



# The soil-root nexus: how soil health shapes plant nutrient uptake and food nutritional security

Nitish Joshi · Romandeep Kaur · Taufiq Nawaz 

Received: 15 April 2025 / Accepted: 13 March 2026 / Published online: 24 March 2026  
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**Abstract** Soil health constitutes a foundational pillar of agroecosystem functionality, directly governing plant nutrient acquisition, crop productivity, and the nutritional composition of food. This review elucidates the complex interplay among soil physical, chemical, and biological parameters that modulate root architecture, rhizosphere dynamics, and nutrient uptake efficiency, with a particular emphasis on implications for global food security. Soil organic matter (SOM), a widely recognized proxy for soil health, has been empirically demonstrated to augment cation exchange capacity (CEC), enhance soil water retention, and foster microbial biodiversity collectively facilitating nutrient bioavailability and uptake. Quantitative analyses indicate that a 1% increase in SOM can elevate soil water holding capacity by approximately 1.5–2.0 mm per cm of soil depth, thereby promoting root proliferation and physiological nutrient absorption. Crucially,

soil microbial consortia including arbuscular mycorrhizal fungi (AMF) and rhizosphere-associated bacteria exert substantial influence over nitrogen mineralization and phosphorus solubilization, thereby modulating nutrient fluxes within the soil–plant continuum. For example, AMF have been reported to enhance phosphorus uptake by 30–50% in *Triticum aestivum* (wheat) under low-input agroecological systems. However, the persistent degradation of soil health, driven by intensive monoculture practices, synthetic nitrogen overapplication, and widespread erosion, has precipitated significant declines in the micronutrient density of staple crops. Longitudinal studies reveal a 5–40% reduction in critical micronutrients such as Fe and Zn in cereal grains over the past five decades, underscoring the unsustainability of conventional agricultural paradigms. Furthermore, conservation-oriented practices such as no-tillage farming have demonstrated a capacity to enhance soil aggregate stability by 20–40%, thereby intensifying microbial metabolic activity and optimizing root-soil interface dynamics. This review offers a novel perspective by explicitly linking soil health decline with micronutrient depletion and global security risks, framing soil degradation as both an agronomic and geopolitical challenge. In doing so, it integrates soil process research with broader implications for food system resilience and policy, an angle seldom emphasized in prior reviews. As global population projections approach 9.7 billion by 2050, safeguarding soil health emerges as a strategic imperative for sustaining agricultural resilience and ensuring food

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Responsible Editor: Kenneth Wilhelmus Loades.

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N. Joshi · R. Kaur  
Department of Agronomy, Horticulture and Plant Science,  
South Dakota State University, Brookings, SD 57007, USA  
e-mail: Nitish.Joshi@jacks.sdstate.edu

R. Kaur  
e-mail: Romandeep.Kaur@jacks.sdstate.edu

T. Nawaz (✉)  
Department of Biology and Microbiology, South Dakota  
State University, Brookings, SD 57007, USA  
e-mail: Taufiq.nawaz@jacks.sdstate.edu

system stability. This review further contextualizes the degradation of soil resources within the framework of national and global security, highlighting the cascading effects of food system fragility, malnutrition, and geopolitical tensions stemming from resource scarcity. Through a comprehensive synthesis of recent empirical advancements, this work underscores the exigency of adopting sustainable soil management strategies aimed at mitigating nutrient depletion, preserving ecosystem services, and fortifying the resilience of global food systems.

**Keywords** Soil health · Root-soil interactions · Nutrient uptake · Plant nutrition · Soil microbial activity · Food security

## Introduction

Soil health is a critical aspect of agricultural sustainability and ecosystem functioning, integrating biological, chemical, and physical properties (Kibblewhite et al. 2008). Healthy soils support plant growth by fostering microbial activity, nutrient cycling, and soil structure maintenance, all of which contribute to long-term agricultural productivity. Thus, an integrative approach that considers physical, chemical, and biological properties is necessary for accurately assessing and maintaining soil health (Cardoso et al. 2013; Frac et al. 2018). There are numerous indicators used to assess soil health, among which soil biological activity is one of the most critical. Soil microorganisms, including bacteria, fungi, and microarthropods, play fundamental roles in the decomposition of organic matter, nutrient cycling, and the enhancement of soil structure through aggregation (Neher & Barbercheck 2019). These organisms are particularly important in nutrient deficient ecosystems, where they can enhance plant productivity and biodiversity (Van Der Heijden et al. 2008). Among the most widely used biological indicators for assessing soil quality and function are soil enzyme activities, including  $\beta$ -glucosidase, phosphatase, and urease (Adetunji et al. 2017). Sustainable agricultural practices, including organic farming and conservation tillage, can enhance soil microbial abundance and diversity, thereby improving nutrient availability and soil structure (Tahat et al. 2020). However, intensive

farming practices and excessive agrochemical use can reduce microbial biodiversity, disrupt nutrient cycling, and degrade soil health (Bhattacharyya & Furtak 2022; Meena et al. 2020).

Soil chemical properties, such as nutrient content, pH, and cation exchange capacity (CEC), directly influence plant nutrient availability (Li et al. 2020a, b). Soil pH, often referred to as the "master soil variable," regulates nutrient solubility and mobility, affecting plant uptake and microbial activity (Neina 2019). Macronutrients like nitrogen, phosphorus, and potassium, along with essential micronutrients such as zinc and iron, are critical for plant growth and metabolic functions (Elias, 2019). The CEC of soil determines its nutrient retention capacity and overall fertility potential (Ballabio et al. 2019). However, spatial variability in soil properties impacts nutrient distribution and availability, necessitating precision management strategies to optimize soil fertility (Navidi & Seyedmohammadi, 2022). The rhizosphere, is the dynamic zone surrounding plant roots, plays a crucial role in modifying soil chemistry through root exudates and microbial interactions, further influencing nutrient availability and uptake (Briat et al. 2020; Rengel 2015). Along with the biological and chemical properties, soil physical properties, including texture, structure, porosity, and bulk density, also significantly affect plant growth and ecosystem functioning (Chapman et al. 2012). These properties influence water retention, aeration, root penetration, and microbial habitat suitability (Forster et al. 2020; Kolb et al. 2017). Plant diversity and root traits contribute to soil structure by improving aggregate stability and hydraulic properties, which are essential for water and nutrient uptake. Conservation agriculture practices, such as minimum tillage and crop residue retention, help maintain soil physical health by enhancing infiltration, reducing erosion, and preventing compaction (Indoria et al. 2016).

Plant roots exhibit remarkable plasticity in response to soil conditions, adapting their architecture to optimize resource acquisition (El Amrani 2023; Giehl & von Wirén, 2014). Root traits, including length, branching patterns, and surface area, are influenced by soil nutrient availability and moisture content (Gruber et al. 2013). This plasticity enables roots to efficiently forage for nutrients, particularly in heterogeneous soils, by altering growth patterns to exploit nutrient-rich patches (Wang et al. 2013). Root exudates, consisting of sugars, amino acids, and organic

acids, play a vital role in modifying the rhizosphere by altering pH, solubilizing nutrients, and stimulating beneficial microbial activity (Vives-Peris et al. 2020). These exudates also chelate essential micronutrients like zinc and iron, enhancing their bioavailability to plants (Rengel 2015). The rhizosphere is a hotspot for plant–microbe interactions, with plants selectively promoting beneficial microbes through exudation to enhance nutrient uptake and disease resistance (Hartmann et al. 2009; Lemanceau et al. 2009). Efficient nutrient uptake by roots occurs through passive mechanisms like mass flow and diffusion, as well as active transport via specialized protein channels (Chapman et al. 2012). Targeted breeding for specific root traits offers promising strategies to improve crop resilience and soil health in challenging environments (Jin et al. 2017).

Besides its role and importance, one of the primary challenges affecting soil health is soil degradation. Soil degradation significantly threatens crop productivity, soil fertility, and global food security by impairing nutrient cycling and soil structure (Lal 2010; White et al. 2012). Unsustainable land use practices, such as excessive tillage and agrochemical application, accelerate soil degradation, leading to declining yields and poor nutritional quality of crops (Lal 2015). Sustainable soil management practices, including conservation tillage, organic amendments, and crop rotation, can restore soil health by enhancing biological activity, improving nutrient availability, and maintaining soil physical properties. Climate change further complicates soil fertility by altering precipitation patterns, temperature regimes, and nutrient cycles, thereby affecting plant nutrition (Elbassiouny et al. 2022; Raman et al. 2025). Soil carbon sequestration is an essential strategy for mitigating climate change while simultaneously improving soil structure and fertility. However, the indiscriminate use of agrochemicals can disrupt microbial communities and undermine soil sustainability (Meena et al. 2020). Therefore, adopting integrated soil management approaches is critical for sustaining soil health, enhancing agricultural productivity, and ensuring food security while minimizing environmental impacts (Tahat et al. 2020). This review explores the mechanisms through which soil health impacts nutrient acquisition by plants, emphasizing the role of soil microbial communities, organic matter dynamics, and nutrient cycling processes. Furthermore, we discuss

how improving soil health through sustainable management practices can enhance food nutritional security, ensuring that agricultural systems remain resilient in the face of environmental stressors. By integrating recent advances in soil science, plant physiology, and agroecology, this paper aims to provide a comprehensive understanding of the soil–root nexus and its implications for global food systems.

## Components of soil health influencing nutrient uptake

### Biological components

Soil microbiomes are integral for plant nutrient acquisition and cycling, playing a pivotal role in sustaining ecosystem productivity. Among the soil microbiomes the most important contributors is AMF, which form symbiotic relationships with plants. These fungi enhance the uptake of immobile nutrients like phosphorus, zinc, and copper by extending the effective root system through fungal hyphae (Azcón-Aguilar & Barea 2015). AMF are particularly effective at accessing insoluble phosphorus sources and enhancing nitrogen uptake, particularly under stress conditions (Javaid 2009). Studies have demonstrated that AMF can improve phosphorus absorption in wheat by approximately 30–50% in low-input agricultural systems (Hou et al. 2021; Li et al. 2016). Additionally, rhizosphere bacteria, including nitrogen-fixing and phosphorus-solubilizing species, contribute significantly to nutrient availability and plant growth (Jacoby et al. 2017; Singh et al. 2022). The mycorrhizosphere, established through AMF colonization, further alters soil properties and bacterial communities, enhancing nutrient cycling and plant performance (Williams et al. 2024). Transition metal transport in plants involves complex interactions with endosymbiotic microorganisms, highlighting the essential role of these organisms in nutrient dynamics (González-Guerrero et al. 2016). Nitrogen-fixing cyanobacteria also hold immense potential as sustainable bio-resources for enhancing soil fertility and crop productivity (Nawaz et al. 2024). These plant–microbe interactions offer promising sustainable alternatives to chemical fertilizers, improving crop nutrient efficiency and fostering

environmentally friendly agricultural practices (Kafle et al. 2019; Lu et al. 2023). Furthermore, soil fauna, such as earthworms and nematodes, are also critical contributors to nutrient cycling and plant growth. Earthworms improve nutrient availability by fragmenting organic matter, enhancing soil structure, and stimulating microbial activity (Bhadoria & Saxena 2010; Medina-Sauza et al. 2019). Nematodes regulate microbial populations and increase nitrogen mineralization, indirectly enhancing plant nutrient uptake (Gebremikael et al. 2016; Zheng et al. 2022). Both organisms interact closely with plant roots and mycorrhizal fungi, influencing soil structure, nutrient concentrations, and plant biomass (Larsen et al. 2015; Milleret et al. 2009). Soil microarthropods contribute to decomposition and pest suppression, supporting agroecosystem health (Neher & Barbercheck 2019). However, emerging contaminants like microplastics pose threats to soil fauna, impairing their ecological functions (Wang et al. 2022). Since soil fauna mediate key rhizosphere processes that influence plant development and nutrient dynamics, understanding these intricate relationships is essential for preserving soil health and advancing sustainable agriculture. In addition to soil fauna and microbiota, soil enzymes are vital in regulating nutrient cycling and maintaining soil health. Enzymes produced by microorganisms and plant roots, such as  $\beta$ -glucosidase, phosphatase, and urease catalyze the decomposition of organic matter and the release of nutrients (Adetunji et al. 2017). These enzymatic activities are highly sensitive to management practices like tillage, crop rotation, and fertilization, making them reliable indicators of soil quality (Samuel et al. 2008). Management practices that incorporate organic amendments and minimize tillage typically improve enzyme-driven nutrient mineralization (Francioli et al. 2016). Enzyme activities also vary across ecosystems and are influenced by climate change (Daunoras et al. 2024). The rhizosphere generally demonstrates greater enzymatic activity compared to bulk soil, primarily due to the abundance of organic carbon substrates (Gianfreda 2015). Extracellular enzymes play a crucial role in regulating carbon storage and nutrient cycling, with their relative ratios offering insights into ecosystem biogeochemistry (Luo et al. 2017). However, plant invasions can significantly alter soil enzyme activities, potentially accelerating

nutrient cycling and disrupting soil processes (Zhou & Staver 2019) (Fig. 1).

### Chemical components

Chemical components are fundamental to soil health, as they influence nutrient availability, pH balance, CEC, and overall soil fertility (Lal, 2016). For instance, soil pH significantly influences nutrient availability and plant uptake, affecting overall soil health. Acidic soils ( $\text{pH} < 5.5$ ) can increase the availability of elements such as aluminum (Al) and manganese (Mn), while alkaline soils ( $\text{pH} > 8$ ) may limit the availability of essential micronutrients like iron (Fe), zinc (Zn), and manganese (Mn) (Läuchli & Grattan 2012). The effect of pH on nutrient availability is complex, involving interactions between soil reactions and plant uptake rates. For example, phosphate uptake decreases with increasing pH, while molybdate availability increases (Barrow & Hartemink 2023). SOM in the soil plays an important role in nutrient availability, particularly for heavy metals (Zeng et al. 2011). Research suggests that a 1% rise in SOM can improve soil water retention by approximately 1.5–2.0 mm per centimeter of soil, which in turn promotes root growth and enhances nutrient uptake efficiency (Hudson 1994; Rawls et al. 2003). Organic matter can bind with metals such as copper (Cu) and lead (Pb), reducing their bioavailability and toxicity to plants. Conversely, it can also form complexes with micronutrients like zinc (Zn) and iron (Fe), enhancing their solubility and uptake by plants. Plants can modify rhizosphere pH through root exudates, affecting micronutrient solubility and mobilization (Rengel 2015). Cation exchange capacity (CEC) is also a crucial soil property that reflects its ability to retain and supply nutrients for plant growth. Soils with higher CEC typically have better nutrient retention, as they possess a greater capacity to adsorb and exchange essential cations such as calcium, magnesium, and potassium, reducing nutrient leaching and enhancing plant availability (Yang et al. 2024). Organic matter content significantly influences cation exchange capacity (CEC) due to its high density of negatively charged functional groups, such as carboxyl ( $-\text{COO}^-$ ) and phenolic ( $-\text{OH}$ ) groups, which facilitate cation adsorption and exchange (Tan 2010; Brady & Weil 2017). Black carbon, a highly aromatic and chemically stable component of organic matter,

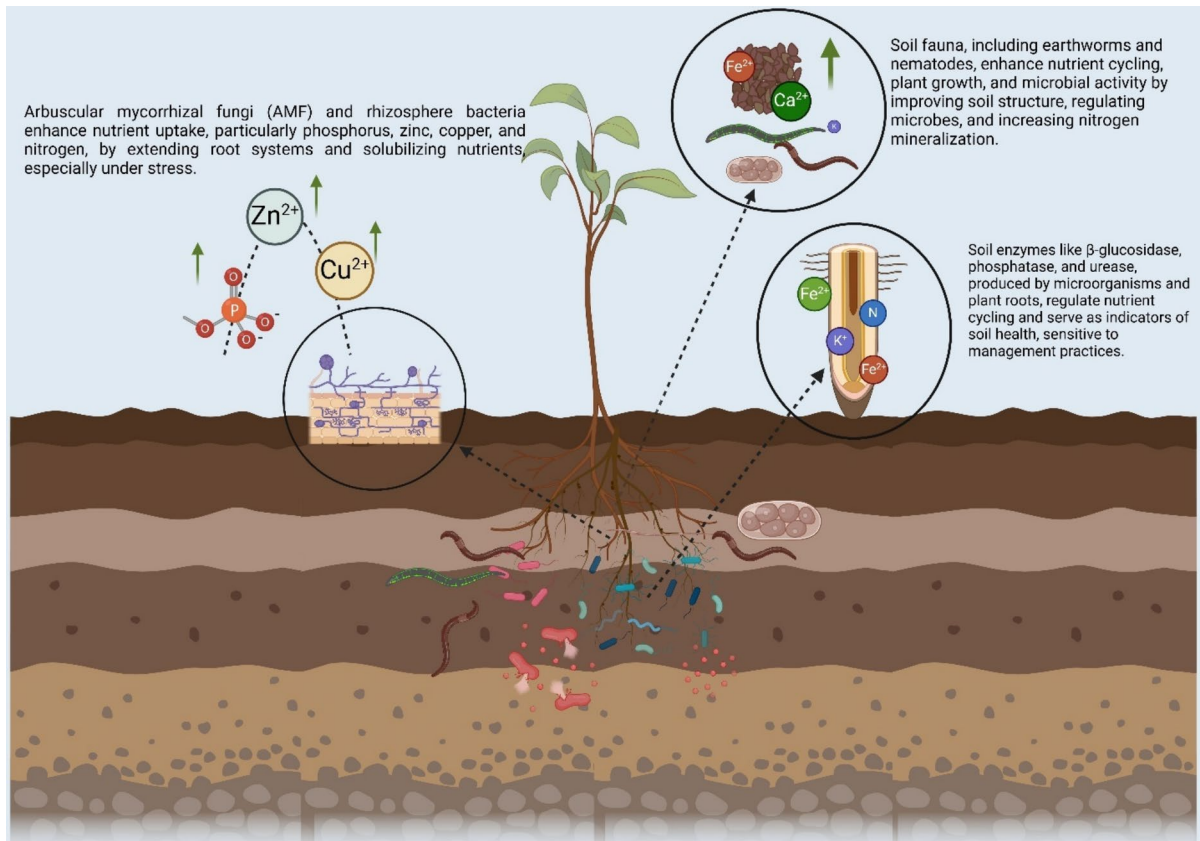


**Fig. 1** This figure illustrates the critical roles of soil microbiomes and fauna in nutrient cycling and plant growth. Arbuscular mycorrhizal fungi (AMF) enhance nutrient uptake, especially immobile nutrients like phosphorus, zinc, and copper, by extending the root system. Rhizosphere bacteria, including nitrogen-fixing and phosphorus-solubilizing species, fur-

ther contribute to nutrient availability. Soil fauna, such as earthworms and nematodes, improve soil structure, enhance microbial activity, and regulate nitrogen mineralization. Soil enzymes, produced by microorganisms and plant roots, mediate nutrient cycling and serve as indicators of soil health

enhances CEC by providing additional surface area and charge density, thereby increasing soil nutrient retention and buffering capacity (Liang et al. 2006; Lehmann & Joseph 2015). This effect is particularly important in weathered and low-clay soils, where black carbon can compensate for the limited CEC of mineral components (Glaser et al. 2001). Furthermore, amendments like biochar can alter soil CEC, but its effects depend on the feedstock and ash content (Antonangelo et al. 2024; Adhikari et al. 2024). A strong correlation has been observed between CEC and SOC content, especially in subsoils with a pH greater than 5.5 (Solly et al. 2020). CEC can be estimated from agronomic soil tests, with Mehlich-3 and ammonium acetate methods being common (Mattila & Rajala, 2022). Balancing exchangeable cations

based on increased CEC can improve soil nutrient availability and plant growth. Innovative approaches to modifying soil CEC include using plant extracts and microbial products (Shah et al. 2024). Soil microorganisms, including mycorrhizal fungi and nitrogen-fixing bacteria, play a crucial role in shaping soil chemical properties by facilitating nutrient uptake and cycling, thereby enhancing plant mineral nutrition (Jacoby et al. 2017). Soil enzymes catalyze nutrient release from organic matter, regulating nutrient availability, particularly for nitrogen and phosphorus (Hamel et al. 2004). In turn, plants actively influence this process by shaping their rhizosphere microbiome through root exudates, which modulate microbial activity and nutrient dynamics (Oldroyd & Leyser 2020). This interaction between soil enzymes,

microbes, and plant roots could be further enhanced by adding biochar, a sustainable soil amendment that improves nutrient retention and reduces leaching losses (Hossain et al. 2020). Furthermore, integrating microbial resources, such as beneficial bacteria and fungi, with mineral fertilizers can improve nutrient cycling and uptake efficiency (Bargaz et al. 2018) (Table 1).

### Physical components

Soil physical structure plays a critical role in root growth and nutrient uptake. Stable soil aggregates create pore spaces essential for root elongation, water retention, and nutrient availability (Dorner et al. 2010). According to recent studies, no-tillage systems have been found to improve soil aggregate stability by 20–40%, promoting microbial activity and enhancing root-soil interactions (Blanco-Canqui & Lal 2007; Mordhorst et al. 2012).

However, high soil strength and bulk density can severely restrict root elongation, with most field soils reducing root growth to less than half of the unimpeded rate (Valentine et al. 2012). Soil compaction, a significant challenge in agricultural soils, alters physical properties by increasing bulk density and decreasing porosity, thereby limiting water and nutrient availability and exacerbating greenhouse gas emissions (Nawaz et al. 2013). The impact of soil compaction on root growth depends on soil texture and moisture content (Yu et al. 2024). For instance, fine-textured soils, such as clay, hold more nutrients but can impede root penetration due to their high cohesion, while sandy soils, although well-aerated, are prone to nutrient leaching (Huang & Hartemink 2020). Soil texture also impacts osmotic potential gradients between bulk soil and the rhizosphere, influencing water availability for plants (Vetterlein et al. 2007). Heterogeneous soil structures can benefit certain plant species by creating macropores that enhance root growth (Giuliani et al. 2024). Advanced imaging techniques, such as X-ray Computed tomography, have revealed that the heterogeneity of soil texture and structure governs changes in bulk density around roots (Phalempin et al. 2021). Another important factor is organic matter, which plays a crucial role in soil fertility by enhancing soil structure, improving water retention, and promoting microbial diversity (Schröder et al. 2016). Root activity further influences rhizosphere soil structure,

often increasing the number of large pores compared to bulk soil (Whalley et al. 2005). Root-soil interactions play a crucial role in shaping soil properties, as roots adapt to prevailing soil conditions and modify the surrounding structure (Jin et al. 2017). For example, root systems can mitigate compaction effects by altering soil structure, thereby improving conditions for subsequent root growth (Forster et al. 2020). Root traits, including stiffness, tip shape, and growth angle, significantly affect a plant's ability to penetrate structured soils (Jin et al. 2017). Notably, smaller root tip radius-to-length ratios are associated with enhanced elongation rates in mechanically challenging soils (Colombi et al. 2017). Soil compaction's adverse effects on root growth and plant performance have long been recognized. Penetrometer resistances above 0.8–2 MPa or matric potentials drier than  $-0.5$  MPa are particularly detrimental, halving root elongation rates (Bengough et al. 2011). Similarly, critical soil strength levels between 1–3 MPa can significantly limit water and nutrient uptake, ultimately affecting crop yields (Passioura 1991; Unger & Kaspar 1994; Valentine et al. 2012). By improving root traits and mitigating compaction effects, we can optimize soil health and ensure better plant growth, even under challenging soil conditions (Table 2).

### The soil-root interface: mechanisms of nutrient uptake

#### Root morphology and architecture

Root architecture and morphology are essential for plant nutrient uptake and adaptation to environmental challenges. Plants exhibit remarkable plasticity in root development, altering traits like root length, branching patterns, and surface area in response to nutrient availability and soil conditions (Giehl & von Wirén, 2014; Yetgin, 2024). This plasticity enables efficient exploration of soil resources and adaptation to heterogeneous environments (El Amrani 2023). Root system architecture significantly influences nutrient uptake, water acquisition, and overall plant productivity (Wang et al. 2006). Auxin has been identified as a central regulator in shaping root architectural traits in response to nutrient and water availability (Leftley et al. 2021). Auxin plays a central role in root development, mediating responses to environmental cues and shaping root

**Table 1** Influence of key chemical components on soil health and plant growth, highlighting their role in nutrient cycling and uptake efficiency

| Chemical Component           | Influence on Soil Health and Plant growth                                                                                                                                     | Key References                                                  |
|------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------|
| Soil pH                      | Regulates nutrient solubility and microbial activity; acidic soils (<5.5) enhance toxic metal bioavailability, whereas alkaline soils (> 8) induce micronutrient deficiencies | (Friedrichsen et al. 2018; Läubli and Grattan 2012)             |
| Electrical Conductivity (EC) | Indicator of soil salinity; excessive EC disrupts osmotic potential, reducing plant water uptake and microbial function, leading to physiological drought stress              | (Rengasamy 2010)                                                |
| Nitrogen (N)                 | Fundamental macronutrient for plant growth; forms amino acids, nucleic acids, and chlorophyll. Nitrogen cycling influences microbial community structure                      | (Koch & Sessitsch 2024; Ward & Jensen 2014)                     |
| Phosphorus (P)               | Crucial for ATP synthesis, root development, and energy transfer; P availability declines under high pH due to fixation with calcium and magnesium                            | (da Silva Cerozi & Fitzsimmons 2016; Péret et al. 2011)         |
| Potassium (K)                | Regulates stomatal function, osmotic balance, and enzyme activation; enhances drought and disease resistance in plants                                                        | (Ahmad et al. 2018; Hasanuzzaman et al. 2018; Wang et al. 2013) |
| Calcium (Ca)                 | Structural component of cell walls; essential for root elongation, membrane permeability, and soil aggregate stability                                                        | (White & Broadley 2003; Thor 2019)                              |
| Magnesium (Mg)               | Central element in chlorophyll; plays a vital role in enzyme activation and cation balance in soil–plant systems                                                              | (Ishfaq et al. 2022; Senbayram et al. 2015)                     |
| Zinc (Zn)                    | Cofactor in enzymatic reactions, protein synthesis, and hormone regulation; deficiency leads to reduced plant growth and productivity                                         | (Hacisalihoglu 2020; Hamzah Saleem et al. 2022)                 |
| Iron (Fe)                    | Integral for redox reactions, electron transport chains, and chlorophyll biosynthesis; deficiency results in interveinal chlorosis                                            | (Pushnik et al. 1984; Rodríguez-Celma et al. 2013)              |
| Boron (B)                    | Involved in cell wall development, reproductive growth, and carbohydrate metabolism; excess can be toxic to plants                                                            | (Behera et al. 2023; Vera-Maldonado et al. 2024)                |
| Chlorine (Cl)                | Essential for photosystem II activity, osmoregulation, and disease resistance; imbalances affect stomatal conductance                                                         | (Raven 2017)                                                    |
| Sodium (Na)                  | Low concentrations can enhance osmotic regulation, but excessive accumulation leads to ion toxicity and soil structure degradation                                            | (Briat et al. 2020; Kronzucker et al. 2013)                     |
| Manganese (Mn)               | Activates enzymes involved in photosynthesis, nitrogen metabolism, and lignin synthesis; deficiency impairs root and shoot growth                                             | (Ivanov et al. 2022; Schmidt & Husted 2019)                     |
| Sulfur (S)                   | Essential for amino acid and coenzyme synthesis; influences nitrogen use efficiency and root development                                                                      | (Becana et al. 2018; Carciochi et al. 2017; )                   |
| Molybdenum (Mo)              | Key component of nitrogenase and nitrate reductase enzymes; deficiency restricts nitrogen assimilation                                                                        | (Glass et al. 2012; Ide et al. 2011)                            |

**Table 1** (continued)

| Chemical Component             | Influence on Soil Health and Plant growth                                                                                                                  | Key References                            |
|--------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------|
| Cation Exchange Capacity (CEC) | Governs soil nutrient retention and exchange processes; high CEC soils provide greater buffering capacity against nutrient leaching                        | (Curtin & Roastad, 1997; Ng et al. 2022)  |
| Soil Organic Matter (SOM)      | Enhances soil fertility, aggregate stability, microbial habitat, and water retention; critical for sustaining nutrient cycling                             | (Fageria 2012; Lal 2020; Murphy 2015)     |
| Soil Salinity                  | Elevated salt concentrations impede plant water uptake, disrupt ionic balance, and alter microbial diversity; saline soils require amelioration strategies | (Muhammad et al. 2024; Zhang et al. 2024) |

system architecture. It regulates primary root growth, lateral root formation, and root hair development through complex signaling networks (Cavallari et al. 2021; Roychoudhry & Kepinski, 2022). Auxin interacts with other phytohormones, particularly ethylene and abscisic acid, to fine-tune root responses to various stresses (Jan et al. 2024; Qin & Huang 2018). The generation and maintenance of auxin gradients are crucial for root development, with auxin biosynthesis, transport, and signaling orchestrating cellular processes from division to differentiation (Lavenus et al. 2013; Overvoorde et al. 2010). Furthermore, root-soil interactions and symbiotic associations with microorganisms contribute to enhanced nutrient acquisition and plant adaptation to challenging soil conditions (Jin et al. 2017). Recent advances in genetic and molecular tools have enhanced our understanding of these regulatory mechanisms, providing insights into strategies for improving crop nutrient-use efficiency and stress tolerance (Leftley et al. 2021). Root-soil interactions in the rhizosphere are fundamental in plant nutrient acquisition through symbiotic associations with microorganisms like mycorrhizal fungi and nitrogen-fixing bacteria (Jacoby et al. 2017; Larsen et al. 2015). These interactions enhance nutrient solubilization, uptake, and plant resilience to suboptimal soil conditions (Balestrini et al. 2024). Arbuscular mycorrhizal fungi improve phosphorus acquisition and overall nutrient uptake (Azcón-Aguilar & Barea 2015), while rhizobia bacteria facilitate nitrogen fixation (Artursson et al. 2006). Plants actively shape their rhizosphere microbiome through root exudates, recruiting beneficial microbes to enhance nutrient acquisition (Pantigoso et al. 2022). Root architecture modifications also play a significant role in improving nutrient

efficiency (Li et al. 2006; Li et al. 2016). Furthermore, plants employ small mobile molecules such as peptides and microRNAs to regulate nutrient homeostasis and symbiotic relationships (Valmas et al. 2023).

#### Root exudates and rhizosphere interactions

Root exudates are integral in shaping the rhizosphere environment and mediating plant–microbe interactions. These exudates, comprising organic acids, amino acids, sugars, and secondary metabolites, influence nutrient cycling, soil pH, and microbial community composition (Huang et al. 2014; Vives-Peris et al. 2020). They enhance nutrient availability by solubilizing minerals and chelating toxic compounds (Chai & Schachtman, 2022). Root exudates also facilitate beneficial plant–microbe associations, such as mycorrhizal fungi and plant growth-promoting rhizobacteria, which improve plant nutrient uptake and stress tolerance (Bais et al. 2006; Narula et al. 2012). The composition and quantity of root exudates are influenced by plant species, growth stage, and environmental factors. Under abiotic and biotic stresses, plants modulate their root exudation to enhance resource-use efficiency and recruit beneficial microbes (Chai & Schachtman, 2022; Parasar et al. 2024). The 'cry-for-help' hypothesis suggests that stressed plants alter their exudation chemistry to assemble protective microbiomes (Rolfé et al. 2019; Rizaludin et al. 2021). These exudates, comprising low and high molecular weight compounds, influence soil properties, nutrient availability, and microbial community composition (Afridi et al. 2024). While root exudates are important, their direct influence may be limited to small spatiotemporal windows near

**Table 2** This table summarizes key soil physical properties and their impact on soil health, including water retention, aeration, moisture content etc. Each parameter plays a crucial role in determining soil health and overall functionality, affecting plant growth and ecosystem sustainability

| Soil Physical Component | Influence on Soil Health                                                                                                                                                                       | Key References                             |
|-------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------|
| Soil Texture            | Governs water retention, aeration, and nutrient dynamics. Sandy soils facilitate drainage but have low nutrient retention, while clayey soils retain moisture but may impede root growth       | (Tahir & Marschner 2017; Zhao et al. 2015) |
| Soil Structure          | Regulates root penetration, water infiltration, and microbial habitat. Stable aggregates enhance soil porosity, reducing erosion and compaction risks                                          | (Yudina & Kuzyakov 2023)                   |
| Soil Porosity           | Determines air and water movement in soil matrices. Higher porosity enhances microbial activity, gas exchange, and root proliferation, while low porosity can lead to anaerobic conditions     | (Schjønning et al. 2003)                   |
| Bulk Density            | High bulk density ( $> 1.6 \text{ g/cm}^{-3}$ ) restricts root expansion, limits oxygen diffusion, and impairs water movement, whereas low bulk density enhances aeration and root penetration | (He et al. 2022; Tracy et al. 2012)        |
| Soil Compaction         | Induces mechanical resistance to roots, impairs infiltration, and increases susceptibility to surface runoff, reducing plant-available water and aeration                                      | (Nawaz et al. 2013)                        |
| Water Holding Capacity  | Defines the soil's ability to retain and supply water for plant uptake. Governed by texture, organic matter, and pore size distribution, influencing drought resilience                        | (Abdallah et al. 2021; Saha et al. 2020)   |
| Infiltration Rate       | Determines the speed at which water percolates through the soil. Compacted soils exhibit reduced infiltration, while organic matter enhances it by improving aggregation                       | (Fueki et al. 2012)                        |
| Aggregate Stability     | Essential for resistance to erosion, compaction, and water stress. Well-aggregated soils provide microbial niches and improve nutrient availability                                            | (Harvey et al. 2020)                       |
| Soil Aeration           | Ensures adequate oxygen diffusion for root respiration and microbial processes such as nitrification. Poor aeration can lead to hypoxia and root suffocation                                   | (Ben-Noah & Friedman 2018)                 |
| Erosion Susceptibility  | Dictated by soil texture, organic matter content, and vegetative cover. Erosion depletes topsoil, reduces fertility, and disrupts microbial communities                                        | (Hao et al. 2022)                          |
| Temperature Regulation  | Influences enzymatic reactions, microbial activity, and plant growth cycles. Soil temperature extremes can inhibit seed germination and nutrient mineralization                                | (Koch et al. 2007; Steinauer et al. 2015)  |
| Moisture Content        | Affects microbial metabolism, root hydraulic conductance, and soil strength. Excess moisture can lead to anoxic conditions, while drought inhibits biological activity                         | (Manzoni et al. 2012; Yan et al. 2016)     |
| Permeability            | Controls the movement of water and gases in the soil profile. High permeability prevents waterlogging, while low permeability increases the risk of anaerobic zones                            | (Benavente et al. 2019)                    |
| Surface Crusting        | Forms impermeable layers that hinder seedling emergence, water infiltration, and gas exchange, often exacerbated by high sodium levels or intense rainfall                                     | (Nciizah & Wakindiki 2015)                 |

root apices, with other rhizodeposits also contributing to rhizosphere carbon pools (Dennis et al. 2010). Despite their localized influence near root apices, root exudates play a pivotal role in shaping rhizosphere

dynamics and driving plant–microbe interactions. However, other rhizodeposits, including mucilage and sloughed-off root cells, also contribute significantly to the rhizosphere carbon pool and microbial

activity. Emerging meta-omics approaches are providing deeper insights into the functional potential of rhizosphere microbial communities, enabling a more comprehensive understanding of plant-soil-microbe interactions and their implications for sustainable soil management (Ma et al. 2022).

### Nutrient transport mechanisms

The movement of nutrients at the soil-root interface is governed by intricate interactions among soil characteristics, plant physiological processes, and environmental conditions. Passive uptake mechanisms such as diffusion and mass flow rely on concentration gradients and water movement (Chapman et al. 2012), while active uptake involves energy-dependent transport proteins in root cell membranes (Luan et al. 2017; Lyzenga et al. 2023). Plants acquire essential nutrients from the soil through intricate transport mechanisms that involve the movement of nutrients toward the root surface and their subsequent uptake into root cells. Nutrient availability in the rhizosphere and the plant's ability to absorb and translocate these nutrients are crucial factors influencing plant health and productivity (Karthika et al. 2018). Nutrient movement to the root surface occurs through three primary processes: root interception, mass flow, and diffusion. Root interception occurs when growing roots physically encounter and absorb nutrients in the soil matrix, a mechanism limited by root proliferation and nutrient distribution (Jungk 2002). Mass flow is driven by the transpiration stream, where nutrients dissolved in soil water move toward the roots as water is absorbed, significantly affecting mobile nutrients such as calcium ( $\text{Ca}^{2+}$ ), nitrate ( $\text{NO}_3^-$ ), and magnesium ( $\text{Mg}^{2+}$ ). Diffusion is crucial for less mobile nutrients like phosphorus (P) and potassium (K), as these nutrients move from regions of higher concentration in the soil to lower concentration near the root surface due to plant uptake. The relative contribution of these mechanisms varies depending on nutrient properties, soil moisture, and root activity (Marschner & Rengel 2023). In addition to direct uptake, many plants establish symbiotic associations with mycorrhizal fungi, particularly AMF, to enhance nutrient acquisition. AMF colonize root cortical cells and extend their hyphae into the surrounding soil, significantly increasing the root's effective surface area for nutrient uptake (Neumann & George 2010). This

symbiosis is particularly important for phosphorus acquisition, as fungal hyphae can access and transport phosphorus from soil microsites beyond the depletion zone around the roots. Moreover, mycorrhizal associations contribute to the uptake of other nutrients, such as nitrogen and micronutrients, while also improving plant resilience to abiotic stresses (Fig. 2).

### Soil health management and its impact on food nutritional security

#### Soil fertility practices

Organic amendments and biofertilizers are essential for advancing sustainable agriculture by enhancing soil fertility and boosting crop productivity. Organic amendments, such as compost and manure, improve soil structure, increase organic matter content, and enhance nutrient availability (Diacono & Montemurro 2011). Biofertilizers, including plant growth-promoting rhizobacteria and mycorrhizal fungi, facilitate nutrient uptake, increase crop yields, and enhance plant tolerance to stress (Bhardwaj et al. 2014; Daniel et al. 2022). These biological inputs contribute to soil microbial diversity and foster symbiotic relationships with plant roots (Rashid et al. 2016). The integration of organic, inorganic, and biofertilizers has proven effective in optimizing crop yields and maintaining soil health across diverse cropping systems. Long-term application of organic amendments can increase soil organic nitrogen content by up to 90% and crop yields by as much as 250% (Watson et al. 2002). Integrated soil fertility management (ISFM), which combines organic amendments and biofertilizers with judicious use of inorganic fertilizers, offers a sustainable framework for agriculture. Organic amendments, such as compost and manure, improve soil physical properties, increase organic carbon content, and enhance crop yields (Diacono & Montemurro, 2011). Biofertilizers, including beneficial bacteria and fungi, promote nutrient availability, plant growth, and stress tolerance (Bhardwaj et al. 2014; Rashid et al. 2016). This integrated approach enhances nutrient use efficiency, especially nitrogen (Adesemoye & Kloepper 2009) and contributes to climate change mitigation by reducing greenhouse gas emissions and sequestering carbon (Bayu 2020; Singh & Strong 2016). Microbial

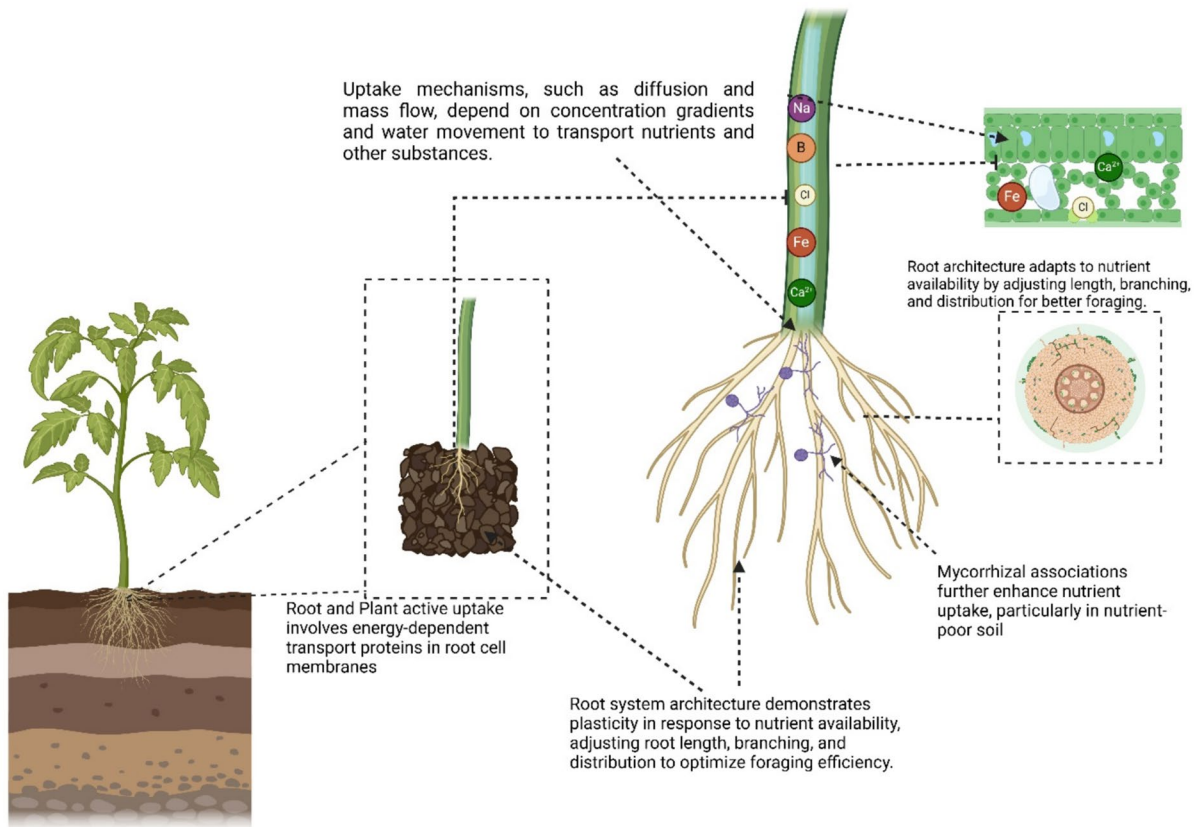


**Fig. 2** This figure illustrates plasticity in root system architecture as a response to varying nutrient availability, highlighting how roots adjust in length, branching, and spatial distribution. In nutrient-poor soils, these modifications optimize foraging efficiency, allowing the plant to access more nutrients.

The figure illustrates how these adaptive changes enable roots to explore a larger volume of soil, improving overall nutrient uptake and enhancing plant growth in resource-limited environments

inoculants, when combined with organic carriers such as biochar, show promise in improving soil health and plant productivity (Bamdad et al. 2022). However, careful management of these inputs is essential to avoid any negative impacts on soil health, requiring an integrated pest and nutrient management strategy (Bitew & Alemayehu 2017). This holistic approach to soil fertility management supports sustainable agriculture and enhances food security (Fig. 3).

#### Sustainable practices

Sustainable agricultural practices play a crucial role in enhancing soil health, plant nutrient uptake, and food security. Conservation agriculture, including reduced tillage and crop residue retention, improves soil physical properties, microbial activity, and nutrient

cycling (Cárceles Rodríguez et al. 2022; Raman et al. (Rahman 2025); Singh et al. 2021). Cover cropping and crop rotation diversify root exudates, enhance microbial communities, and promote balanced nutrient utilization (Huang et al. 2014). Organic amendments and proper nutrient management contribute to soil organic matter, fertility, and water retention (Al-Shammary et al. 2024). These practices collectively promote a strong soil-root nexus, supporting optimal plant growth and nutrient-rich food production (White et al. 2012). Additionally, they enhance soil microbial diversity and activity, which are key components of soil health and agricultural sustainability (Larkin 2015). Ecological nutrient management (ENM) principles emphasize building soil organic matter, minimizing nutrient losses, and maximizing agroecosystem capacity (Drinkwater & Snapp 2022).

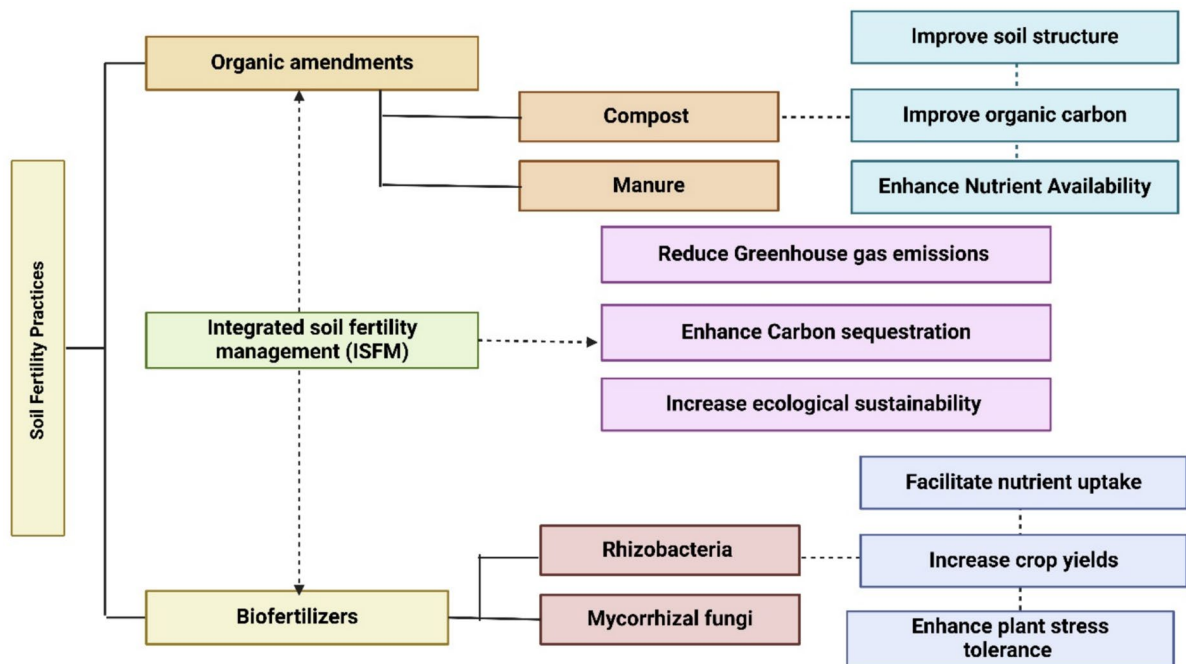


**Fig. 3** The flowchart illustrates the contributions of organic amendments (e.g., compost, manure) and biofertilizers (e.g., plant growth-promoting rhizobacteria, mycorrhizal fungi) in enhancing soil fertility, nutrient availability, and crop productivity. Organic amendments improve soil structure, increase organic carbon content, and support microbial diversity, while

biofertilizers facilitate nutrient uptake, promote plant growth, and enhance stress tolerance. The integration of organic, inorganic, and biofertilizers within an Integrated Soil Fertility Management (ISFM) framework optimizes nutrient use efficiency, mitigates climate change through carbon sequestration, and ensures sustainable agricultural productivity

Integrating soil health assessments with ecological resilience theory can provide a framework for understanding management impacts on soil function (Davis et al. 2023). Various soil and crop management strategies, such as integrated nutrient management and conservation agriculture, can optimize crop yields while maintaining environmental sustainability (Shah & Wu 2019; Shahane & Shivay 2021). Practices like agroforestry and cover crops consistently reduce runoff, erosion, and improve carbon sequestration (Tully & Ryals 2017). Soil health depends on maintaining carbon transformations, nutrient cycles, soil structure, and pest regulation (Kibblewhite et al. 2008). Agroforestry systems and biochar application show promise for long-term carbon sequestration (Stavi & Lal 2013). Restoring soil organic carbon can enhance agronomic production and ecosystem services (Lal 2010). Implementing these integrated approaches can be beneficial for maintaining productivity while ensuring environmental sustainability and long-term soil stewardship (Fig. 4).

### Precision agriculture

Precision agriculture integrates advanced technologies to optimize nutrient management and crop production. Soil sensors provide real-time data on moisture, pH, and nutrient levels, enabling targeted fertilization (Kashyap & Kumar 2021; Yin et al. 2021). Remote sensing techniques, including multispectral and hyperspectral imaging, allow for large-scale monitoring of crop health and nutrient deficiencies (Agrahari et al. 2021; Zilberman et al. 2016). Machine learning and predictive modeling refine nutrient management strategies, ensuring optimal supply aligned with crop demands (Ennaji et al. 2023; Zhang et al. 2021). This technology-driven approach improves efficiency of nutrient use, reduces environmental impacts, and enhances soil health (Gebbers & Adamchuk 2010). By combining soil sensors, remote sensing, and data analytics, precision agriculture enables site-specific management of resources, leading to improved crop yields, reduced input costs, and more sustainable

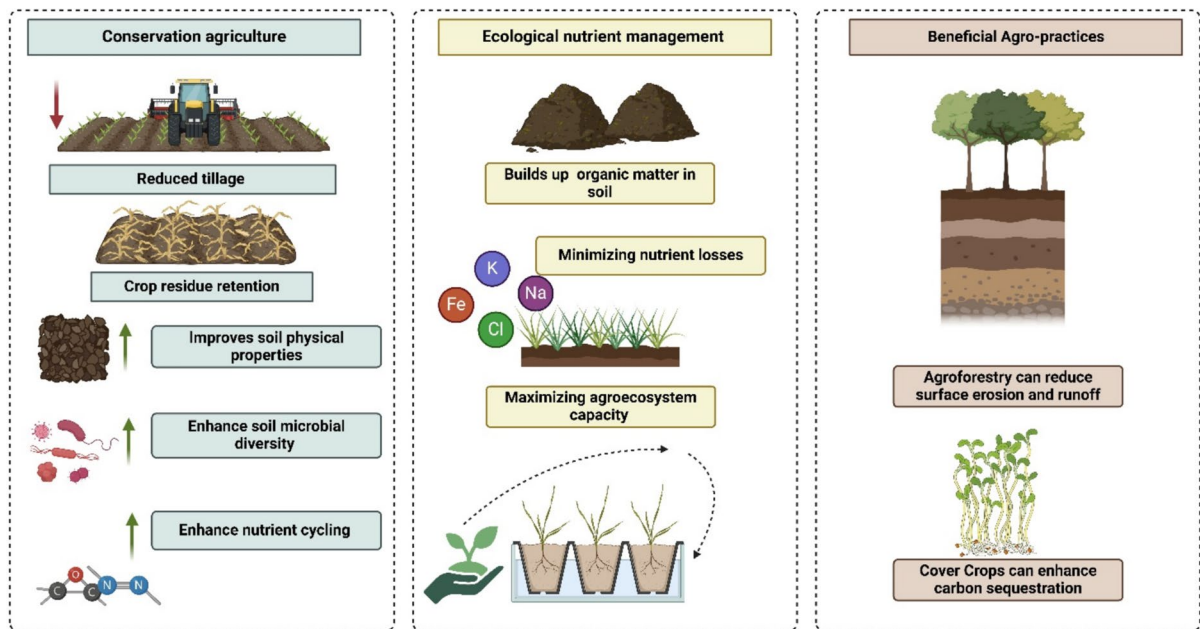


**Fig. 4** This figure illustrates the role of sustainable agricultural practices in enhancing soil health, nutrient uptake, and food security. By improving soil structure, microbial activity, and nutrient cycling, these practices contribute to long-term

soil sustainability. Strategies such as conservation agriculture, cover cropping, organic amendments, and agroforestry promote resilience, carbon sequestration, and overall ecosystem stability

farming practices (Hedley 2015). Soil sensors play a critical role in precision agriculture, providing real-time data on moisture, pH, and nutrient levels, enabling targeted fertilization (Sharma 2023). Remote sensing techniques, including multispectral and hyperspectral imaging, allow for large-scale monitoring of crop health and nutrient deficiencies (Singh 2024). Machine learning and predictive modeling refine nutrient management strategies, ensuring optimal supply aligned with crop demands (Naresh et al. 2024). This technology-driven approach improves nutrient use efficiency, reduces environmental impacts, and enhances soil health (Hedley 2015). However, challenges related to cost, accessibility, and data management need to be addressed for widespread adoption.

### Linking soil-root dynamics to food nutritional quality

#### Nutritional quality parameters

The soil-root interface plays a critical role in plant nutrition and human health. Soil properties and

microbial interactions influence the availability and uptake of essential macro- and micronutrients (Oliver & Gregory 2015). Agronomic biofortification, through targeted soil management and fertilization techniques, emerges as a vital strategy for addressing global micronutrient deficiencies, particularly in resource-limited regions (Kiran et al. 2022; Szerecent et al. 2022). By enhancing micronutrient concentrations in edible plant parts, this approach contributes to improved dietary nutrient intake (Schiavon et al. 2020). It is cost-effective and sustainable, capable of delivering nutrient-dense crops to large populations (Koç & Karayigit, 2022). Agronomic biofortification has shown promise in enriching crops with essential elements like zinc, selenium, and iron, which not only improve nutritional quality but also enhance crop stress defense (Paharaj et al. 2021). The effectiveness of this strategy depends on factors such as crop type, genotype, climate, and soil conditions (Teklu et al. 2023). The cultivation of micronutrient-efficient genotypes, combined with proper agronomic practices, offers a sustainable solution for improving crop yield and nutritional quality. Integrating agronomic and genetic approaches can further

optimize biofortification efforts, addressing nutritional security challenges in developing countries (Dhaliwal et al. 2022) (Table 3).

### Soil health and micronutrient biofortification

Biofortification of crops with essential micronutrients, particularly zinc (Zn), is a promising strategy to combat global malnutrition (Younas et al. 2023). Healthy soils are pivotal in enhancing biofortification by promoting nutrient cycling and beneficial microbial interactions (Mishra et al. 2023). Agro-nomic approaches, such as soil and foliar application of micronutrient fertilizers, have proven effective in increasing Zn concentrations in staple crops like wheat (Dhaliwal et al. 2022). Genetic biofortification through breeding and biotechnology provides long-term solutions (Praharaj et al. 2021). Micronutrient-efficient crop genotypes play a crucial role in sustainable agriculture by improving yields and nutritional quality while reducing fertilizer use. These genotypes thrive in nutrient-deficient soils due to enhanced root traits, such as increased surface area and chelating agent exudation (Rengel 2001; Rose et al. 2013). Modifications in root architecture significantly enhance nutrient acquisition efficiency (Li et al. 2016; Shen et al. 2013). Efficient genotypes alter rhizosphere chemistry and biology, increasing nutrient availability through mechanisms like soil acidification and organic compound exudation (Rengel 2015). Breeding for nutrient efficiency traits offers a promising avenue for developing crops with superior nutrient uptake and utilization (Fageria et al. 2008). However, practical implementation of these traits in breeding programs is limited, requiring more field studies to identify genes and traits that enhance nutrient acquisition under real-world conditions (Chen & Liao 2017; Rose et al. 2013). Recent research emphasizes enhancing micronutrient content in staple crops to address malnutrition, especially in developing countries (Mayer et al. 2008). Studies on molecular mechanisms of nutrient acquisition, transport, and storage highlight the importance of genetic variation for breeding nutrient-dense crops (Roorkiwal et al. 2021; Sperotto et al. 2014). Efforts focus on increasing iron, zinc, provitamin A and folate in major food staples through conventional breeding and genetic engineering (La Frano et al. 2014). Additionally, researchers explore the effects of abiotic and

biotic stresses on nutrient uptake and utilization to develop stress-resilient crops (Hu & Schmidhalter 2005; Kissoudis et al. 2014). The bioavailability of micronutrients in biofortified crops is higher than in non-biofortified varieties, demonstrating the efficacy of biofortification strategies in addressing hidden hunger (Dwivedi et al. 2023). Studies show biofortification's success in improving nutritional quality and addressing health issues, particularly in developing regions (Kihara et al. 2020). Selenium biofortification has also garnered attention for its potential health benefits (Schiavon et al. 2020). Integrating soil health management with biofortification techniques is essential for sustainable agriculture and improving global food and nutritional security. These strategies aim to address the dual challenges of feeding a growing population and ensuring nutritional adequacy. Enhancing soil health, promoting sustainable nutrient management, and developing nutrient-rich crops provide a pathway to improved food security and environmental sustainability. Achieving these goals demands interdisciplinary research, policy support, and innovative farming technologies.

### Degraded soils and nutritional deficits

Poor soil health significantly impairs nutrient density in staple crops, posing a major challenge to global food security and human nutrition (Kihara et al. 2020). Previous studies indicate that the concentration of essential micronutrients, including iron and zinc, in cereal grains has decreased by 5–40% over the past 50 years (Debnath et al. 2023). Micronutrient deficiencies, particularly zinc, iron, and selenium, are widespread in soils across Sub-Saharan Africa and South Asia, leading to nutrient-deficient crops and malnutrition in local populations (Bevis & Kim 2022; Waters & Sankaran 2011). The connection between soil nutrient availability and human health is well-established. Micronutrient deficiencies in soils often translate to insufficient nutrient concentrations in crops, impacting human health (Bevis & Kim 2022; Morton et al. 2023). Zinc, iron, selenium, and iodine deficiencies in soils are particularly linked to human health issues (Nubé & Voortman 2011; Oliver & Gregory 2015). For instance, soil zinc availability is associated with children's linear growth, while soil iron availability correlates with hemoglobin levels (Morton et al. 2023). Selenium deficiency in soils can lead to selenium-deficient diets, affecting human

**Table 3** This table summarizes the critical parameters influencing plant nutrient uptake and biofortification strategies, outlining their physiological and biochemical roles, regulating factors, and targeted interventions to enhance nutrient availability and sustainability

| Parameter                                 | Physiological and Biochemical Role                                                                     | Regulating Factors                                                               | Strategic Interventions for Bio-fortification                                                       | References                                                      |
|-------------------------------------------|--------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|-----------------------------------------------------------------|
| Soil-Root Interface Dynamics              | Mediates rhizospheric nutrient fluxes via root exudation and microbial synergy                         | Soil physicochemical properties, microbial consortia, redox potential            | Rhizosphere engineering, microbial inoculation, targeted amendments                                 | (Hinsinger et al. 2009; York et al. 2016; Zhalnina et al. 2018) |
| Macronutrient Homeostasis                 | Governs plant metabolic pathways, cellular energetics, and biomass allocation                          | Ion exchange capacity, rhizodeposition, nutrient translocation                   | Precision fertilization, rotational intensification, organic inputs                                 | (Gojon et al. 2011; Luan et al. 2017)                           |
| Micronutrient Bioavailability             | Essential for enzymatic catalysis, oxidative stress mitigation, and redox cycling                      | Soil pH, ligand complexation, mycorrhizal associations, metal chelation          | Chelated fertilizers, foliar nutrient translocation, mycorrhizal symbiosis                          | (Dhaliwal et al. 2019; Violante et al. 2010)                    |
| Biofortification Efficacy                 | Augments elemental density in edible plant tissues, improving dietary quality                          | Genotypic variation, soil nutrient bioaccessibility, atmospheric deposition      | Zinc, iron, selenium fortification, genotype-specific nutrient modulation                           | (Bouis & Welch 2010; Bouis et al. 2011)                         |
| Sustainability and Ecosystem Impact       | Enhances agronomic resilience and nutrient-use efficiency while mitigating environmental perturbations | Agroecosystem management, nutrient cycling efficiency, carbon–nitrogen dynamics  | Integrated soil fertility optimization, conservation tillage, agroecological intensification        | (Lal 2010; Tully & Ryals 2017)                                  |
| Genotypic Nutrient Acquisition Strategies | Determines root system plasticity and adaptive responses to soil heterogeneity                         | Root system ontogeny, hormonal regulation, rhizospheric nutrient gradients       | Breeding for nutrient-use efficiency, root phenotyping, molecular marker-assisted selection         | (Giehl, & von Witrén, 2014; Li et al. 2016)                     |
| Holistic Integration Approaches           | Synergistic enhancement of biofortification via agronomic and genetic interventions                    | Plant-soil-microbe interactions, nutrient partitioning, epigenetic modifications | Multi-modal fertilization strategies, transgenic biofortification, precision agriculture techniques | (Kiran et al. 2022; Koç & Karayigit 2022)                       |

selenium status (Bevis & Kim 2022). These deficiencies can result in stunted growth, anemia, compromised immune function, and increased susceptibility to diseases (Bhaskaram 2002; Knez & Graham 2012). While agronomic fortification shows promise in addressing some deficiencies, its effectiveness varies by region and is influenced by factors such as malaria pressure (Berkhout et al. 2019). Biofortification strategies, including agronomic approaches and genetic improvements, have shown promise in enhancing crop nutrient content and addressing human mineral deficiencies (White & Broadley 2009). Studies have demonstrated links between soil nutrient availability and human health outcomes, such as child mortality, stunting, and anemia (Berkhout et al. 2019; Morton et al. 2023). Improving soil health and implementing biofortification techniques are crucial for enhancing nutrient bioavailability and ensuring food systems can support adequate human nutrition globally (Kiran et al. 2022). The global implications of these issues are profound. Micronutrient malnutrition affects over two billion people worldwide, with severe economic and health consequences. Addressing these challenges requires a multifaceted approach that combines soil health restoration, biofortification technologies, and targeted nutritional interventions. By improving the nutrient density of staple crops, these strategies not only enhance food security but also contribute to the broader goals of reducing health disparities and improving quality of life in vulnerable populations. Enhanced collaboration among agronomists, nutritionists, soil scientists, and policymakers is crucial to advancing these solutions and ensuring their long-term success in mitigating nutrient deficiencies on a global scale (Table 4).

## Challenges and knowledge gaps

### Complex soil–plant interactions

The rhizosphere, the interface between plant roots and soil, is a hub of complex interactions critical for plant nutrient uptake and growth (Lemanceau et al. 2009). Soil microorganisms play a vital role in enhancing plant mineral nutrition by improving nutrient availability and acquisition (Jacoby et al. 2017; Pantigoso et al. 2022). These interactions are mediated by root exudates, which shape microbial communities and influence nutrient dynamics (Bais

et al. 2006). The rhizosphere microbiome, encompassing bacteria, fungi, and soil fauna, drives essential biogeochemical processes and nutrient cycling, playing a pivotal role in soil fertility and ecosystem functioning (Finzi et al. 2015; Larsen et al. 2015). Microbial activities in the rhizosphere facilitate nutrient cycling, organic matter decomposition, and soil structure formation (Bhattacharyya & Furtak 2022; Mueller et al. 2024). Plant species and soil type collaboratively shape microbial community structure and function within the rhizosphere (Berg & Smalla 2009). Biophysical processes, such as water organization in soil pores and microbial dispersion, significantly influence microbial life in soils (Tecon & Or 2017). Similarly, abiotic factors, including pH, temperature, and soil type, modulate soil and rhizosphere microbiome diversity (Pizano et al. 2017). The intimate connection between soil biology, physics, and chemistry generates spatially and temporally heterogeneous microenvironments in the rhizosphere (Hinsinger et al. 2009). The spatially heterogeneous distribution of soil nutrients impacts plant performance and ecosystem functioning, with soil microorganisms potentially regulating these effects (Adomako et al. 2022). Combinatorial nutrient stress reveal emergent properties in plant responses, highlighting the complexity of nutrient interactions (Bouain et al. 2019). Understanding these intricate plant–soil–microbe interactions is essential for developing sustainable agricultural practices and improving crop productivity (Das et al. 2022). Emerging research emphasizes integrating rhizosphere studies with advanced technologies such as metagenomics, isotopic tracing, and in situ imaging to unravel these complexities. These insights can inform precision agriculture systems and microbial inoculants tailored to specific crop and soil conditions. Ultimately, advancing our knowledge of rhizosphere ecology holds promise for achieving food security, mitigating climate change impacts, and restoring degraded ecosystems.

### Soil degradation and food security

Soil degradation is a significant challenge that threatens both global food security and environmental sustainability. Key issues include erosion, salinization, nutrient depletion, and loss of soil organic matter (SOM) (Gomiero 2016). These processes

**Table 4** This table highlights how soil conditions influence micronutrient availability, their subsequent impact on plant nutrient uptake, and the broader consequences for human health, emphasizing the need for targeted soil and crop management strategies to mitigate deficiencies

| Micronutrient  | Soil Deficiency Effects                                                                                                 | Crop Nutrient Deficiency                                                                                | Human Health Implications                                                                  | Mitigation Strategies                                                                                             |
|----------------|-------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|
| Zinc (Zn)      | Reduced Zn bioavailability due to high soil pH, phosphorus overuse, and organic matter depletion (Alloyway 2008)        | Decreased Zn concentrations in cereals and legumes, impairing bioavailability (Cakmak 2008)             | Stunted growth, impaired immune function, increased morbidity in children (Prasad 2013)    | Agronomic Zn fertilization, Zn-efficient crop genotypes, biofortification (Bouis & Saltzman 2017)                 |
| Iron (Fe)      | High soil pH and carbonate presence reduce Fe solubility; soil erosion exacerbates Fe depletion (Lindsay & Schwab 1982) | Low Fe accumulation in staple grains, particularly in calcareous soils (Marschner 1995)                 | Anemia, cognitive deficits, reduced work productivity (World Health Organization 2001)     | Soil acidification techniques, Fe-coated fertilizers, Fe biofortified crops (Velu et al. 2014)                    |
| Magnesium (Mg) | Soil acidification, excessive potassium application, and erosion reduce Mg availability (Gransee & Führs 2013)          | Reduced Mg uptake in grains and vegetables, leading to deficiencies in human diets (Ceylan et al. 2016) | Muscle cramps, cardiovascular issues, impaired nerve function (Rosanoff et al. 2012)       | Dolomitic lime application, Mg-enriched fertilizers, crop rotation with Mg-accumulating plants (Chen et al. 2018) |
| Manganese (Mn) | High soil pH, organic matter accumulation, and poor drainage reduce Mn availability (Reddy et al. 2003)                 | Decreased Mn concentrations in legumes and cereals, impairing plant metabolism (Fageria 2001)           | Neurological disorders, impaired growth, weakened immune function (Aschner & Aschner 2005) | Soil acidification, Mn foliar applications, Mn-efficient crop varieties (Huang et al. 2018)                       |
| Iodine (I)     | Soil erosion, excessive precipitation, and lack of marine influence reduce soil I content (Fuge & Johnson 2015)         | Low I content in plant-based foods grown in iodine-deficient soils (Zhu et al. 2022)                    | Goiter, hypothyroidism, impaired cognitive development (Zimmermann et al. 2008)            | Iodized salt programs, agronomic biofortification with I-enriched fertilizers (Li et al. 2020a, b)                |
| Calcium (Ca)   | Acidic soils, excessive leaching, and low organic matter reduce Ca availability (White & Broadley 2003)                 | Low Ca in fruits and vegetables, reducing dietary intake (Broadley et al. 2012)                         | Bone demineralization, increased osteoporosis risk (Lanham-New 2006)                       | Lime application, organic matter amendments, Ca-rich crop selection (Goswami et al. 2014)                         |

impair soil fertility, structure, and water retention, leading to reduced crop yields and nutritional quality (Kopittke et al. 2019; White et al. 2012). The intensification of agriculture to meet growing food demands has exacerbated soil degradation, creating unsustainable systems (Jones et al. 2013; Lal 2015). Salinity, particularly in arid regions, disrupts soil properties and plant growth, necessitating targeted management strategies. Addressing these challenges requires adopting sustainable practices such as conservation agriculture, integrated nutrient management, and erosion control measures (Lal 2009). Additionally, recognizing soil's role in ecosystem services and incorporating its value into economic frameworks is crucial for long-term food security and environmental protection (Amundson et al. 2015) (Table 5).

### Research gaps in soil health indicators

Recent research highlights the complex relationship between soil health, plant nutrition, and food security. While soil health frameworks typically focus on physical, chemical, and biological parameters (Zhang & Zhang 2020), there's a growing recognition of the

need for integrative approaches that link soil properties directly to crop nutritional outcomes (Herforth et al. 2014). Researchers propose various indicators and assessment methods, including the "Soil Health Gap" concept (Maharjan et al. 2020) and multi-domain evaluations incorporating nutritional quality, economic viability, and environmental sustainability (Herforth et al. 2014). Despite advances in understanding soil processes and their effects on human health (Oliver & Gregory 2015), challenges persist in developing universally accepted indicators that connect soil health to food nutritional security (Wood & Blankinship 2022). Future research should focus on quantitative, empirical approaches to soil health assessment (Wade et al. 2022) and explore the intricate soil–plant–microbiota interactions influencing crop performance and nutritional quality (Giovannetti et al. 2023).

### Future perspectives

#### Innovations in soil health monitoring

Recent advances in soil health monitoring have significantly enhanced our understanding of the soil–root

**Table 5** Soil health priorities across major agroecosystems and their implications for global food security

| Region/Climate Zone            | Dominant Agricultural System             | Key Soil Health Focus                      | Key Findings/Implications for Food Security                                                                      |
|--------------------------------|------------------------------------------|--------------------------------------------|------------------------------------------------------------------------------------------------------------------|
| North America (Temperate)      | No-till maize–soybean rotations          | Soil aggregation, SOM, microbial activity  | No-till enhances aggregate stability by 20–40% and increases microbial metabolic activity (Lehman et al. 2019)   |
| South Asia (Sub-tropical)      | Rice–wheat systems (intensive)           | Nutrient depletion, micronutrient trends   | Continuous monocropping linked to 30–40% decline in Zn and Fe in cereals over decades (Nadeem & Farooq 2019)     |
| Sub-Saharan Africa (Semi-arid) | Low-input maize-based small-holder farms | Soil fertility, SOM depletion              | Low fertilizer use and erosion drive SOM decline, limiting yields and micronutrient density (Lelei et al. 2025)  |
| Europe (Temperate)             | Diversified cereal–legume systems        | SOM and microbial consortia                | Crop diversification improves SOM retention and AMF-mediated phosphorus uptake (Reckling et al. 2022)            |
| Latin America (Tropical)       | Soybean and pasture systems              | Soil compaction, erosion, nutrient cycling | Expansion of soybean cultivation contributes to soil compaction and reduced nutrient cycling (Pariz et al. 2017) |

nexus and its implications for sustainable agriculture. Molecular tools like metagenomics provide unprecedented insights into soil microbiomes, revealing microbial diversity and functional genes linked to nutrient cycling and plant health (Bertola et al. 2021; Djemiel et al. 2022). Concurrently, advanced soil sensors have emerged as transformative tools for real-time monitoring of soil nutrient dynamics, utilizing technologies such as ion-selective electrodes and spectroscopic techniques (Burton et al. 2020; Xu et al. 2024).

Advancements in soil health monitoring are pivotal for sustainable agricultural management, enabling precise assessment of soil quality parameters and biogeochemical processes. Emerging technologies, such as proximal soil sensing, remote sensing, and artificial intelligence-driven analytics, are revolutionizing how soil health is evaluated at spatial and temporal scales (Dor et al. 2023). Spectroscopic techniques, including mid-infrared (MIR) and near-infrared (NIR) spectroscopy, provide rapid, non-destructive quantification of soil organic carbon, nutrient composition, and microbial activity (Viscarra Rossel et al. 2017). Coupled with machine learning algorithms, these methodologies enhance predictive capabilities, facilitating data-driven soil management strategies (Ramirez-Lopez et al. 2019). High-resolution X-ray computed tomography (X-ray CT) further enables structural assessments of soil aggregates and pore networks, elucidating the dynamics of water retention and soil physical properties in diverse soil matrices (Katuwal et al. 2015). The integration of Internet of Things (IoT)-enabled soil sensors and wireless networks allows real-time monitoring of soil moisture, temperature, and electrical conductivity, optimizing precision agriculture interventions (Bhakta et al. 2023). Moreover, the increasing application of isotopic and spectrometric techniques, such as laser-induced breakdown spectroscopy (LIBS) and stable isotope probing (SIP), offers deeper insights into nutrient cycling and organic matter decomposition pathways (Reeves et al. 2024). Future research should focus on the synergistic integration of these technologies to develop holistic soil health assessment frameworks, enhancing the resilience of agroecosystems under changing climatic conditions.

### Breeding nutrient-efficient crops

Current advancements reveals the critical role of root system architecture (RSA) in enhancing

nutrient acquisition efficiency for sustainable agriculture. Studies have identified key root traits such as increased root length, lateral root proliferation, and deep rooting that improve uptake of nutrients like phosphorus and zinc (Rose et al. 2013; White 2019). Advanced phenotyping techniques, including shovelomics and digital imaging, are enabling better characterization of these traits (Mathew & Shimelis 2022; Paez-Garcia et al. 2015). Genetic variation in root traits offers opportunities for breeding more nutrient-efficient crops (Chen & Liao 2017; Li et al. 2016). Plants can adapt their RSA in response to nutrient availability through specific molecular mechanisms (Giehl & von Wirén, 2014). Integration of root traits in breeding programs, supported by genomic tools, is seen as a promising strategy for developing crops with improved nutrient acquisition, particularly for low-input agricultural systems (Kong et al. 2014; Mathew & Shimelis 2022).

### Policy and outreach

Bridging the gap between scientific innovation in root system architecture (RSA) and soil health and their practical application in improving nutrient uptake and food nutritional security requires cohesive policy support and effective outreach mechanisms. Policymaking must prioritize sustained investments in root and soil health research, the development of nutrient-efficient crop varieties, and the equitable distribution of high-quality, regionally adapted seeds. Strengthened extension and advisory services are essential for translating research findings into actionable knowledge for farmers, particularly concerning soil–root interactions, nutrient acquisition strategies, and regenerative soil management practices. Collaborative efforts among researchers, policymakers, extension professionals, and farming communities are critical for tailoring innovations to local agroecological and socioeconomic contexts. Initiatives such as the European Union Soil Mission, which aims to establish 100 living labs and lighthouses by 2030 to improve soil health, provide a model for integrating research, innovation, monitoring, and policy to accelerate sustainable transitions. Incorporating participatory approaches and continuous feedback mechanisms into outreach programs enhances the relevance, adoption, and long-term success of these technologies. Such integrated frameworks are vital for advancing

sustainable agricultural systems that simultaneously improve soil health, optimize plant nutrient uptake, and contribute to food and nutritional security.

## Conclusion

The soil-root nexus represents a critical interface where biophysical, biochemical, and microbial processes converge to regulate plant nutrient acquisition, with profound implications for crop productivity, nutrient density, and ultimately, global food and nutritional security. Soil health defined by optimal structure, nutrient availability, organic matter content, and a functionally diverse microbiome directly governs root system architecture (RSA) and function. In turn, the root system modulates rhizosphere processes, mediates nutrient mobilization, and shapes microbial associations essential for nutrient uptake efficiency. Disruptions to this nexus, often driven by anthropogenic stressors such as intensive tillage, chemical overuse, erosion, and pollution, lead to declines in soil functional capacity, impaired root performance, and reduced translocation of essential nutrients to edible plant tissues thereby exacerbating micro-nutrient deficiencies and malnutrition on a global scale. Addressing these challenges necessitates a paradigm shift toward integrated soil-root management frameworks rooted in ecological principles. Practices such as conservation tillage, organic amendments, cover cropping, and site-specific nutrient management enhance soil biophysical properties, stimulate beneficial microbial consortia, and optimize RSA traits, thereby reinforcing nutrient acquisition pathways. Furthermore, leveraging advances in root phenotyping, soil microbiome profiling, and systems-based nutrient modeling offers new opportunities to mechanistically link soil function, root biology, and nutritional outcomes. Prioritizing the soil-root continuum in both research and policy is essential to designing resilient agroecosystems capable of withstanding climatic variability and securing equitable access to nutritious food. As such, the soil-root nexus should be recognized not merely as a biological interaction but as a strategic foundation for sustainable agriculture and global nutritional resilience.

**Acknowledgements** The authors would like to acknowledge the support of South Dakota State University, Brookings, SD 57007, USA, for providing the academic environment and resources that facilitated this work.

**Author contributions** Conceptualization: N.J. and T.N., Writing – Original Draft: N.J. and R.K.; Writing – Review & Editing: N.J., T.N., and R.K.

**Funding** Not applicable.

**Data Availability** No datasets were generated or analyzed during the current study.

## Declarations

**Ethics approval and consent to participate** Not applicable.

**Consent of publication** Not applicable.

**Competing interests** The authors declare that they have no competing interests.

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