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Optimizing soil nutrient dynamics: Recent insights into soil-plant interactions

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Abstract

Nutritional soil states are the foundation of productivity and sustainability of agro-ecosystems. Recent progress in studies of soil-plant interactions has elucidated the complex processes by which nutrients are turned over, rendered bioavailable and taken up by plants. This paper aims to review latest research advances in optimization of soil nutrient dynamics and to address synergistic relationships that exist among soil properties, microbial activity, root exudates and nutrient transport. Attention is paid to innovative strategies (precision agriculture, biotechnological interventions, regenerative practices) aimed at improving nutrient use efficiency and minimizing environmental pollution. It is essential to understand these dynamics to manage global food security and at the same time preserve nutritional security.

Keywords: Soil nutrient dynamics, soil-plant interactions, nutrient cycling, microbial activity, precision agriculture, regenerative agriculture, root exudates, nutrient use efficiency

Introduction

Soil is the primary substrate for plant growth and the basis of the global nutrient cycle. It is a system that has physical, chemical and biological components controlling the availability, fixation and uptake of nutrients by plants [15, 44]. Soil nutrient dynamics are fundamental factors impacting plant productivity, ecosystem health and environmental sustainability. Soil nutrients are nutrient chemical elements which are necessary for plant growth and development [27]. These nutrients are usually classified into macronutrients, such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) and micronutrients including iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), boron (B), chlorine (Cl) and nickel (Ni) [35]. The soil nutrient dynamics and availability are subject to interactions related to mineral weathering, organic matter mineralisation, microbial activity and environmental conditions [45, 63]. Soil-plant interactions refer to the relationship between soil components and plant roots, including physical (root penetration and soil structure), chemical (nutrient exchange and pH changes) and biological (microbial symbioses and root exudation) aspects controlling the uptake of nutrients and thus plant growth and health [64]. Knowledge of the soil-plant interactions is essential for the development of sustainable agricultural practices which consider and promote nutrient use efficiency. Since early agricultural research and development, scientific paradigms have changed and concepts of soil-plant interactions have developed throughout time. Early researchers, for example Justus von Liebig, whose work in the 19th century birthed agricultural chemistry, published the Law of the minimum - whereby the least available resource constrains plant growth [16, 26, 86].

Noteworthy scientists reading Farmnews include Sir Albert Howard, who was a strong proponent of organic and holistic farming practices in the early 20th century and F.H. King, who promoted sustainable agriculture through his extensive research on soil fertility and crop rotation practices. Many soil researchers in recent decades recognized the work of Rattan Lal, whose research has focused attention on soil organic matter and the potential to sequester soil carbon for nutrient cycling and mitigating climate change [65, 113]. Similarly, Johan Six and collaborators have made contributions to our understanding of soil microbial ecology and aggregate stability in relation to nutrient dynamics opening new door to soil nutrient dynamics.

Maximizing soil nutrient dynamics is integral to maximizing crop production. However, research on nutrient dynamics is also important for mitigating the negative environmental consequences of nutrient loss through leaching and runoff and the contribution of modern agriculture to greenhouse gas emissions, especially nitrous oxide. While many positive aspects of modern agriculture have been observed, improper management can lead to soil nutrient imbalances and degradation, bringing the need for novel, science-based practices to restore soil health while providing long-term sustainable agriculture [28, 53]. More recently, research on soil-plant interactions has deepened our understanding of the processes underpinning nutrient cycling, the role microbial communities play in these processes and root traits that encourage nutrient acquisition and will offer agriculture technologies related to precision agriculture, biotechnology and regenerative agriculture that are designed to balance productivity with sustainability [1, 46].

This article reviews recent developments in soil nutrient dynamics and the approaches that integrate soils to optimize nutrient dynamics for food security and environmental resilience.

Soil Nutrient Dynamics

Soil nutrient dynamics encompass the processes that determine the transformation, movement, retention and bioavailability of important nutrients in soils. These dynamic processes are core to plant nutrition, soil fertility and ecosystem function [29]. Soil nutrient dynamics includes the physical, chemical and biological processes that determine the storage, cycling and uptake of nutrients by plant roots [36].

Essential Soil Nutrients and Their Dynamics

Nitrogen (N): Nitrogen is important for amino acid and protein formation and has a large influence on vegetative growth. Nitrogen moves freely in soil and is often in the form of nitrate (NO_3^-) or ammonium (NH_4^+). Nitrogen undergoes mineralization, nitrification and denitrification. For example, when urea is applied to maize crops, it is quickly converted to ammonium and nitrate, forms that can potentially be taken up by crops, or leached, that is why management is very important [17].

Phosphorus (P): Phosphorus provides energy transfer (ATP) and root development, but it tends to bind to soil particles

making it less bioavailable to crops. It typically forms insoluble complexes with iron and aluminium in acidic soils or with calcium in alkaline soils. In terms of grain yield, applying rock phosphate in wheat fields is less effective in soils that have a higher level of microbial activity that can solubilize that phosphorus [47, 87].

Potassium (K): Potassium helps with the water balance and enzyme activation and it is absorbed as K^+ ions. Unlike N, K does not leach out of the soil as easily; however, it can be fixed between clay particles. In banana plantations, fertilizer high in potassium improves fruit quality and increases resistance to drought stress [54, 112].

Calcium (Ca): Calcium aids in the structure of cell walls and in root development. It is absorbed in the form of Ca^{2+} and may be lacking in acidic soils. Calcium nitrate is used in tomato cultivation to prevent blossom-end rot, a disorder caused by deficiency of calcium [115].

Magnesium (Mg): magnesium is the core element of chlorophyll and thus, critical in photosynthesis. Symptoms of deficiency show as interveinal chlorosis on older leaves. In Epsom orchards, magnesium deficiency is corrected with Epsom salts, also known as magnesium sulphate [88, 111].

Sulphur (S): As an essential component in protein synthesis and the development of certain vitamins, sulphur mainly becomes available through the decomposition of organic matter, where it can be absorbed in the form of sulphate (SO_4^{2-}). Brassica crops, such as mustard and cabbage, need sulphur for glucosinolate formation, which affects taste and strength against pests [18, 66, 114].

Micronutrients: Iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), boron (B), chlorine (Cl) and nickel (Ni) all combine to form Micronutrients with specific physiological functions. For instance, Zinc is important for production of enzymatic and hormonal substances. In rice, growth stagnation and chlorosis occur due to lack of zinc, which is then treated with zinc sulphate [2, 3, 110].

Different essential nutrients in plants, their deficiency symptoms and example crops where deficiencies are commonly observed:

Nutrient	Role in Plants	Deficiency Symptoms	Examples of Affected Plants
Nitrogen (N)	Promotes leaf and stem growth; component of chlorophyll and amino acids	Yellowing of older leaves (chlorosis), stunted growth	Rice, Wheat, Maize
Phosphorus (P)	Energy transfer (ATP), root development, flowering	Purplish discoloration of leaves, poor root growth	Maize, Sugarcane, Tomato
Potassium (K)	Water regulation, enzyme activation, improves fruit quality	Leaf edge browning or scorching, weak stems	Potato, Banana, Tomato
Calcium (Ca)	Cell wall structure, root and leaf development	Curling of young leaves, blossom end rot in tomato	Tomato, Apple, Lettuce
Magnesium (Mg)	Central part of chlorophyll, enzyme activation	Interveinal chlorosis (yellowing between veins) in older leaves	Citrus, Maize, Tobacco
Sulphur (S)	Component of amino acids and vitamins	General yellowing of young leaves, stunted growth	Cabbage, Onion, Canola
Iron (Fe)	Chlorophyll synthesis, electron transport in photosynthesis	Interveinal chlorosis in young leaves	Soybean, Citrus, Spinach
Zinc (Zn)	Enzyme activation, hormone regulation	Reduced leaf size, interveinal chlorosis, short internodes	Maize, Rice, Citrus
Copper (Cu)	Photosynthesis, lignin synthesis	Dieback of stems and twigs, wilting, stunted growth	Wheat, Citrus, Tomato
Manganese (Mn)	Photosynthesis, enzyme activation	Interveinal chlorosis with small necrotic spots	Oats, Soybean, Sugar beet
Boron (B)	Cell wall formation, fruit and seed development	Death of growing points, brittle leaves, fruit cracking	Apple, Cauliflower, Sunflower
Molybdenum (Mo)	Nitrogen fixation, enzyme function	Yellowing of leaves, poor growth, similar to nitrogen deficiency	Cauliflower, Legumes, Tomato
Chlorine (Cl)	Osmotic and ionic balance, photosynthesis	Wilting, chlorosis, leaf bronzing (rare)	Cereal crops, Tomato

Processes Influencing Nutrient Dynamics

There are numerous processes that aid and help in making nutrients accessible to plants. This includes both biotic and abiotic processes regulating the transformation, mobility and uptake efficiency of nutrients to plants ^[4, 55].

Below are the primary processes involved Mineralization and Immobilization

- Mineralization is defined as the microbial degradation of organic constituents; organic nutrients contained within are released inorganic forms suitable for absorption by plants. Crop residue organic nitrogen in fertilizer is first transformed to ammonium (NH₄⁺), which is eventually assimilated by plants or further transformed to nitrate for better growth of plants ^[56, 109].
- Denitrification takes place when soil microbes use inorganic nutrients, such as nitrate or ammonium, to sustain themselves and, in doing so, render those nutrients temporarily inaccessible to plants ^[67, 68].
Example: Incorporating green manure into the soil may result in a phase of initial immobilization where high-carbon materials for some microbes will decompose, delaying the nitrogen availability for crops like corn ^[19, 108]. Adsorption and Desorption.
- Adsorption is nutrient ions binding to soil, in particular clay minerals and organic matter, leading to immobilization ^[69].
- Desorption marks the release of nutrients back into the soil solution ^[37].

Example: In acidic soils, phosphorus often combines with iron and aluminium oxides, reducing its availability to plants like legumes for foliage development. The use of organic acids or phosphate-solubilizing microorganisms can increase desorption rates ^[30].

Leaching

The downward movement of dissolved nutrients through the soil profile due to water percolation is known as leaching in soil dynamics. The nutrients that are leached become unavailable to vegetation and may contaminate aquifers for long duration of time. Example: Sandy soils subjected to high rainfall are prone to leaching, for instance, nitrate (NO₃⁻) leaching decreases nitrogen concentration for crops like lettuce, but increases groundwater contamination ^[48].

Volatilization

The loss of nitrogen in the form of ammonia (NH₃) gas into the atmosphere, especially after urea fertilizers are applied on the surface, is termed volatilization. This process occurs readily and efficiently at higher pH, warm temperatures and windy conditions. Example: In wheat fields, significant nitrogen loss and reduced fertilizer efficiency occur as a result of surface urea application and lack of incorporation in reduced zone of soils ^[20, 70, 107].

Redox Reactions

Redox (reduction-oxidation) reactions alter the chemical forms and solubility of nutrients, especially in soils with fluctuating moisture levels at time to time. Example: In flooded rice paddies, anaerobic conditions reduce iron and manganese oxides to more soluble forms (Fe²⁺ and Mn²⁺), increasing their availability but potentially reaching toxic levels for soil and residual effect for plants. Similarly, under anaerobic conditions, nitrate can be converted to gaseous forms via denitrification, resulting in nitrogen loss causing further problems in environment ^[5, 71, 116].

The table below summarizes real-world examples, highlighting how different environmental conditions and management practices influence nutrient availability and cycling:

Agroecosystem/Farming Practice	Nutrient Dynamics Affected	Examples/Outcomes
Tropical Agriculture	Rapid decomposition, high microbial activity and heavy rainfall lead to leaching and low nutrient retention	Nutrient leaching of nitrates and potassium in cassava and maize; reduced long-term fertility
Temperate No-Till Farming	Slower decomposition of residues; enhanced microbial cycling; improved nutrient retention	Corn and soybean systems benefit from consistent nitrogen mineralization from surface residues
Flooded Rice Paddies	Anaerobic conditions change redox state, affecting N, P and S availability	Increased ammonium (NH ₄ ⁺) availability; loss of nitrogen through denitrification; sulphur reduction
Sandy Soils	Low cation exchange capacity; high leaching potential for mobile nutrients	Frequent potassium and nitrate leaching in vegetable cultivation like carrots and lettuce
Clayey Soils	High adsorption capacity; slow infiltration; potential nutrient fixation	Phosphorus fixation limits availability in legumes; better potassium retention in crops like sugarcane
Organic Farming Systems	Dependence on mineralization of organic inputs; slower nutrient release	Compost and manure provide steady nitrogen and phosphorus to crops like spinach and tomatoes
Arid and Semi-Arid Regions	Low microbial activity and organic matter; nutrient concentration in upper layers	Limited nitrogen mineralization; phosphorus immobility in dry wheat and sorghum systems
High-Input Monoculture Farming	Risk of nutrient imbalances, leaching and soil degradation	Over-application of nitrogen in corn fields leads to nitrate pollution and reduced fertilizer efficiency
Agroforestry Systems	Deep-rooted species recycle nutrients from subsoil; increased organic matter	Leguminous trees like Gliricidia enhance nitrogen availability and reduce erosion in alley cropping

Nutrient Forms and Availability

Nutrients in the soil exist in both organic and inorganic forms and their availability to plants depends largely on a variety of chemical, physical and biological transformations ^[21, 106]. The plant-available form of a nutrient is typically ionic and dissolved in the soil solution, allowing it to be absorbed through root uptake ^[38]. The transformations between different forms are governed by soil conditions such as pH, moisture, temperature,

microbial activity and the presence of other ions ^[9, 72].

Organic Forms of Nutrients: Organic forms are found in plant residues, animal manures, composts and soil organic matter. These nutrients are not directly available to plants and must undergo microbial decomposition, particularly the process of mineralization, to be converted into inorganic, plant-available forms ^[57, 117].

For example, nitrogen in organic matter exists as proteins and amino acids and is mineralized to ammonium (NH_4^+), then potentially to nitrate (NO_3^-) [73, 74].

Inorganic Forms of Nutrients: Inorganic forms are usually the result of mineral weathering, chemical fertilization, or microbial transformation. These forms include ions like NO_3^- , NH_4^+ , H_2PO_4^- , K^+ , Ca^{2+} , Mg^{2+} and SO_4^{2-} , which plants can readily absorb. The solubility and movement of these ions in the soil solution determine their bioavailability [31].

Soil Microbial Activity

Biological activity in soil is fundamental to nutrient circulation and overall soil health. A varied community of microorganisms, comprising bacteria, fungi, protozoa, actinomycetes and nematodes, facilitates crucial processes like organic matter decomposition, nitrogen fixation, nitrification and the solubilization of phosphorus and other essential micronutrients [39, 76]. These organisms engage in intricate food webs and play a role in the transformation and movement of nutrients essential for plant growth. Among these, mycorrhizal fungi establish symbiotic connections with plant roots, expanding their hyphal networks to improve water and nutrient absorption, particularly phosphorus [49]. Nitrogen-fixing bacteria including *Rhizobium* found in legumes is a free-living *Azotobacter* species which transform atmospheric nitrogen into ammonium for plant assimilation for growth and development of plants. Protozoa and nematodes consume bacteria and fungi residing in soils, releasing nutrients in forms that plants can use through their metabolic activities [10, 118]. The rhizosphere, a confined area of soil affected by root secretions and exudates, serves as a hotspot for microbial activity, abundant in sugars, amino acids and organic acids that encourage microbial growth effectively. This area facilitates vigorous biochemical interactions that enhance nutrient mineralization, inhibit pathogens and effect plant health and development [75, 105]. In general, the biological processes in soil not only enhances nutrient cycling but also strengthen soil composition, airflow and durability against ecological pressures, rendering it an essential aspect of sustainable soil management [6, 89].

Soil-Plant Interactions: Mechanisms and Influences

Root Architecture and Nutrient Absorption: The structure of the root system (RSA) is essential in influencing the efficiency with which plants uptake nutrients from the soil [76]. The arrangement of roots in space—covering aspects like depth, length, branching structures and density—impacts the plant's capacity to explore soil volumes and reach nutrient reserves. Crops with deep roots, such as maize and alfalfa, can access subsoil reserves of water and nutrients like nitrate and sulphate, whereas shallow and spreading roots, typical of many grasses and legumes, excel in absorbing phosphorus and potassium from the nutrient-rich topsoil [77, 90]. Progress in phenotypes and genomics has facilitated and advanced the identification of RSA traits associated with improved nutrient use efficiency for better understanding of soil dynamics [11, 22]. For instance, rice types plants with shallow root angles have been developed to enhance and increase phosphorus absorption in environments lacking top soil. Likewise, wheat varieties featuring more compact lateral root systems demonstrate enhanced nitrogen uptake in low-input environments [32, 91].

Root Exudates and Microbial Interactions: Plants secrete a wide variety of substances into the rhizosphere, known as root

exudates, which encompass sugars, organic acids, amino acids, flavonoids and secondary metabolites [40, 119]. These exudates perform several roles: they function as chemical signals that attract helpful microbes, dissolve fixed nutrients and repel soil-borne pathogens. For example, white lupin roots release citric and malic acids that can make insoluble phosphorus available by binding metal ions in acidic soils [50, 104]. In legumes such as soybean, flavonoids present in exudates start the symbiotic relationship with nitrogen-fixing *Rhizobium* bacteria. Additionally, specific maize varieties generate benzoxazinoids that influence microbial communities in manners that enhance nutrient accessibility and plant durability. The interactive interplay between root exudates and microbial communities establishes the foundation of a plant's extended phenotype and significantly affects soil nutrient dynamics [23, 78, 92].

Symbiosis: Plant microbe symbiosis is central to nutrient foraging in several ecosystems. The most famous examples are the association between legumes and *Rhizobium* bacteria, which leads to the formation of root nodules, which fix atmospheric N to NH_3 and provide an alternative nitrogen source for the host plant [58]. Another important symbiosis is between the majority of land plants and arbuscular mycorrhizal fungi (AMF) is known to mankind for very long time. These fungi have extensive hyphal networks that extend outside of the root zone increasing the uptake of immobile nutrients, such as phosphorus and micronutrients like zinc and copper [79, 80]. Crops such as sorghum and maize grow more and produce higher yields in phosphorus deficient soils when they are inoculated with mycorrhizal fungi in them [103]. Additionally, bacteria inoculants from nitrogen-fixing nodules in non-legume trees, contributes to nutrient cycling and soil productivity in forest ecosystems. Understanding and harnessing these symbiotic mechanisms is key to developing sustainable biofertilizer strategies and reducing reliance on synthetic nutrient inputs and better sustainability [7, 93].

Innovations in Soil Nutrient Management

Precision Agriculture: Precision agriculture signifies a revolutionary method for managing soil and crops by utilizing advanced technologies to apply inputs with exceptional spatial and temporal precision [59, 102]. Instruments like GPS-controlled equipment, variable rate application technologies, drones and soil sensors enable farmers to track soil nutrient levels, moisture content and crop health instantly [103, 120]. Remote sensing methods that utilize satellite images or drone spectral analysis can identify nutrient shortages in crops such as wheat and maize in early trends facilitating the targeted fertilization [94, 95]. This minimizes input waste, decreases production expenses, lessens environmental hazards like nitrate leaching or phosphorus runoff and improves overall crop yield. Precision nutrient mapping promotes a more sustainable application of fertilizers in diverse fields, enhancing nutrient utilization efficiency and long-term soil vitality [12, 81].

Biotechnological Methods: Biotechnology provides effective tools to enhance soil nutrient interactions and optimize plant nutrient utilization [102]. Genetic engineering has facilitated the creation of transgenic plants featuring better root systems, increased nutrient transporter expression, or resilience to nutrient-deficient environments [41]. Rice and corn types have been modified naturally in environment to enhance phosphorus uptake transporters and resulting in improved growth in phosphorus-deficient soils. Moreover, progress in microbial

biotechnology has resulted in the development and use of biofertilizers such as microbial agents that enhance nutrient solubilization, facilitate nitrogen fixation or stimulate plant growth. Modified strains of *Rhizobium*, *Azospirillum* and phosphate-solubilizing bacteria are currently undergoing field tests to aid cereal and legume crops [82,96]. Synthetic biology methods seek to create microbial consortia customized crops and soil types there by improving the effectiveness of these inoculants under actual conditions (invitro) [13].

Regenerative agriculture: Regenerative farming is not so much a set of prescribed methods, but a philosophy that focuses on rehabilitating soil and the ecosystem, by following processes that support natural nutrient cycles and ecosystem processes [42]. Practices like cover cropping, reduced or no-tillage, addition of compost and agroforestry not only enhance soil structure and organic matter but also promote a diversity of rich and productive microbial communities which enhances the soil productivity [33, 97]. Cover crops such as clover and rye, which fix atmospheric nitrogen, inhibit weed growth and provide a break from erosion of nutrients during off-seasons. Minimal tillage conserves soil structure and indigenous microbial habitats and composting both recycles nutrients and inoculates the soil with beneficial organisms [60]. Agroforest systems intercrop trees with crops or livestock and have integrated cycling of nutrients, including nutrients derived from deep root systems and organic litterfall. These practices build resilient soil systems capable of maintaining productivity under climatic and nutrient stress conditions, making them central to sustainable nutrient management and climate-smart agriculture [24, 83].

Environmental Considerations and Challenges

Nutrient Leaching and Runoff: The excessive use or improper application of synthetic fertilizers particularly those containing nitrogen and phosphorus presents considerable environmental hazards and challenges for future references [51, 101]. When used excessively or under unsuitable conditions (e.g., prior to heavy rain), these nutrients can seep into groundwater or be transported through surface runoff into rivers, lakes and coastal waters further claiming more disastrous effect. This leads to a decline in soil fertility and promotes the eutrophication of water bodies, resulting in algal blooms, hypoxia and the deterioration of aquatic ecosystems [61]. Efficient nutrient management strategies like split fertilizer applications, slow-release formulation use, precision agriculture tools and buffer strips are crucial for minimizing these losses and safeguarding water quality for future generation and agricultural bonanza. For example, farmers in the Midwestern U.S. have adopted controlled drainage systems and nutrient management strategies to reduce nitrate runoff into the Mississippi River Basin [8, 98].

Soil Degradation and Climate Change: Soil degradation includes various problems that hinder nutrient retention and plant accessibility, such as erosion, compaction, salinization, acidification and loss of organic matter. These types of degradation diminish the soil's natural fertility and lower its ability to sustain healthy plant growth and development [62]. In South Asia and certain regions of sub-Saharan Africa, monoculture practices and inadequate irrigation have caused extensive salinization and nutrient deficiencies in soils adding further deterioration in soil. Climate change exacerbates these issues which heightens the occurrence of extreme weather events and speeding up the decomposition of organic matter [84]. Elevated temperatures may boost microbial activity and losses

through volatilization, whereas unpredictable rainfall heightens nutrient leaching and erosion in soil which add further damage to flora. Enhancing soil organic matter, implementing conservation tillage and incorporating climate-smart practices can assist in protecting soils from these stressors for sustainable programming [14, 99].

Socioeconomic and Policy Aspects: The effective implementation of sustainable nutrient management methods relies not only on scientific progress but also on encouraging socioeconomic and policy structures [52, 85]. Numerous smallholder farmers, especially in developing areas, do not have access to quality inputs, modern technologies or the necessary training to adopt advanced nutrient practices [43, 100]. Additionally, financial limitations and uncertain land ownership may discourage long-term soil management. Combining scientific studies with traditional knowledge and engaging local communities in decision-making processes guarantees that interventions are contextually appropriate and broadly endorsed in today time. Initiatives such as India's Soil Health Card program efforts highlight the endeavours to connect scientific knowledge with practical application and learning for understanding of soil dynamics [8, 25, 34].

Conclusion

Enhancing soil nutrient management is crucial for attaining sustainable agricultural yield and environmental stability amid global issues like climate change, soil degradation and food scarcity. The intricate interactions among physical, chemical and biological processes in the soil-plant system dictate nutrient accessibility and absorption, ultimately affecting plant health and productivity. A grasp of these interactions from the molecular processes of nutrient conversion to the ecological functions of root exudates and microbial partnerships facilitates more accurate and efficient nutrient management approaches. Advancements in precision farming, biotechnological methods and regenerative techniques present viable solutions to improve nutrient utilization, minimize environmental contamination and rehabilitate degraded soils. Nonetheless, effectively carrying out these strategies necessitates combining scientific progress with local expertise, policy backing and socioeconomic factors. Tackling obstacles to access, education and infrastructure especially in low-income and smallholder farming settings is essential for fair and extensive adoption.

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