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REVIEW

Role of Redox Reactions and AI-Driven Approaches in Enhancing Nutrient Availability for Plants

Papel de las Reacciones Redox y los Enfoques Basados en IA en la Mejora de la Disponibilidad de Nutrientes para las Plantas

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ABSTRACT

Empirical studies have shown that environmental variability in the field remains uncontrolled in certain cases, with research often conducted at a limited number of agricultural sites. Direct measurements of redox potential in soils have been reported, yet quantifying rapid changes in this variable across microsites proves inaccessible in situ. Existing measurements of redox potential also fail to account for variability in the identity of reduced or oxidized compounds. Additionally, methodological constraints and researcher bias, particularly in studies focusing on processes in reduced sediments, may impair interpretations of anabolic reactions resulting from oxidation. Case studies further indicate that the effects of redox potential on nitrification, net mineralization, or immobilization of other nutrients often remain unmeasured. As a result, increased denitrification might stimulate nitrification, reducing the effects of nitrogen immobilization due to increasing carbon storage in environments where reduction predominates. Given the absence of studies specifically exploring the balance between reduction and oxidation in relation to nutrient availability, assessing the magnitude and likelihood of methodological shortcomings based on prior field research remains challenging. Existing research serves as a foundation for understanding how this balance may significantly influence nutrient dynamics and availability at larger scales. Future studies manipulating redox potential in the field should consider factors that could disproportionately facilitate reductions before an eastward shift occurs in the balance between oxidation and reduction in response to organic matter addition. Addressing these gaps will enhance understanding of redox reactions and their potential role in stimulating denitrification and sulfide responses.

Keywords: Redox Reactions; Nutrient Availability; Plants; Oxidation; Reduction.

RESUMEN

Los estudios empíricos han demostrado que la variabilidad ambiental en el campo sigue siendo incontrolada en ciertos casos, con investigaciones que a menudo se llevan a cabo en un número limitado de sitios agrícolas. Se han reportado mediciones directas del potencial redox en suelos; sin embargo, la cuantificación de cambios rápidos en esta variable a través de micro sitios resulta inaccesible in situ. Las mediciones existentes del potencial redox tampoco consideran la variabilidad en la identidad de los compuestos reducidos u oxidados. Además, las limitaciones metodológicas y el sesgo del investigador, especialmente en estudios centrados en procesos en sedimentos reducidos, pueden afectar la interpretación de las reacciones anabólicas derivadas de la oxidación. Los estudios de caso indican además que los efectos del potencial redox sobre la nitrificación, la mineralización neta o la inmovilización de otros nutrientes a menudo no se miden. Como resultado, un aumento en la desnitrificación podría estimular la nitrificación, reduciendo los efectos de la inmovilización de nitrógeno debido al incremento del almacenamiento de carbono en entornos donde predomina la reducción. Dada la ausencia de estudios que exploren específicamente el equilibrio entre reducción y oxidación en relación con la disponibilidad de nutrientes, evaluar la magnitud y la probabilidad de deficiencias metodológicas basándose en investigaciones previas en campo sigue siendo un desafío. La investigación existente sirve como base para comprender cómo este equilibrio puede influir significativamente en la dinámica y disponibilidad de nutrientes a escalas mayores. Los estudios futuros que manipulen el potencial redox en el campo deberían considerar factores que podrían facilitar desproporcionadamente las reducciones antes de que ocurra un desplazamiento hacia el este en el equilibrio entre oxidación y reducción en respuesta a la adición de materia orgánica. Abordar estas lagunas permitirá mejorar la comprensión de las reacciones redox y su posible papel en la estimulación de la desnitrificación y las respuestas al sulfuro.

Palabras clave: Reacciones Redox; Disponibilidad de Nutrientes; Plantas; Oxidación; Reducción.

INTRODUCTION

Globally, plants are exposed to various abiotic and biotic stressors, including water deficiency, nutrient shortages, and attacks by herbivores and pathogens.[1,2,3,4] Defense responses against these pressures are energy-demanding and induce reactive oxygen species (ROS) synthesis in plants. While ROS are highly toxic under normal circumstances, redox reactions play a crucial role in plant growth, development, and nutrient availability. Redox reactions involve the transfer of electrons from donors to acceptors, impacting metabolic pathways such as glycolysis, hydroxylation, photosynthesis, and respiration. These reactions not only catalyze biochemical processes but also regulate oxidative metabolism, preventing excess reactive oxygen and nitrogen species accumulation, thereby influencing nutrient transport, uptake, assimilation, and accumulation.

Redox homeostasis is critical for nutrient availability in ecosystems, affecting geochemical transformations that govern soil chemistry. The dissolution and precipitation of compounds depend on redox energy fluxes, which influence ecosystem health, infrastructural integrity, and plant productivity. For instance, nitrate assimilation and sulfate reduction are fundamental redox-driven pathways that influence nutrient cycling, with direct implications for plant physiology. Despite their significance, the mechanisms through which redox reactions release and regulate nutrient availability remain poorly understood.[2,3,4,5] A knowledge gap exists in understanding how varying redox environments impact different plant species' ability to acquire and assimilate essential nutrients, particularly under fluctuating soil conditions.

Artificial Intelligence (AI) presents new opportunities to enhance our understanding of redox-mediated nutrient availability by integrating advanced computational tools with experimental methodologies. AI-driven soil monitoring systems, real-time oxidation-reduction potential (ORP) sensors, and machine learning-based predictive models enable precise tracking of redox fluctuations, providing insights into nutrient solubility and uptake efficiency. Additionally, AI-assisted bioinformatics tools analyze microbial communities to identify key species involved in redox transformations, optimizing microbial interventions to enhance plant nutrition. AI-based simulations of redox interactions facilitate the development of data-driven fertilization strategies, reducing reliance on traditional fertilizers and minimizing environmental impact.[4,5,6,7,8] By integrating AI into redox chemistry research, this study aims to bridge existing knowledge gaps, offering innovative, sustainable solutions for precision agriculture. Future advancements in AI-driven approaches can support predictive models of soil-plant-microbe interactions, leading to optimized nutrient management strategies that enhance plant resilience, improve agricultural productivity, and contribute to global food security.

Definition and Types of Redox Reactions

In this research, we will explain the concept of redox reactions and the effect of this type of chemical reaction on nutrient availability to plants.[1] We will also discuss the main physiological changes observed in plants and the ways to overcome the stress caused by the establishment of conditions promoting a reduced or oxidized environment in the soil of the cultivation systems.[2] Understanding the formation mechanisms of certain nutrient forms in soil and, consequently, observing which type of chemical reaction occurs among the various species that interact with these nutrients is very important. It should be noted that all of the species we will present in this research, when combined with other nutrients, are necessary for plant development.

Redox reactions are those in which a substance gains and loses electrons in the same reaction.[3] This coupling process is called the oxidation-reduction reaction. It is hard to imagine an oxidation state that has existed on its own.[4] Rather, oxidation can only be considered if coupled with its reaction or inverse reaction. For example, iron changes from five valence electrons to iron by giving its electrons to an oxygen molecule to form the oxide iron. It is a strong chelate in all complexes and a weak ligand. In the latter case, the complexing ligand of iron is usually water, but also, for example, bipyridine and acetylacetone, and a large number of other ligands also form complexes. The consequence of change in the oxidation state or in the complexation is an alteration of both the radius and ionic charge of iron; the resulting complex influences both the color and reactivity of the complex.

Importance of Nutrient Availability in Plants

Soils contain inorganic nutrients necessary for plant growth in the form of cations (NH^{4+}, K^{+}, Ca^{2+}, Mg^{2+}), anions (NO_{3-}, HPO_{42-}, SO_{42-}) and anions/molecules (Fe^{2+}, Mn^{2+}, Zn^{2+}, Cu^{+}, $B(OH)_{42-}$). However, the forms in which these nutrients are initially found in the soil do not necessarily correspond to those which can be potentially taken up by the plant's root system. Making these nutrients available for absorption by plants involves oxidative, reductive, and hydrolytic chemical reactions. Other important factors include soil acidity, cation exchange processes, nutrient concentration in the soil solution, and other microorganisms associated with plant roots, which can compete for the soil's inorganic nutrients or act beneficially in their acquisition.[5,6,7,8,9]

The term nutrient availability in plants is frequently mentioned in discussions related to the chemical nature of soil inorganic nutrients and their uptake by plants. However, this concept often lacks precision and more thorough discussion regarding the mechanisms involved in the nutrient availability process for absorption by the plant.[10,11,12,13,14,15] At first, the term only conveys an idea related to the necessity or not of adding nutrients to the soil, especially via fertilization. In particular, an evaluation should be made of the economic viability of adding the nutrient, with the aim of correcting any deficiencies revealed by leaf analysis. All this information is useful and is widely used by plant crop advisors and agriculture professionals in general, with some becoming certified to interpret such conclusions.

Redox reactions in soil environments

Terrestrial redox reactions are involved in many soil processes such as organic matter decomposition, binding or release of pollutants, and mineral weathering. Redox reactions also act as an energy source for certain soil microorganisms and affect nutrient availability. Slower microbially driven oxidation-reduction reactions in soil can also influence the fate of environmental contaminants, the transformation of both natural and anthropogenic molecules, and the detoxification and immobilization of many elements in the soil.[11,12,13,14,15,16,17] Oxic soils are characterized by their high oxygen concentration and drive the oxidation of most organic and inorganic reduced compounds that are present in the soil solution, such as ferrous iron and sulfide. Allowing plants to thrive, and in turn influencing climate dynamics, is related to the fact that soils sustain the productivity of terrestrial ecosystems and work as vast biogeochemical pumps enhancing carbon in the soil and extracting nutrients from soil organic matter. Semiterrestrial wetlands, on the other hand, have periods of hypoxia or anoxia caused by both plant transpiration and water table seasonality. These waterlogged soils conform to almost the same variety of processes, but some reactions are mirrored in respect to their relative volume. During anoxic or hypoxic conditions, most sources of energy to sustain these complex reactions do not involve photosynthesis but instead are driven by previously stored organic compounds in the soil matrix, which can induce anaerobic ecology or redox reactions. Non-hydromorphic wetland soils that are found in rapidly drained landscapes represent a missing link between the processes that occur under hydromorphic conditions and upland systems.[14,15,16,17,18,19] The redox reactions in these soils resemble the soil microsites of hydromorphic systems according to their physical and chemical properties but are driven by oxic reactions during rapid desiccation and respiration, similar to those in upland soils. Understanding the functions and complex interactions between microorganisms and inorganic elemental fluxes in both hydromorphic and non-hydromorphic conditions is critical for interpreting the long-term effects of hydrological changes that have been predicted to occur due to ongoing climate change.[20] In this review, we provide a summary of the interactions between the listed redox reactions and nutrient cycling.

Role of Microorganisms in Redox Reactions

Microorganisms drive key redox transformation reactions that govern nutrient availability and inform plant nutritional status. In oxygenated natural and agricultural soil, highly regulated biological processes involving microorganisms contribute to nutrient transformation and forms, most notably to nitrogen, iron, sulfur, carbon, and, albeit less well recognized, carbon dioxide.[17,18,19,20,21] Specifically, the reduction of nitrate, ammonia, or nitrogen gas and aerobic and anaerobic oxidation of a variety of organic and mineral sulfur compounds fuel transformations among ammonia, ammonium, nitrate, nitrite, nitric oxide, and nitrogen gas and organic forms

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of sulfur and carbon, often leading to toxic nitrogen and sulfur compound forms.[18,19,20,21,22,23] The capability of microbially driven redox transformation extends beyond nitrogen, sulfur, and carbon to phosphorus, iron, and manganese, which play critical roles in the formation of reduced P, Fe, and Mn forms that participate as electron acceptor co-regulators with the redox-active carbon forms.

Microorganisms affect the growth of many plants through their actions that are modulated by redox transformation reactions. These actions culminate predominantly in the regulation of plant biomass gains, the enhancement of plant growth rates, and the availability of plants to absorb nutrients.[22,23,24,25,26,27,28] Characterization of microbial traits and their importance in plant growth promotion has helped elucidate earlier observations of the intimate interactions between microorganisms and plants. These multifaceted mechanisms include the release of plant hormones, which stimulate lateral root growth, in addition to the regulation of the response of plants to abiotic factors, inactivation of substances that negatively affect plant growth, and production of metal chelators that facilitate the uptake of essential metal micronutrients.

Factors Influencing Redox Potential in Soils

Soil redox potential is determined by the reduction-oxidation (redox) status of the system. In an equilibrium reaction in a soil matrix, the overall redox system is an interaction between the environment and the living system. The main driving forces for redox processes in a soil are the input of organic matter and the consumption of O_2 in the presence of SOMs. The formula, which combines the input of organic matter and the consumption of O_2 for calculating the soil redox potential, allows for the possibility of a quantitative correlation. Seasonal changes in soil redox potential are a consequence of the dynamics of organic transformations, the O_2 consumption for maintaining the reaction, the presence of mineral-redox zones, and the transport of O_2 through the soil matrix. Simplified data analysis can identify the role of vegetation in gas exchange and is very often associated with the amount of O_2 that is needed to oxidize organic matter inputs and elements existing in their reduced forms.[24,25,26,27,28,29,30,31,32]

Understanding redox potential is important for interpreting soil conditions and quality relating to fertility, trace element dynamics, and water quality. Soils with the presence of low redox potentials have certain properties such as color, soil morphology, seasonal differences in moisture, periodic flooding, mottling, and odors, symptoms of water saturation and reduced oxygen levels, water-limited intake of oxygen, and certain plant communities. The difficulty of maintaining the oxidation status as well as the organic matter pyrolysis and thermal ramped mass spectrometry extraction confirm that soil porosity and permeability govern the underlying factors of soil features involved in the redox process.[33] An improvement in our understanding of the relationship between vegetation and the soil redox potential in situ is needed and could help to clarify this significant biotic influence in soils. Understanding the role of vegetation in biogeochemical cycles and the concept of rhizosphere redox potential, one of the most influential factors in biogeochemical processes, is important for the detection of significant plant-environment dynamics.

Redox Reactions and Plant Uptake of Nutrients

Plant cells have remarkable metabolic and developmental plasticity to optimize allocation and usage of nutrients for attaining networking metabolic balance. Nutrient assimilation and their carrier-mediated mobilization and distribution are crucial to establish key plant specializations such as root morphogenesis, plant growth, and yield. Redox changes that modulate the redox potential of numerous key regulatory interactions in cells provide an additional efficient and quick mechanism for metabolic turnover.[21,22] The maintenance of homeostasis during fluxes of carbon and reduced nitrogen from the aerial parts of the plant to the source-sink organs and the remobilization of nutrients will affect downstream metabolism and directly impact seed yield. The high energy requirements and concurrent generation of oxidative stress often result in a significant perturbation of antioxidant and oxidative systems.

Redox reactions mediate the assimilation and transport of nutrients, which play decisive roles in all biological processes in plants. These processes are extensively studied by scientists focused on enriching plants with essential nutrients and providing nutrients solely through inorganic compounds. The uptake of essential nutrients such as nitrate, phosphate, sulfate, iron, and copper ions by a plant organism is mainly based on regulated proteins that maintain the homeostasis of nutrient ions.[34,35,36,37] Uptake systems for other elements have also been studied, for instance, zinc, nickel, molybdenum, boron, or cobalt. Various other metal ions also affect the intercellular matrix and upregulate the specific proteins involved in their transport, such as cadmium, lead, mercury, aluminum, or selenium ions. The binding of specific ions accompanies the transport, while important regulators of redox balance include their sequestration and storage. Mitochondria during aging remobilize in a controlled, sequence-dependent manner the stored nutrients within the cell before the seeds become dormant, which often occurs under stressful environmental conditions.

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Redox Reactions in Plant Physiology

Introduction Redox chemistry is an essential basis of plant physiology. The closely related types of redox reactions occurring in plants are enzyme-catalyzed biotransformation's, oxidative phosphorylation in mitochondria in which oxygen serves as the terminal electron acceptor, and energy conversion taking place during photosynthesis, as well as the regulation of metabolic pathways involving reactive oxygen species (ROS). In plant systems, many cellular events such as post-transcriptional and post-translational responses are connected with the control of cellular states characterized by oxidative phosphorylation and energy allocation for metabolism in the chloroplasts. These states exhibit a dynamic balance between the corresponding reduced and oxidized states, which are mandatorily connected for the given function. In general, the flow of electrons via redox reactions determines the dynamics and gating of cellular function and energy flows for the metabolism of plants.[38]

Redox processes are inevitably necessary to cope with certain types of stress. When appropriate redox homeostasis is lost, ROS such as O_{2-}, H_2O_2, and OH are produced, which can be cytotoxic when their concentration surpasses the antioxidative capacity of a cell. Furthermore, two of these reactive oxygen species, H_2O_2 and nitric oxide (NO), act as signal molecules that activate stress acclimation and defense reactions. In plants, a multitude of enzymatic and non-enzymatic low molecular mass antioxidants buffer the oxidative circumstances when protective mechanisms are overloaded or unavailable.[39] In summary, redox chemistry determines cellular flexibility in general, and beyond that, the functional state of a plant exposed to changes in the natural environment. A comprehensive overview of the relevance of redox components and changes in the natural environmental stress responses is given in the review.

Iron and Manganese Redox Cycling

Iron is essential for plants, not only as an element in the synthesis of essential pigments and cofactors, but also plays an important role in redox signaling cascades due to its ability to both donate and accept electrons, thereby providing reversible redox chemistry with catalytic centers of enzymes and cofactors. However, excess accumulation of Fe^{2+} due to anoxia or high light intensity can lead to Fenton-mediated generation of damaging hydroxyl radicals, which can be mitigated through the induction of an iron/stress/odorant binding protein. Conversely, the formation of Fe^{3+} precipitates under aerobic conditions can prevent root cell expansion and lead to leaf chlorosis, often contributing to enhanced aluminum and boron toxicity.[40] Thus, to regulate excessive iron accumulation and to maintain a high intracellular iron-to-cell-wall-iron ratio, the radical-induced cold two protein was shown to be involved in transferring Fe^{2+} from the cytosol to the cell wall.

Manganese Manganese is also a very redox-active nutrient, increasing from about 2 % as Mn^{2+} to nearly 80 % as Mn^{3+} within the catalytic centers of almost all Mn-embedded redox-active enzymes. Surprisingly, in many land plants, Mn^{2+} is the only form available.[41,42] In order to achieve sufficient Mn^{3+} for incorporation within Mn-embedded redox-active enzymes, the rapid, reversible redox chemistry of Mn^{2+} superoxide dismutase can rapidly mediate the generation of Mn^{3+}. This ability to capture superoxide and reduce it to hydrogen peroxide is a pivotal protective, redox-based enzymatic defense mechanism that can critically impact important energy-yielding redox reactions such as oxidative phosphorylation and photosynthesis.

Phosphorus Availability in Redox-Prone Environments

The availability of phosphorus (P) for plant growth is strongly influenced by the oxidation state of the surrounding environment. The ionic species present in aerobic environments differ substantially from those found under low-oxygen or anoxic conditions. For example, reduced soil environments contain preferentially H_2PO_{4-}, HPO_{42-}, and PO_{43-}, while in soils in the presence of oxygen, these anions are often more strongly associated with metals. Bacterial activity in the rhizosphere results in a substantial reduction of rhizosphere oxygen to micropoxic or anoxic conditions. The reducing ability of bacteria appears to be under genetic control, with benefits to host plant nutrition. It has been suggested that bacteria in the rhizosphere can also transform organic P compounds, including P species present in the external shield of oomycetes, thereby overcoming host plant resistance.[41,42,43,44,45,46]

Techniques for Studying Redox Reactions in Plant Systems

The study of redox-active components in a biological system is not a trivial task. It is becoming increasingly clear that most species are responding to their environment in real time by altering the pattern of gene expression and/or through rapid induction of specific biochemical pathways. However, current instruments can quantify, at best, only a small fraction of the likely number of redox-active molecules that are present at any one time.[43] Therefore, most experimental techniques are designed to structurally or functionally define the functions of specific groups of molecules. There are many ways to study the effects of sulfur oxidation and sulfate reduction on nutrient availability. These range from craftsman-like studies of plants fed defined nutrient solutions and real-time measurement of redox activities to molecular genetic analyses to alter or disrupt the

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activities of key components of essential pathways.[44] The vast majority of such studies use specific methods to infiltrate single isolated leaves with specific gene products.[44] The powerful techniques of genetics have not yet been applied to explain important aspects of the nutrient metabolism of these most important organisms.

Non-invasive quantitative analyses of physiological state in plants have been developed. Light scatter measurements, proton-induced X-ray emission techniques, and various forms of spectroscopy have been applied to the non-invasive analysis of plants, but none of these techniques have been used to evaluate the significant coeval nature of redox and nutrient metabolism. Plant systems are highly sensitive indicators of environmental chemistry, and many methods of pollutant detection have been developed.[43] Unfortunately, few of these techniques are capable of simultaneously measuring a variety of redox-active metabolites and events, using real-time measurement of redox activity through to molecular genetic analyses to alter or disrupt the activities of key components of essential pathways.[44] The vast majority of such studies use specific methods to infiltrate single isolated leaves with specific gene products. The powerful techniques of genetics have not yet been applied to explain important aspects of the nutrient metabolism of these most important organisms.

Role of Redox Reactions in Plant Metabolism

Redox reactions are not isolated phenomena; rather, they are a part of various metabolic pathways taking place within plants.[44] The primary energy currency of the cell, adenosine triphosphate (ATP), is formed through redox processes via oxidative phosphorylation in the mitochondria, whereas in photosynthesis, redox reactions provide energy through the generation of nicotinamide adenine dinucleotide phosphate (NADPH) as well as ATP. Redox reactions are also a part of the biosynthetic pathways required for the formation of nitrogenous bases. In many cases, metabolites serve as reactants or products of redox processes, clearly indicating a relationship or integration of redox changes in primary metabolism. Photosynthesis can amply exemplify this fact. For instance, the accumulation of reduced ferredoxin is required for nitrogen metabolism, resulting in the incorporation of NH_{4+} into carbon skeletons that subsequently enter the biosynthetic pathways.[45] Photosynthesis, respiration, and nitrogen fixation—three major metabolic processes in which energy metabolism is redox regulated to a large extent—are fundamental in plant growth and development. Furthermore, redox status, by modifying various proteome functions, indirectly modulates the interaction between plant metabolism and growth and development. Because most of the carbon flows via respiration and photosynthesis are regulated by redox status, redox imbalance could strongly modify biological productivity.[46] The cell has a sophisticated control system for allosteric enzymes, thereby regulating metabolic flux. Redox plays a crucial part in regulation, as it not only influences the variety of enzyme expression and activity but also influences substrate availability. Redox has an influence on the phosphorylation state of enzymes, thereby modifying their activity. Moreover, there is a direct correlation between metabolic flux control and redox modifiers across various metabolic pathways. Furthermore, biochemical steps link NADP(H) allostery and sorbitol production. Additionally, changes in redox modify carbon flux. In addition, redox imbalance can lead to a metabolic phenomenon associated with the regulation of cell growth and division, herein known as quiescence. Overall, the redox status of the cell and the early soluble phosphorylation level of metabolites such as glucose are closely related. Whether in nitrogen or carbon metabolism, therefore, the redox status in plants is not only a fundamental element affecting metabolic efficiency but also the basic basis for the life activities of plants.[47] Future research might focus more on this metabolic cross-talk in response to redox dynamics in plants.

Nutrient Uptake and Transport in Plants

Elemental uptake and its subsequent movement in plants is a complex network. Plants can absorb and acquire various inorganic elements and convert them into a form that can be used by other tissues through different uptake pathways. In the soil, various forms of the elements are available for acquisition; once the flux reaches a specific cell type in a plant body, transporters and various associated proteins are required for acquiring the specific form for its subsequent homeostasis. Generally, acquisition involves two types of processes: passive uptake and active transport.[48] In passive uptake, the ion channels in the plasma membrane of roots directly move ions following electrochemical gradients into the root cell symplast. In contrast, active transport involves transporter-mediated uptake against the gradient coupled with energy. The transporters responsible for nutrient acquisition may be present at the plasma membrane or in mitochondria, chloroplasts, and specific membrane vesicles related to the acquisition of a special nutrient in a protoplast. Transporter activities are significantly correlated to the nutrient physiological state of the plant.

The growth and developmental pattern of a plant are directly related to various nutrients that exist in the soil from which they acquire water. Soils with many nutrients are most conducive for supporting vigorous plant growth. However, the availability of essential nutrients is limited due to several environmental factors such as pH, moisture, temperature, and the nature of adsorption with soil colloids. If an environment has a limited nutrient flux scenario, the actual uptake strategy in higher plants provides a mechanism for acquiring nutrients as efficiently as possible. Nutrient fluxes at early and late growth promote inorganic nutrient needs; at the

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same time, the nutrient uptake scenarios change.[52] The uptake of nutrients is regulated by various proteins called nutrient transporters involved. Transporters are essential players critically related to nutrient dynamics in plant systems. Deficiency in any transporters results in active uptake of available nutrients, affecting plant growth and causing a wide range of morphological changes.

Mechanisms of Nutrient Uptake in Plants

Nutrient uptake in plants is mainly governed by ion transporters, channels, and aquaporins present at the outer membrane of root epidermal cells and their respective structures. There are two main transport processes that result in the uptake of nutrients in plant roots. Passive transport systems are voltage-gated and generate a negative membrane potential inside the root epidermal cells. They are activated by excessive reduction in the apoplast, resulting in electrochemical activation of uptake.[53] On the other hand, active transporters regulate the uptake of non-essential and essential nutrients by utilizing ATP or proton-motive force. To optimize nutrient uptake, plants possess a sophisticated root architecture that can efficiently adapt to the environment. Root exudates or rhizodeposits are thought to mitigate the redox state of metal ions in addition to providing a source of organic carbon in the rhizosphere. Interactions between root exudates and the rhizosphere community are dose-dependent, and single exudate compounds may behave differently in microbial systems compared with mixtures.[54]

Under metal-deficient conditions, plants are able to take up relatively more metal than plants growing in high metal environments. The constitutive uptake of essential metals at normal concentrations is accompanied by exosomalization to detoxify excessive metal loads inside the plant body. Nutrient transport mechanisms are variable and can be adjusted to changing environmental conditions such as nutritional status, metabolic status, and physico-chemical conditions. Nutrient transport can be induced by chemical signals or signaling molecules to maintain homeostasis as part of the plant's adaptation to abiotic and stress conditions. Although nutrient transporters and channels are well characterized, our understanding of the aspects and effects of the redox state of the metals, metal speciation in soils, and the activation of nutrient transporters by antioxidants or redox reactions and signaling molecules is still pending. Additionally, little is known about the influences of hormones or respective transport systems.

Role of Redox Reactions in Nutrient Transport

Redox states can directly affect the activities of specific transport proteins and channels, metering nutrient uptake.[50,51,52,53,54,55] One of the best-known effects of redox reactions on transport is in the iron homeostasis network, where the reduction of metals at the root is utilized to enhance uptake rates. Phytosiderophores are released that chelate soil iron; upon chelating, the iron-phytosiderophore complex is reduced to Fe^{2+} ions by reacting with a deoxymugineate, releasing the Fe^{2+} ion from the enterprise of the ligand. Redox-modulated transport occurs in large part via the regulation of metal transport proteins by the ferric reductase oxidase two-part system, where a copper protein, ferric chelate reductase, is oxidized when DNA is solvated by a quinone protein; a ferrochelatase that is the recipient of the incoming electron is reduced. Iron homeostasis in Arabidopsis thaliana has shown that these proteins are connected to the plasma membrane and are likely a component of the iron uptake machinery.

Reduced thiol pools are also known to partition substrates for transport across the plasma membrane, in animals as well as plants. Recently, it has been found that the control of nutrient mobility in the xylem (as in other parts of the plant) depends in part on the redox environment. Overall, a plant's investment in the phloem system is controlled in part by the NADPH/NADP+ ratio; reducing power is 'expensive' in terms of a plant's overall energy budget. Redox-dependent signalling can be initiated by abiotic stress, which may modulate the distribution of nutrients to growing tissues, and the influence may be either chronic or acute, depending on the pattern and degree of stress.[54] Long-term disruption to nutrient uptake from the soil will not only impinge directly on the resilience and growth of plants due to the rerouting of nutrient flows but is also associated with oxidative disruptions in major metabolic pathways that will result in both a direct loss of energy metabolism and enhanced oxidative signatures. Each of these quite obviously has implications for plant productivity. In coming decades, associative knowledge around these interactions will make a significant contribution to proxy surrogates for commercial performance even before supporting gene technologies, because observed plant chemotypes would be expected to predict a broad suite of robust performances in various, unmodeled environments.

DEVELOPMENT

CASE STUDIES AND EXPERIMENTAL EVIDENCE

Case Study 1: The Role of Redox Reactions in Iron Uptake in Rice (Oryza sativa)[2,47,53]

Overview: rice is commonly grown in flooded paddy fields, where anaerobic conditions promote iron reduction (Fe^{3+} to Fe^{2+}). This transformation enhances Fe bioavailability, but excessive Fe^{2+} can lead to toxicity, affecting

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root morphology and nutrient uptake.

Findings: studies show that rice plants release oxygen through their roots, oxidizing Fe^{2+} back to Fe^{3+}, which precipitates as ferrihydrite. The balance between reduction and oxidation regulates Fe availability, influencing overall plant growth.

Implications: understanding Fe redox cycling in paddy soils can help develop iron-efficient rice cultivars and optimize fertilization strategies in flooded conditions.

Case Study 2: Phosphorus Mobilization in Wetland Ecosystems[23,27]

Overview: phosphorus (P) availability in wetland soils is often governed by redox-dependent mineral dissolution and precipitation. Under reducing conditions, Fe-bound P is released into the soil solution, enhancing plant uptake.

Findings: research on wetland plants, such as cattails (Typha spp.), indicates that seasonal redox fluctuations influence P dynamics, leading to periodic increases in nutrient availability. However, prolonged reduction can deplete available P as it diffuses into deeper soil layers.

Implications: managing water levels in wetlands and agricultural fields can optimize P availability, improving plant productivity and minimizing environmental losses.

Case Study 3: Manganese Cycling in Acidic Soils and Its Effect on Crop Health[23,24,25,26,27,28,29,30,31,32,33,34]

Overview: manganese (Mn) is an essential micronutrient involved in photosynthesis and enzyme activation. Mn availability is highly sensitive to redox changes, with Mn^{2+} being more soluble under reducing conditions.

Findings: studies on soybean (Glycine max) grown in acidic soils show that Mn deficiency occurs in well-aerated conditions where Mn oxidation reduces its bioavailability. Conversely, waterlogging increases Mn^{2+} levels, sometimes reaching toxic concentrations.

Implications: soil aeration management and pH adjustments are crucial for maintaining optimal Mn levels and preventing deficiencies or toxicities in crops.

Case Study 4: Nitrogen Redox Transformations and Their Impact on Maize Growth[34-39]

Overview: nitrogen (N) availability is largely controlled by microbial redox processes, including nitrification and denitrification. In aerobic conditions, ammonium (NH_4^+) is oxidized to nitrate (NO_3^-), which is easily taken up by plants but also prone to leaching.

Findings: maize (Zea mays) grown in well-drained soils benefits from nitrification, whereas in waterlogged fields, denitrification leads to nitrogen loss as N_2 gas, reducing soil fertility. Cover cropping and organic amendments help mitigate these losses.

Implications: balancing soil oxygen levels through proper drainage and crop management is essential for maintaining nitrogen availability and minimizing environmental impacts.

Application of AI In Studying Redox Reactions and Nutrient Availability in Plants

Artificial Intelligence (AI) is revolutionizing agricultural research, particularly in understanding the role of redox reactions in nutrient availability. Researchers can gain deeper insights into how redox processes affect soil chemistry and plant nutrient uptake by leveraging AI techniques such as machine learning (ML), deep learning, and big data analytics.

AI-Driven Soil and Nutrient Monitoring

AI-powered sensors and remote sensing technologies enable real-time monitoring of soil redox conditions. These systems use spectral imaging, electrochemical sensors, and Internet of Things (IoT) devices to collect vast amounts of data on oxidation-reduction potential (ORP), soil pH, moisture levels, and nutrient concentrations. ML algorithms then process this data to identify patterns and predict changes in nutrient availability, helping farmers optimize fertilization and irrigation practices.

Predictive Modeling of Redox Reactions

Machine learning models can simulate redox reactions under varying environmental conditions, predicting how factors like temperature, microbial activity, and soil aeration influence oxidation states of essential nutrients like iron (Fe), manganese (Mn), and sulfur (S). These predictive models allow researchers to understand the long-term impacts of redox fluctuations on soil fertility and plant health.

AI in Microbial Community Analysis

Microorganisms play a crucial role in redox reactions, influencing nutrient solubility and bioavailability. AI-driven bioinformatics tools analyze massive datasets from metagenomic sequencing to identify microbial species responsible for redox transformations. This helps researchers design microbial inoculants that enhance nutrient availability by promoting beneficial redox processes in the rhizosphere.

Smart Decision-Support Systems for Agriculture

AI-integrated decision-support systems use real-time data to provide farmers with recommendations on soil management. By analyzing historical data, weather patterns, and redox-related parameters, these systems suggest the best fertilization strategies, reducing nutrient losses and improving crop productivity.

Automation in Redox Research

AI-powered robotics and automation streamline laboratory experiments on redox reactions. High-throughput screening of soil samples, automated spectroscopy for redox potential measurement, and AI-assisted chemical analysis accelerate research, allowing scientists to explore complex interactions between redox processes and nutrient cycles efficiently. The integration of AI in redox research offers significant advancements in understanding and optimizing nutrient availability in plants. By leveraging AI-driven predictive modeling, real-time monitoring, and bioinformatics, researchers can develop sustainable agricultural practices that enhance soil health and crop yields.[55] As AI technology continues to evolve, its applications in redox chemistry and plant nutrition will become even more precise and impactful.

Limitations of the Study

Empirical studies have shown that environmental variability in the field remains uncontrolled in certain cases, with research often conducted at a limited number of agricultural sites. Direct measurements of redox potential in soils have been reported, yet quantifying rapid changes in this variable across microsites proves inaccessible in situ. Existing measurements of redox potential also fail to account for variability in the identity of reduced or oxidized compounds. Additionally, methodological constraints and researcher bias, particularly in studies focusing on processes in reduced sediments, may impair interpretations of anabolic reactions resulting from oxidation.Case studies further indicate that the effects of redox potential on nitrification, net mineralization, or immobilization of other nutrients often remain unmeasured. As a result, increased denitrification might stimulate nitrification, reducing the effects of nitrogen immobilization due to increasing carbon storage in environments where reduction predominates.Given the absence of studies specifically exploring the balance between reduction and oxidation in relation to nutrient availability, assessing the magnitude and likelihood of methodological shortcomings based on prior field research remains challenging. Existing research serves as a foundation for understanding how this balance may significantly influence nutrient dynamics and availability at larger scales. Future studies manipulating redox potential in the field should consider factors that could disproportionately facilitate reductions before an eastward shift occurs in the balance between oxidation and reduction in response to organic matter addition. Addressing these gaps will enhance understanding of redox reactions and their potential role in stimulating denitrification and sulfide responses.

Recommendations

The results have provided practical implications that can be useful for future measures. To continue research in this expanding area, we recommend further experimental studies where redox conditions in soils have been amended. By providing variations in redox potentials with a wide range of plants, it would be possible to develop a range of key redox potential thresholds that could be used to provide evidence of when newly developed treatments for over-permeable wheat soils would make overall reductions in yield. This study also provides further evidence for the impact of oxygen availability on plant nutrient uptake and provides an area of future research. Based on the results, it is therefore possible to make the following recommendations: An improved understanding of soil redox potential thresholds would provide a more precise understanding of these interactions and would enable more accurate treatment design, as well as providing this research area with a threshold that could be used as an index for assessing potential redox damage in future research to a wider audience. Coastal protection and food security are key societal challenges. The implementation of peat in modern agriculture is problematic and requires the management of agricultural practices to ensure soils are not too oxidizing, supporting a growing range of cultivated plants over time. A better understanding of the connection between Eh and soil function, particularly regarding the implications for plant nutrient availability, is needed. Making such knowledge accessible will bridge a significant gap between scientific research and agricultural practices and will ultimately be the basis of applied innovations desired by both scientists and stakeholders. Together, future studies in the fields of natural science, especially soil science, together with social science to identify specific values should explore and adapt optimal redox potentials that can be used to direct both organic and loamy sand fields.

CONCLUSIONS

Redox reactions govern the behaviour of phosphorus (P), iron (Fe), and manganese (Mn) in the pericellular zones of maize roots, whereas nitrogen (N) and potassium (K) remain unaffected. The reactivity of P, Fe, and Mn increases during transient reduction through distinct mechanisms, with pericellular regions acting as electron shuttles to facilitate metal diffusion into the reduced layer, where ferrihydrite precipitates. Localized iron deposition, regulated by lactate-driven reduction, suggests that substrate availability and microscale diffusion influence pericellular redox processes. Redox reactions also regulate elemental dynamics within the broader rhizosphere, where increased reduction leads to the release of Fe, Mn, and P in rice-system soils, while N and K remain stable. Microbial and plant-mediated redox processes play a crucial role in nutrient cycling, requiring advanced microsensor techniques for experimental resolution. Additionally, redox signaling influences systemic defense activation, nitric oxide transport, and metabolic reprogramming, affecting source-sink dynamics in plants. The integration of Artificial Intelligence (AI) into redox research enhances our ability to study these complex interactions, offering new ways to optimize nutrient availability through AI-driven soil monitoring, machine learning-based predictive modeling, and microbial bioinformatics analysis. AI-powered sensors track oxidation-reduction potential (ORP) in real-time, enabling precise predictions of nutrient solubility and uptake efficiency. Machine learning models simulate redox fluctuations, helping to refine fertilization strategies for improved crop performance. AI-assisted bioinformatics tools analyze microbial communities to identify key species driving redox transformations, while automation accelerates experimental workflows in soil chemistry and plant physiology. By combining AI and redox chemistry, this study highlights new possibilities for precision agriculture, where data-driven insights optimize nutrient management, enhance soil health, and promote sustainable crop growth. The ability to model redox processes with AI supports the development of innovative agricultural practices that improve plant resilience and reduce environmental impact. Future research should continue exploring AI-driven approaches to decipher redox interactions, offering sustainable solutions for global food security and advancing our understanding of soil-plant-microbe interactions in nutrient cycling.

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