- and controlled-release fertilizers provide sustained nutrient availability while minimizing losses through leaching and volatilization (Nimanka *et al.*, 2023)^[32]. Nitrification and urease inhibitors help reduce nitrogen losses and greenhouse gas emissions, while biofertilizers and microbial consortia enhance soil biological activity and nutrient cycling (Yadav *et al.*, 2025)^[13]^[13]. These technologies represent

sustainable alternatives to traditional synthetic fertilizers, offering improved climate resilience and reduced environmental footprint (Nimanka *et al.*, 2023)^[32].

Crop-Based Nutrient Adaptation Strategies

Crop Diversification and Rotations -

Legume Inclusion and Biological Nitrogen Fixation

Legume inclusion in cropping systems provides significant benefits through symbiotic nitrogen fixation (SNF), which reduces dependence on nitrogen fertilizers (Li *et al.*, 2023)^[19]. Legumes like soybean can acquire nitrogen through their symbiotic relationships with rhizobial bacteria, making them valuable participants in rotation and intercropping systems or as green manure cover crops (Li *et al.*, 2023)^[19]. This biological nitrogen fixation process helps mitigate excessive fertilizer use while maintaining soil fertility and crop productivity.

Cover Crops and Nutrient Scavenging

Cover crops enhance nutrient acquisition through specialized root modifications and scavenging mechanisms. Plants develop larger root systems, longer root hairs, and thinner roots to explore more soil zones for limited nutrients (Balemi *et al.*, 2012)^[2]. These crops also form symbiotic associations with mycorrhizal fungi to enhance nutrient uptake and can exude organic acids, protons, and enzymes like phosphatases to improve nutrient availability (Balemi *et al.*, 2012)^[2].

Stress-Tolerant and Nutrient-Efficient Crop Varieties

Breeding for Nutrient Use Efficiency

Breeding strategies focus on improving both nutrient acquisition efficiency and utilization efficiency in crops (Chen *et al.*, 2017)^[4]. This involves developing varieties that can take up more nutrients under limiting conditions and produce higher yields per unit of nutrient absorbed (Balemi *et al.*, 2012)^[2]. Genetic improvement targets the molecular basis of nutrient efficiency, including regulation of gene expression and development of high-affinity nutrient transporters (Chen *et al.*, 2017)^[4].

Root Traits Enhancing Nutrient Uptake Under Stress

Root architecture modifications are crucial for improving crop nutrient efficiency under stress conditions (Li *et al.*, 2016)^[5]. Plants adapt by inhibiting primary root growth while promoting lateral root and root hair development to explore larger soil volumes (Francis *et al.*, 2023)^[7]. Additional root-based mechanisms include enhanced exudation of organic compounds, improved cytoplasmic nutrient homeostasis, and increased expression of nutrient transporters, all contributing to better nutrient acquisition under stressful conditions (Balemi *et al.*, 2012)^[2]. Landrace germplasm provides valuable genetic resources for identifying alleles that enhance nutrient uptake efficiency and stress adaptation (Dwivedi *et al.*, 2016)^[5].

Nutrient Management for Major Climate Extremes

Nutrient Strategies under Drought Conditions

Managing nutrient concentration and mobility

Managing nutrient concentration and mobility: Under drought conditions, nutrient availability and uptake are significantly compromised due to reduced soil moisture and restricted root growth (Kouame *et al.*, 2024)^[16]. Plants adopt avoidance strategies including stomatal closure, reduced photosynthesis, and suppressed transpiration to maintain water status (Kouame *et al.*, 2024)^[16]. The reduced water availability limits nutrient mobility in soil, making it crucial to optimize fertilizer placement and timing to ensure nutrients remain accessible to

plant roots during water-stressed periods.

Role of organic amendments and soil moisture conservation

Role of organic amendments and soil moisture conservation: Organic amendments play a critical role in drought mitigation by improving soil structure and water retention capacity (Kouame *et al.*, 2024) ^[16]. The integration of organic and inorganic fertilizers through Integrated Soil Fertility Management (ISFM) has proven effective in semi-arid zones where drought stress is severe (Kouame *et al.*, 2024) ^[16]. Organic matter application helps maintain soil moisture, reduces soil temperature, and provides slow-release nutrients that remain available during extended dry periods. Cover crops and mulching techniques further enhance soil moisture conservation while contributing organic matter to the system.

Nutrient Management under Flooding and Waterlogging

Nitrogen losses and mitigation strategies

Nitrogen losses and mitigation strategies: Soil waterlogging promotes significant nitrogen losses through multiple pathways including denitrification, leaching, and runoff (Kaur *et al.*, 2020) ^[15]. Under anaerobic conditions created by waterlogging, soil redox potential decreases, leading to the reduction of nitrate to gaseous forms through denitrification processes (Kaur *et al.*, 2020) ^[15]. Studies show that waterlogged soils can lose 1.1-2.6% of applied nitrogen fertilizer as N₂O compared to only 0.03-0.04% in non-waterlogged conditions (Kaur *et al.*, 2020) ^[15]. Mitigation strategies include the use of enhanced efficiency fertilizers, controlled-release formulations, and nitrification inhibitors to reduce nitrogen losses during flooding events.

Use of nitrate-tolerant crops and fertilizers

Use of nitrate-tolerant crops and fertilizers: Management practices for waterlogged conditions include selecting flood-tolerant crop varieties and implementing adaptive nutrient management strategies (Kaur *et al.*, 2020) ^[15]. Rescue nitrogen applications after waterlogging events have shown effectiveness, with post-flood urea applications containing urease inhibitors successfully increasing yields in corn waterlogged for up to 3 days (Kaur *et al.*, 2020) ^[15]. The timing and source of nitrogen application become critical, with split applications and enhanced efficiency fertilizers providing better nutrient use efficiency under waterlogged conditions.

Nutrient Management under Heat Stress

Nutrient interactions with heat tolerance

Nutrient interactions with heat tolerance: Heat stress significantly affects nutrient uptake and plant metabolism, requiring specific management approaches (Kouame *et al.*, 2024) ^[16]. Plants under heat stress exhibit increased respiration rates and altered photosynthetic activity, which affects their nutrient requirements and utilization efficiency (Kouame *et al.*, 2024) ^[16]. The combination of drought and heat stress creates unique transcriptional responses in plants, with specific genes being upregulated to cope with the combined stress conditions (Kouame *et al.*, 2024) ^[16].

Micronutrient and potassium management

Micronutrient and potassium management: Under heat stress conditions, micronutrients and potassium play crucial roles in maintaining plant physiological functions (Ashokan *et al.*, 2024) ^[1]. Nutrients such as nitrogen, potassium, calcium, and magnesium increase the production of antioxidant enzymes including superoxide dismutase, peroxidase, and catalase, which

help reduce reactive oxygen species production under heat stress (Ashokan *et al.*, 2024) ^[1]. Micronutrients such as iron, boron, and zinc, along with biofertilizers, improve plant adaptation to heat stress through the activation of antioxidant enzyme systems (Ashokan *et al.*, 2024) ^[1]. Proper potassium management is particularly important as it helps maintain cellular osmotic balance and enzyme activation during high-temperature stress periods.

Nutrient Management, Greenhouse Gas Emissions, and Climate Mitigation

Nitrous Oxide Emissions and Agricultural Significance

Nitrous oxide (N₂O) is a potent greenhouse gas with a global warming potential approximately 298 times that of carbon dioxide over a 100-year period "The role of nutrient management in mitigation". Agriculture is responsible for about 3% of total greenhouse gas emissions through N₂O, contributing approximately one-third of non-CO₂ agricultural emissions, primarily from nitrogen fertilizer applications and soil microbial processes (Wajid *et al.*, 2025) ^[26].

Mechanisms of N₂O Production and Reduction

N₂O is produced through microbial transformations of nitrogen in soil under both aerobic and anaerobic conditions, specifically through nitrification and denitrification processes (Wajid *et al.*, 2025) ^[26]. Emissions are directly related to nutrients added through mineral fertilizers and animal manure, though these additions are highly inefficient, leading to nitrogen losses via leaching, volatilization, and atmospheric emissions "The role of nutrient management in mitigation".

Nutrient Management Strategies for Emission Reduction

Effective nutrient management includes optimizing fertilizer types, application rates, timing, and placement to reduce N₂O emissions (Wajid *et al.*, 2025) ^[26]. Enhanced-efficiency fertilizers, nitrification inhibitors, controlled-release formulations, and precision fertilization techniques can significantly reduce emissions while maintaining crop productivity (Liu *et al.*, 2025) ^[20].

Carbon Sequestration Through Nutrient Practices

Improved nutrient management can increase carbon sequestration in agricultural soils through practices such as returning crop residues, conservation tillage, and integrated organic-inorganic fertilizer applications (Lal *et al.*, 2011) ^[18]. Organic fertilizers improve soil structure and aggregate stability, generally lowering net CO₂ and N₂O emissions while promoting medium- to long-term soil organic carbon stocks (Liu *et al.*, 2025) ^[20].

Integrated Nutrient Management Benefits

Combining organic and inorganic nutrient sources through Integrated Nutrient Management (INM) can reduce emissions compared to single-source approaches, particularly when treatments have low carbon-to-nitrogen ratios (Graham *et al.*, 2017) ^[18]. The highest carbon sequestration (12 mg/kg) was achieved when farmyard manure was applied with NP fertilizer, while also reducing N₂O emissions through increased nitrogen-use efficiency (Bayu *et al.*, 2020) ^[3].

Productivity vs. Environmental Sustainability Trade-offs

While nutrient management can provide both production and environmental benefits, potential trade-offs exist between yield and N₂O emissions for certain practices like fertilizer placement

(Maaz *et al.*, 2021)^[22]. The challenge lies in maintaining food security while minimizing environmental impacts, requiring tailored approaches that keep nutrient balances within safe limits to achieve high crop yields while reducing emissions (Maaz *et al.*, 2021)^[22].

Comprehensive Management Approaches

Successful mitigation strategies require coordinated approaches including conservation practices, crop rotations, optimized irrigation, and precision conservation management at field and watershed levels (Lal *et al.*, 2011)^[18]. These integrated systems can help prevent soil erosion, sequester carbon, enhance methane consumption, and reduce the overall environmental footprint of agriculture (Johnson *et al.*, 2007)^[10].

Regional and Agro-Ecological Perspectives

Regional variations in agricultural systems require tailored approaches that consider local biophysical and socioeconomic conditions. (Joshi *et al.*, 2004)^[11] emphasizes that more than two-thirds of agricultural land and rural populations in developing countries like India are found in rainfed areas that have been largely bypassed by conventional agricultural transformation. (Roy *et al.*, 2020)^[36] notes that for mega-diverse countries, national-level studies cannot propose sound approaches for varied agro-climatic regions, necessitating region-specific research across diverse agro-climatic zones. (Ryan *et al.*, 2001)^[37] highlights that future research agendas must account for regional differences in resource endowments and infrastructure, with labor-intensive technologies being appropriate for poor regions in South Asia and labor-saving technologies for sub-Saharan Africa.

Socio-Economic and Policy Dimensions

The socio-economic and policy framework is fundamental to successful agricultural transformation. (Joshi *et al.*, 2004)^[11] demonstrates that several technical interventions for resource conservation that neglected economic and policy dimensions have failed in the past, leading to the evolution of watershed and community-based approaches that maintain people's livelihoods at the heart of natural resource management debates. identifies that regenerative agriculture faces significant challenges including knowledge gaps, inadequate policy frameworks, and economic barriers that require collaboration among academics, policymakers, farmers, and stakeholders for widespread adoption.

Emerging Tools and Future Innovations

Technological innovations are showing significant promise in sustainable agriculture. (Mohanty *et al.*, 2025)^[27] reports that agroecological practices can enhance crop yields by 20-30% while reducing chemical inputs by up to 50%, with future innovations including climate-resilient crop varieties, optimizing microbiome interactions, and scaling up successful agroecological models. (E Birch *et al.*, 2011)^[6] highlights that Integrated Pest Management (IPM) offers a 'toolbox' of complementary crop- and region-specific solutions, utilizing precision pest monitoring tools, rapid diagnostics, semiochemicals, and biopesticides to reduce pesticide use while increasing yields.

Research Gaps and Future Directions

Significant research gaps persist across agricultural disciplines. (Neve *et al.*, 2018)^[31] identifies that research challenges rest on the need for continued efforts to diversify and integrate

agroecological, socio-economic and technological approaches through a more system-oriented and transdisciplinary research agenda. (Tomich *et al.*, 2011)^[42] emphasizes the need for forward-looking scientific questions to enhance agroecology's relevance for mitigating environmental impacts while dramatically increasing global food production and improving livelihoods. (Ryan *et al.*, 2001)^[37] suggests that future research should focus on thematic, problem-driven agendas rather than crop-specific mandates, including village-level studies and gender-sensitive technology options.

Conclusion

The synthesis of agricultural research points toward an urgent need for integrated, collaborative approaches. concludes that advancing technologies, governance, and policy interventions are crucial for fostering resilient, productive, and sustainable agricultural systems globally. The evidence demonstrates that sustainable agricultural transformation requires simultaneous attention to ecological restoration, economic viability, social equity, and policy support, with success dependent on multi-stakeholder collaboration and region-specific implementation strategies that address local challenges while contributing to global food security and environmental sustainability.

References

1. Ashokan A, Mini V, Rani B, Anand S. Mitigation of abiotic stresses in plants through nutrient management. *Int J Environ Clim Change*. 2024;14(7):254-267. DOI:10.9734/ijec/2024/v14i74267
2. Balemi T, Negisho K. Management of soil phosphorus and plant adaptation mechanisms to phosphorus stress for sustainable crop production: a review. *J Soil Sci Plant Nutr*. 2012;12(3):547-562.
3. Bayu T. Review on contribution of integrated soil fertility management for climate change mitigation and agricultural sustainability. *Cogent Environ Sci*. 2020;6(1):1823631.
4. Chen L, Liao H. Engineering crop nutrient efficiency for sustainable agriculture. *J Integr Plant Biol*. 2017;59(10):710-735.
5. Dwivedi SL, Ceccarelli S, Blair MW, Upadhyaya HD, Are AK, Ortiz R. Landrace germplasm for improving yield and abiotic stress adaptation. *Trends Plant Sci*. 2016;21(1):31-42.
6. Birch ANE, Begg GS, Squire GR. How agro-ecological research helps to address food security issues under new IPM and pesticide reduction policies for global crop production systems. *J Exp Bot*. 2011;62(10):3251-3261.
7. Francis B, Aravindakumar CT, Brewer PB, Simon S. Plant nutrient stress adaptation: a prospect for fertilizer-limited agriculture. *Environ Exp Bot*. 2023;213:105431.
8. Graham RF, Wortman SE, Pittelkow CM. Comparison of organic and integrated nutrient management strategies for reducing soil N₂O emissions. *Sustainability*. 2017;9(4):510.
9. Hamel C, Landry C, Elmi A, Liu A, Spedding T. Nutrient dynamics: utilizing biotic-abiotic interactions for improved management of agricultural soils. *J Crop Improv*. 2004;11(1-2):209-248.
10. Johnson JMF, Franzluebbers AJ, Weyers SL, Reicosky DC. Agricultural opportunities to mitigate greenhouse gas emissions. *Environ Pollut*. 2007;150(1):107-124.
11. Joshi PK, Pangare V, Shiferaw B, Wani SP, Bouma J, Scott C. Socioeconomic and policy research on watershed management in India: synthesis of past experiences and needs for future research. *Global Theme on*

- Agroecosystems Rep No. 7. 2004.
12. Kabato W, Hailegnaw N, Mutum L, Molnar Z. Managing soil health for climate resilience and crop productivity in a changing environment. *Sci Total Environ*. 2025;1000:180460.
 13. Yadav KK, Singh AK, Chaturvedi SK, Singh SN, Kumar V, Gupta P, *et al*. Integrated nutrient management in sustainable agriculture: advances and challenges. *Int J Plant Soil Sci*. 2025. DOI:10.9734/ijpss/2025/v37i95710
 14. Kannan P, Arunachalam P, Govindaraj M. Implications and ways to enhance nutrient use efficiency under changing climate. 2015.
 15. Kaur G, Singh G, Motavalli PP, Nelson KA, Orlowski JM, Golden BR. Impacts and management strategies for crop production in waterlogged or flooded soils: a review. *Agron J*. 2020;112(3):1475-1501.
 16. Kouame KP, Aghahari RK, Konjengbam NS, Koyama H, Kobayashi Y. Ability of nutrient management and molecular physiology advancements to overcome abiotic stress: a study on sub-Saharan African crops. *Agriculture*. 2024;14(2):285.
 17. Kushwah N, Billore V, Sharma OP, Singh D, Chauhan APS. Integrated nutrient management for optimal plant health and crop yield. *Plant Sci Arch*. 2024;8(3):10-12.
 18. Lal R, Delgado JA, Groffman PM, Millar N, Dell C, Rotz A. Management to mitigate and adapt to climate change. *J Soil Water Conserv*. 2011;66(4):276-285.
 19. Li X, Zhang X, Zhao Q, Liao H. Genetic improvement of legume roots for adaptation to acid soils. *Crop J*. 2023;11(4):1022-1033.
 20. Liu JJ, Wu H, Riaz I. Advanced technologies for smart fertilizer management in agriculture: a review. *IEEE Access*. 2025.
 21. Liu Y, Liang F, Yan S, Tu T, Shi Z, Pezzuolo A, *et al*. Optimizing fertilization strategies for low-carbon agriculture: balancing greenhouse gas mitigation, soil health, and productivity. *Results Eng*. 2025:107094.
 22. Maaz TM, Sapkota TB, Eagle AJ, Kantar MB, Bruulsema TW, Majumdar K. Meta-analysis of yield and nitrous oxide outcomes for nitrogen management in agriculture. *Glob Change Biol*. 2021;27(11):2343-2360.
 23. Maharajan T, Ceasar S, Krishna TP, Ignacimuthu S. Management of phosphorus nutrient amidst climate change for sustainable agriculture. *J Environ Qual*. 2021. DOI:10.1002/jeq2.20292
 24. Medhi K, Bhardwaj R, Laxmi R. Climate change with its impacts on soil and soil microbiome regulating biogeochemical nutrient transformations. In: *Climate Change and the Microbiome: Sustenance of the Ecosphere*. Cham: Springer; 2021. p. 95-138.
 25. Miao Y, Stewart BA, Zhang F. Long-term experiments for sustainable nutrient management in China: a review. *Agron Sustain Dev*. 2011;31(2):397-414.
 26. Mohammed Wajid I, Sathiya Bama K, Meena S, Kathirvelan P, Prabu PC. Nitrogen management and nitrous oxide emission from agriculture: implication for climate change. 2025.
 27. Mohanty LK, Yadav SS, Kumar V, Gopal R, Panotra N, Singh G, *et al*. Sustainable crop production practices: a comprehensive review of agroecological approaches. *Arch Curr Res Int*. 2025;25(10):305-319.
 28. Mooshammer M, Hofhansl F, Frank AH, Wanek W, Hämmerle I, Leitner S, *et al*. Decoupling of microbial carbon, nitrogen, and phosphorus cycling in response to extreme temperature events. *Sci Adv*. 2017;3(5):e1602781.
 29. Nakachew K, Yigermal H, Assefa F, Gelaye Y, Ali S. Review on enhancing the efficiency of fertilizer utilization: strategies for optimal nutrient management. *Open Agric*. 2024;9(1):20220356.
 30. Nasiro K, Mohammednur T. Precision nutrient management amid climate change challenges: a review. *Sci Front*. 2024.
 31. Neve P, Barney JN, Buckley Y, Cousens RD, Graham S, Jordan NR, *et al*. Reviewing research priorities in weed ecology, evolution and management: a horizon scan. *Weed Res*. 2018;58(4):250-258.
 32. Nimanka S, Fernando N, Madhavi S, Munaweera I, Kottegoda N. Climate smart agriculture: the role of fertilizer innovations and efficient plant nutrient management. *J Sci*. 2023. DOI:10.31357/vjs.v1i1.6709
 33. Pilbeam DJ. Breeding crops for improved mineral nutrition under climate change conditions. *J Exp Bot*. 2015;66(12):3511-3521.
 34. Powlson D, Cai ZC, Lemanceau P, Banwart E, Noellemeyer E, Milne E. Soil carbon dynamics and nutrient cycling. 2015. DOI:10.1079/9781780645322.0098
 35. Rashmi MR, Gopalakrishnan M, Rajeswari R, Senthil KM, Kavitha M, Maragatham S. Resilient soils for a changing climate: navigating the future of sustainable agriculture. *Plant Sci*. 2024;11.
 36. Roy N, Roychoudhury S, Nautiyal S, Agarwal SK, Baksi S. Socio-economic and eco-biological dimensions in resource use and conservation: epilogue. In: *Socio-economic and Eco-biological Dimensions in Resource Use and Conservation*. Cham: Springer; 2020. p. 547-553.
 37. Ryan JG, Spencer DC. Future challenges and opportunities for agricultural R&D in the semi-arid tropics. *Patancheru: ICRISAT*; 2001.
 38. Shah SS, van Dam J, Singh A, Kumar S, Kumar S, Bundela DS, *et al*. Impact of irrigation, fertilizer, and pesticide management practices on groundwater and soil health in the rice-wheat cropping system. *Environ Sci Pollut Res*. 2025;32(2):533-558.
 39. Singh R, Patel K, Chaurasia M. Climate change and nutrient dynamics of soil. In: *Climate Change and the Microbiome: Sustenance of the Ecosphere*. Cham: Springer; 2021. p. 521-549.
 40. Sivakumar MV. Climate extremes and impacts on agriculture. *Agroclimatology*. 2020;60:621-647.
 41. Soares JC, Santos CS, Carvalho SM, Pintado MM, Vasconcelos MW. Preserving the nutritional quality of crop plants under a changing climate: importance and strategies. *Plant Soil*. 2019;443(1):1-26.
 42. Tomich TP, Brodt S, Ferris H, Galt R, Horwath WR, Kebreab E, *et al*. Agroecology: a review from a global-change perspective. *Annu Rev Environ Resour*. 2011;36(1):193-222.
 43. Vogel E, Donat MG, Alexander LV, Meinshausen M, Ray DK, Karoly D, *et al*. The effects of climate extremes on global agricultural yields. *Environ Res Lett*. 2019;14(5):054010.
 44. Wu W, Ma B. Integrated nutrient management for sustaining crop productivity and reducing environmental impact: a review. *Sci Total Environ*. 2015;512:415-427.
 45. Yimer AH, Tarnawa A. Advancing nutrient management strategies for sustainable crop productivity in a changing climate: a systematic review. *Sci World J*. 2025;2025(1):7101060.