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Agricultural soil health-crop nutrition-human health continuum: Soil processes, nutritional quality and sustainable management

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Abstract

Agricultural soil degradation threatens not only crop productivity but also the nutritional quality and safety of food. Soil physical, chemical and biological processes regulate the nutrient availability, plant nutrient acquisition, contaminant mobility and synthesis of nutritionally important compounds, thus providing an important link between soil condition and crop nutritional quality. This review examines the continuum connecting the agricultural soil health, crop nutrient density, food safety, nutritional security and human health, with particular emphasis on the mechanisms through which soil properties and management practices influence these outcomes. The evidence indicates that soil organic matter, pH, nutrient availability, water relations, microbial activity and soil-plant-microbe interactions collectively regulate crop acquisition of macro and micronutrients. These effects are generally more evident for micronutrients and phytochemicals than for macronutrients, although responses vary with crop genotype, soil type, climate and management conditions. Organic amendments, diversified cropping systems, reduced soil disturbance, integrated nutrient management and beneficial microbial associations can improve soil functioning and, under suitable conditions, enhance the nutritional quality of crops. However, the evidence does not support a simple distinction between organic and conventional production systems, because individual management practices and their interactions with environmental and crop-specific factors strongly influence outcomes. Soil contamination presents an additional food safety pathway through the transfer of potentially toxic elements and agricultural chemical residues into crops. Although links between the soil properties and crop nutrient composition are increasingly supported, evidence directly connecting soil health interventions with dietary intake and measurable human health outcomes remains comparatively limited. Future research should therefore integrate soil indicators, crop nutritional profiles, dietary exposure and health related measurements through long-term, multi-site and interdisciplinary approaches. A stronger soil crop nutrition framework can help identify the management strategies that simultaneously support soil functioning, nutritional quality, food safety and sustainable agricultural production.

Keywords: agricultural soil health; crop nutritional quality; food safety; human health; nutrient density; sustainable agriculture; micronutrients

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1. Introduction

Healthy soil provides the physical, chemical and biological conditions needed for sustainable food production. Maintaining productivity and long-term functional capacity is increasingly important for food and nutritional security, yet soil degradation, including erosion, loss of soil organic matter, nutrient imbalance, salinisation, contamination, compaction and biodiversity loss, is widespread and threatens agricultural productivity (1, 2). Malnutrition remains a major global health challenge, with micronutrient deficiencies (“hidden hunger”) affecting vulnerable populations and

coexisting with overweight and obesity in many settings (3). Food security therefore depends not only on adequate calories but also on nutritional quality. Soil nutrient availability, chemical properties and biological processes influence plant nutrient acquisition and the composition of edible tissues, linking soil condition to this broader dimension of food security (2, 4).

Soil also affects food safety through the transfer of potentially toxic elements from contaminated agricultural soils to crops. Cadmium, lead, arsenic, chromium and mercury may enter soils through industrial emissions, wastewater irrigation, atmospheric deposition, mining and contaminated agricultural inputs. Their transfer to crops depends on contaminant characteristics, soil properties, crop species and bioavailability rather than the total soil concentrations alone (5–7). Soil degradation can further alter the crop nutritional composition by affecting the nutrient availability, water relations, root development and biological activity. Soil organic matter (SOM) and soil organic carbon (SOC) contribute to nutrient retention, aggregation, water regulation and microbial processes supporting nutrient cycling (2, 8). However, evidence for differences in crop nutritional quality among production systems remains heterogeneous across crops, cultivars, environments and management practices (4, 9, 10). Soil health should therefore be viewed as an interacting determinant of crop nutritional composition rather than a universal predictor of higher nutrient density.

Management practices such as organic amendments, crop diversification, reduced soil disturbance, residue retention and integrated nutrient management can modify soil properties, nutrient cycling and plant nutrient acquisition (10–13). Their nutritional effects remain context dependent, varying with soil type, climate, crop genotype, nutrient status and management duration. Soil microorganisms are central to these processes through organic matter decomposition, nutrient mineralisation and mobilisation, rhizosphere interactions and plant nutrient acquisition (14–17). Although evidence is relatively strong for individual links between soil properties, crop composition and contaminant transfer, the complete pathway from soil condition through food composition and dietary exposure to human health remains less established (1, 2, 5, 18). This review synthesises evidence linking soil physical, chemical and biological properties with crop nutritional quality and food safety, examines soil management and microbial processes and considers their implications for nutritional security and human health within a soil–crop–food–health framework. The conceptual relationships among soil properties, plant nutrient acquisition, crop nutritional quality and safety, dietary exposure and human health are summarised in Fig. 1.

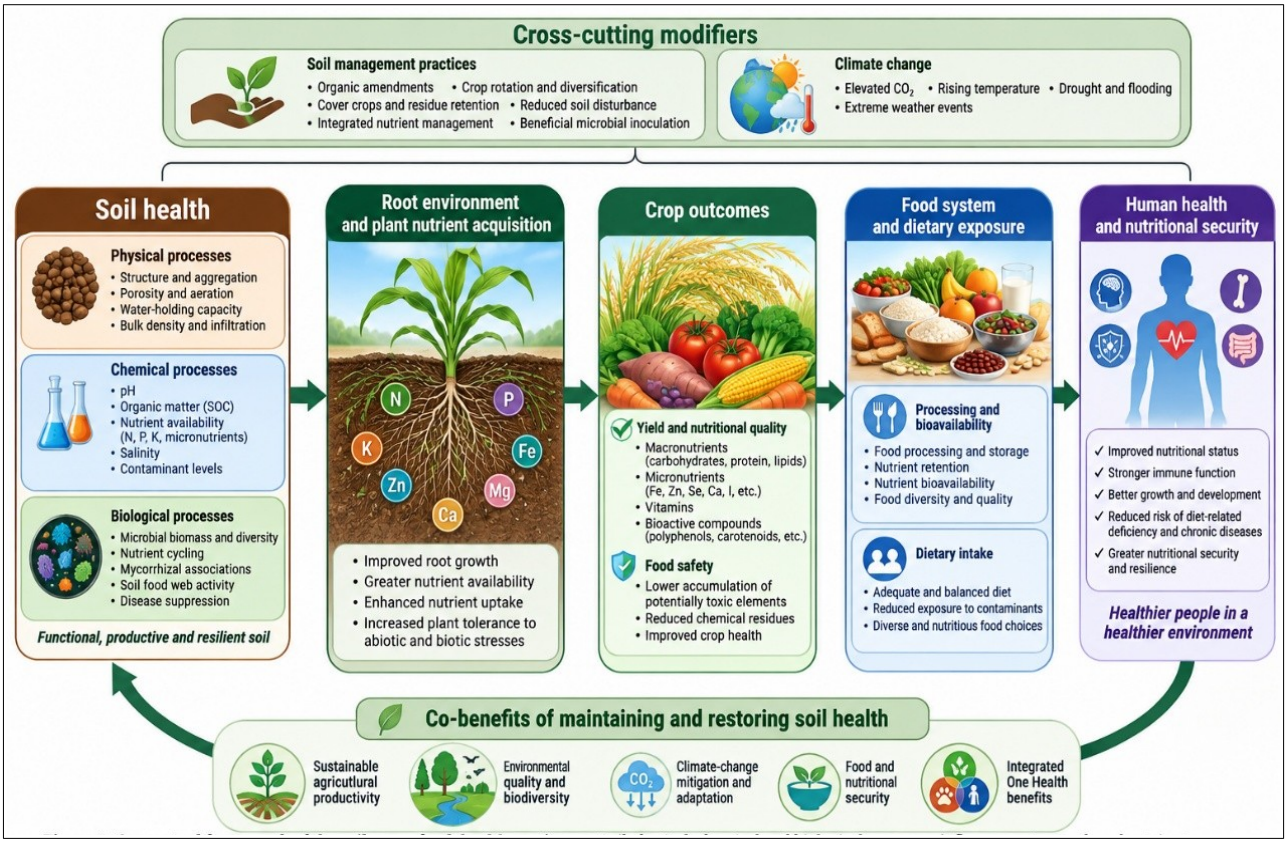


Fig. 1. Conceptual framework of the soil-crop-food-health continuum.

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2. Methodology

This article presents a narrative review of the relationships among agricultural soil health, crop nutritional quality and human health, focusing on how soil physical, chemical and biological processes influence crop nutrient availability and quality, food safety, nutritional security and human health. Relevant literature was identified through searches by Google Scholar, PubMed, Scopus, ScienceDirect/Elsevier and other academic resources conducted from December 2025 to May 2026. Search terms included combinations of "soil health," "crop quality," "human health," "sustainable agriculture," "organic agriculture," "malnutrition," "climate change," "soil nutrition," "crop nutritional quality," and related terms. Search also addressed soil fertility, soil organic matter and carbon dynamics, nutrient availability, soil-plant-microbe interactions, micronutrient density, soil contamination and food safety, soil degradation, nutritional security and related topics. Additional relevant publications were identified from reference lists of selected articles and related literature.

The literature was evaluated thematically rather than according to a formal systematic review protocol. Priority was given to peer reviewed research and established scientific sources relevant to the mechanisms linking soil processes with crop nutrition and human health, particularly studies addressing nutrient dynamics, microbial processes, crop composition, soil management practices, climate related impacts and food safety. Evidence was synthesised across four interconnected levels: (i) soil physical, chemical and biological properties; (ii) nutrient cycling, soil–plant–microbe interactions and plant nutrient acquisition; (iii) crop nutritional quality and food safety; and (iv) implications for dietary nutrition and human health. Context dependent findings and evidence insufficient to establish causal relationships were interpreted cautiously. Accordingly, this review provides an integrated narrative synthesis rather than a systematic review or quantitative meta-analysis.

Agricultural soil health: Components, functions and fertility

Concept and multidimensional nature of soil health

Soil health is the capacity of soil to function as a living system that sustains biological productivity, maintains environmental quality and supports agricultural and ecosystem functions. Unlike assessments focused primarily on crop production, the soil health concept encompasses nutrient cycling, water regulation, carbon (C) storage, biological habitat, disease suppression and contaminant retention or transformation (2). Soil health is therefore dynamic and context dependent.

It is assessed through interacting physical, chemical and biological attributes. Physical properties such as structure, aggregation, bulk density, porosity and infiltration influence root growth, aeration, water storage and transport. Chemical properties, including pH, SOC, nutrient availability, salinity and cation exchange capacity (CEC), regulate nutrient solubility and retention, whereas the biological properties such as microbial biomass, enzyme activity, respiration, diversity and soil fauna reflect decomposition, nutrient cycling and plant-microbe interactions (2, 19). Because no single indicator captures these functions, integrated assessment is necessary; the principal dimensions and indicators are summarised in Table 1.

Interpretation should also account for inherent soil characteristics and land use context. Texture, mineralogy, climate, parent material and topography influence measured properties independently of management; therefore, assessment should distinguish inherent from management sensitive attributes and consider whether soil performs the functions required for its specific use (2, 17). This is particularly important for crop nutritional quality because responses to the same management practice can differ among soils, climates, crops and production systems (20).

Table 1. Major soil health dimensions, indicators and relevance to crop nutrition

Soil health dimension	Representative indicators	Relevance to crop nutrition	Key references
Physical	Structure, aggregate stability, bulk density, porosity, infiltration, water holding capacity	Determines root growth, aeration, water availability and movement of nutrients toward roots	(2, 21)
Chemical	pH, soil organic carbon (SOC), soil organic matter (SOM), cation exchange capacity (CEC), electrical conductivity, nutrient availability	Regulates nutrient solubility, retention, transformation and plant availability; also influences contaminant mobility	(22, 33)
Biological	Microbial biomass, respiration, enzyme activity, microbial functional diversity, mycorrhizal activity	Supports organic matter decomposition, nutrient mineralisation and mobilisation and plant–microbe interactions	(15, 17)
Nutrient and contaminant status	Available N, P, K, Fe, Zn, Se; potentially toxic elements such as Cd, Pb and As	Directly affects plant nutrient supply and the potential transfer of contaminants into edible tissues	(34, 55)

N: nitrogen; P: phosphorus; K: potassium; Fe: iron; Zn: zinc; Se: selenium; Cd: cadmium; Pb: lead; As: arsenic.

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Physical and chemical functions relevant to crop nutrition

Soil physical and chemical properties jointly determine root access to water and nutrients. Structure and aggregation regulate pore distribution, infiltration, drainage, aeration, water storage and root penetration. Compaction increases bulk density and reduces macro-porosity, restricting roots and the movement of water, oxygen and dissolved nutrients, whereas stable aggregates and connected pore networks can improve infiltration, water retention and conditions for roots and microorganisms (21). Chemical properties determine nutrient form, mobility and availability. Soil pH influences nutrient solubility, microbial activity and the retention or precipitation of essential elements. Organic carbon and organic matter contribute to nutrient retention, while CEC affects the retention and exchange of positively charged nutrients. Availability of nitrogen (N), phosphorus (P) and potassium (K) is further governed by interactions among minerals, organic matter, microorganisms, moisture and roots; consequently, total nutrient concentration does not necessarily reflect plant available nutrient pools (22, 23).

Nitrogen availability depends on decomposition, mineralisation, immobilisation, nitrification, denitrification and biological fixation. Phosphorus is regulated by mineralisation, sorption–desorption, precipitation and microbial and root mediated solubilisation, whereas K availability depends partly on exchange processes and release from mineral and non-exchangeable pools. These processes are influenced by biological activity, moisture, pH and management (14, 23). Thus, maintaining fertility requires management of nutrient cycling and availability rather than simply increasing fertiliser inputs.

Salinity and sodicity provide additional examples of interacting chemical and physical constraints. Excess salts reduce plant water uptake and can disrupt nutrient balance, while sodicity promotes clay dispersion and impairs infiltration. These interactions can consequently affect both crop productivity and nutrient acquisition.

Soil and organic matter biological function

The SOM provides microbial substrates, contributes to aggregation and water retention and participates in nutrient retention and cycling. Because organic matter pools differ in composition, turnover and mineral association, SOM quantity alone does not fully describe soil functioning or nutrient dynamics (2, 8). During decomposition, microbial mineralisation releases nutrients, whereas microbial assimilation can temporarily immobilise them. Balance depends on the carbon to nitrogen ratio (C : N) of organic inputs as well as temperature, moisture, oxygen and microbial community composition. High C: N residues may temporarily immobilise mineral N, whereas lower C: N residues generally promote more rapid N release. Thus, organic inputs do not necessarily increase plant available nutrients immediately; their quality and timing must correspond to crop demand (24, 25).

The SOM also supports aggregate formation through interactions among organic compounds, minerals, roots and microorganisms. Fungal hyphae and roots contribute to aggregate stabilisation, improving infiltration and reducing erosion, while greater water holding capacity can buffer crops against water stress (8, 21). These effects illustrate the role of SOM as a functional link among the physical, chemical and biological dimensions of soil health. Microbial activity is similarly central to nutrient cycling. Microorganisms decompose residues and produce enzymes involved in C, N, P and sulphur (S) transformations, while microbial biomass temporarily stores nutrients and root associated interactions influence nutrient mobilisation and uptake. However, microbial abundance alone does not indicate functional capacity; community composition, functional traits, activity and environmental conditions determine soil microbial function (15, 26).

Soil health, soil fertility and ecosystem functions

Soil fertility is a component of soil health but has a narrower focus: the capacity to supply the essential nutrients for plant growth. Soil health additionally encompasses structure, water regulation, biological activity, C cycling, biodiversity, disease suppression and retention or transformation of potentially harmful substances (2, 23). Thus, a nutrient rich soil may still have impaired health if compaction, poor water regulation, salinity, biological degradation, or contamination limits other functions.

This distinction is important for crop nutritional quality. Maximising short-term nutrient availability does not necessarily improve long-term soil functioning; excessive or imbalanced fertilisation can increase nutrient losses, acidification, salinity, or contamination. Conversely, practices that improve organic matter, aggregation, microbial activity and nutrient retention can support multiple functions, although effects on crop nutrient composition remain dependent on crop, soil and environmental conditions (20, 23).

Healthy soil consequently provide interconnected ecosystem services relevant to food and nutrition. Nutrient cycling supplies essential elements; structure and organic matter regulate water and root growth; microbial communities support nutrient transformation and disease suppression; and SOC contributes to C storage and ecosystem regulation (2, 15). Because these functions interact, soil health management should be evaluated using integrated physical, chemical and biological indicators rather than yield or nutrient availability alone (15, 21). Integrated assessment of physical, chemical and biological indicators provides a more informative basis for understanding whether management practices improve the capacity of agricultural soils to sustain productivity, nutrient cycling, environmental quality and crop nutritional quality over time (2, 20).

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Soil-plant-microbe interactions governing crop nutrition

Rhizosphere processes and microbial regulation of nutrient availability

The rhizosphere is the soil zone influenced by plant roots and is a major interface among plants, microorganisms, minerals and organic matter. Root exudates, including sugars, amino acids, organic acids and other metabolites, provide substrates and signals that shape microbial activity, while rhizosphere microorganisms influence nutrient availability, root development and plant responses to environmental stress (16, 27). The principal microbial groups and complementary mechanisms through which soil microorganisms influence nutrient availability, plant growth and crop nutritional outcomes are illustrated in Fig. 2.

Microorganisms regulate nutrient availability through decomposition, extracellular enzyme activity, mineralisation, immobilisation, acidification, chelation, mineral weathering, redox reactions and enzymatic hydrolysis. The effectiveness of these processes depends on soil pH, moisture, organic matter availability, mineral composition, microbial communities and plant–microbe interactions (15, 28). Plant growth-promoting rhizobacteria (PGPR) can further influence plant nutrition through biological N fixation, phosphate solubilisation, siderophore production, hormone regulation and ACC deaminase activity. Indirect effects include pathogen suppression, competition, antimicrobial production and induction of plant defence responses. These functions may occur simultaneously, but their effectiveness depends strongly on microbial strain, host genotype and environmental conditions (27, 29).

Microorganisms involved in nitrogen, phosphorus and potassium mobilisation

Biological N fixation contributes directly to plant N supply, particularly through legume–rhizobium symbioses in which atmospheric N_2 is reduced to ammonia within root nodules. Fixed N can support plant growth and may contribute to subsequent crops through residual N and altered soil N dynamics. Fixation efficiency depends on host genotype, microbial strain, soil mineral N, acidity, temperature, moisture and other environmental factors; therefore, it should not be regarded as a universal substitute for fertiliser N (28, 30).

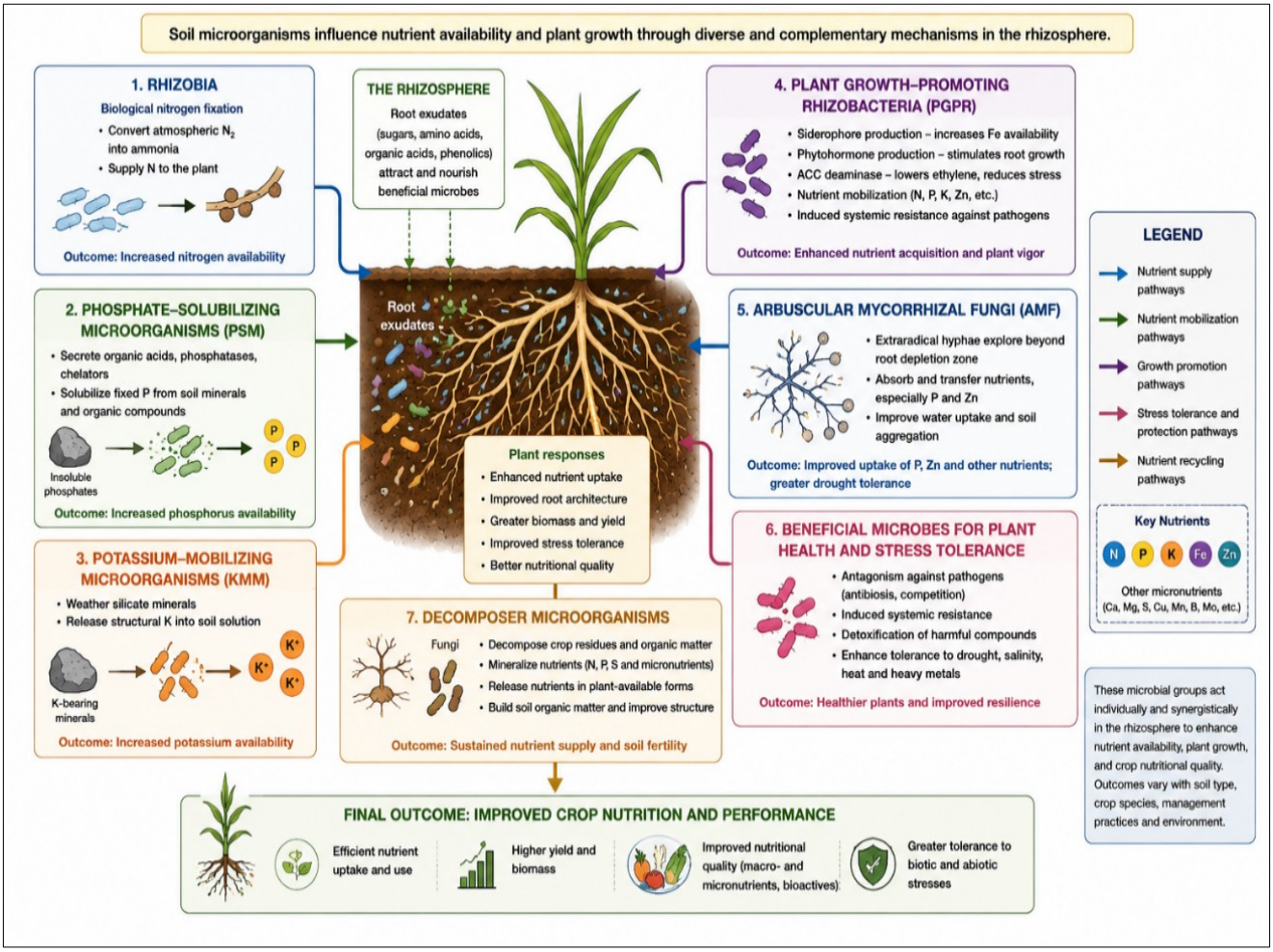


Fig. 2. Soil-plant-microbe mechanisms governing crop nutrition.

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Phosphorus solubilising microorganisms mobilise poorly available P through organic acid production, proton release, chelation and phosphatase activity. Bacterial genera such as *Bacillus*, *Pseudomonas* and *Streptomyces*, together with several fungal groups, can contribute to P acquisition, although effectiveness depends on soil P forms, pH, mineralogy, C availability and microbial activity (15, 28). Microorganisms may also release K from mineral and non-exchangeable pools through weathering and dissolution, although evidence and responses are more site-specific than for N and P (27, 28). Microbial groups interact through competition, cooperation, metabolite exchange and chemical signalling, influencing the cycling and acquisition of N, P, K, iron (Fe), zinc (Zn) and other nutrients. Their effects may be synergistic, neutral, or antagonistic rather than uniformly additive (15, 27). Key microbial groups and nutrient acquisition mechanisms are summarised in Table 2.

Arbuscular mycorrhizal fungi and nutrient acquisition

Arbuscular mycorrhizal fungi (AMF) form mutualistic associations with many terrestrial plants, receiving plant derived carbon in exchange for enhanced access to soil resources. Their extraradical hyphae extend beyond root depletion zones and are particularly important for acquiring relatively immobile nutrients such as P and, in some systems, Zn and other mineral nutrients (17). The AMF can also influence nutrient mobilisation, water relations, stress responses and soil aggregation through interactions with soil microorganisms, roots, fungal hyphae and associated organic compounds (17, 31). However, benefits vary with plant and fungal genotype, soil P status, nutrient availability, environmental conditions and existing microbial communities. High P availability and some management practices can reduce mycorrhizal dependence or colonisation, so AMF inoculation does not guarantee uniform improvements in nutrient uptake (17, 31). Interactions among AMF, phosphate solubilising microorganisms, PGPR and other rhizosphere organisms may provide complementary pathways for nutrient acquisition and stress tolerance. Such consortia are being investigated as multifunctional biofertilisers, although field scale performance remains variable and depends on crop, soil, climate and management conditions (17, 27).

Microbial contributions to plant health and nutrient use efficiency

Microorganisms influence crop nutrition both directly, through nutrient mobilisation and indirectly, through effects on plant health and root function. Beneficial rhizosphere microorganisms can suppress pathogens through competition, antimicrobial compounds, enzymatic activity and induced systemic resistance, thereby supporting root function and nutrient acquisition (15, 29). Some PGPR produce or regulate plant signaling compounds, including auxins, cytokinins, gibberellins and ethylene related pathways, thereby modifying root architecture and soil exploration. 1-aminocyclopropane-1-carboxylate (ACC) deaminase producing bacteria can reduce stress associated ethylene accumulation under some conditions and support root growth during environmental stress. These effects remain dependent on microbial strain, plant genotype, environmental conditions and timing of microbial activity (29). Thus, microbial contributions to nutrient use efficiency reflect both direct nutrient mobilisation and changes in the plant's capacity to acquire and utilise nutrients. This multifunctionality provides a basis for incorporating microbial processes into broader soil health management (15, 27).

Table 2. Key soil microorganisms and mechanisms influencing crop nutrient acquisition

Microbial group/process	Principal mechanism	Nutritional relevance to crops	References
N fixing bacteria (rhizobia and other diazotrophs)	Biological fixation of atmospheric N_2 into plant available forms	Increases biological N supply and can improve crop N nutrition, particularly in N limited systems	(27, 30)
Phosphate solubilizing microorganisms	Organic acid production, phosphatase activity and mineral P mobilisation	Increases availability and acquisition of otherwise poorly available P	(27, 28)
Arbuscular mycorrhizal fungi (AMF)	Extraradical hyphae extend beyond root depletion zones and increases the soil volume explored by roots	Enhances acquisition of relatively immobile nutrients, particularly P and selected micronutrients such as Zn	(17, 28)
Plant growth promoting rhizobacteria (PGPR)	Nutrient mobilisation, siderophore production, phytohormonal regulation and modification of root growth	Can promote root development and improve acquisition of selected macro and micronutrients under suitable conditions	(15, 27)
Decomposer and nutrient cycling microorganisms	Decomposition, mineralisation, immobilisation and transformation of organic nutrients	Regulates the release and recycling of N, P, S and other nutrients that contribute to plant nutrient supply	(15, 24)

N: nitrogen; P: phosphorus; S: sulphur.

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Constraints and context dependence of microbial interventions

Microbial inoculants and biofertilisers do not produce consistent outcomes across agricultural environments. Their establishment and activity are influenced by native microbial communities, soil pH and nutrient status, temperature, moisture, organic matter content, crop genotype and management history; consequently, results from controlled environments may not translate directly to field conditions (27, 29). Effectiveness also depends on the underlying soil constraint. For example, a P solubilising microorganism may provide little benefit when P is not limiting, while AMF colonisation may decline under high P availability or management that disrupts fungal networks. Microbial interventions should therefore complement, rather than replace, appropriate soil and crop management (17, 31). Overall, soil microorganisms provide multiple pathways for influencing crop nutrition through N fixation, nutrient mineralisation and mobilisation, P solubilisation, K release, mycorrhizal acquisition, root development, stress tolerance and disease suppression. Because their effects are context dependent, effective soil health strategies should prioritise microbial functions and ecological interactions rather than the presence or abundance of individual taxa (26–28).

Soil properties and crop nutritional quality

Soil structure, water availability and nutrient uptake

Soil structure, aggregate stability, porosity, bulk density and hydraulic properties regulate infiltration, water storage, aeration and root penetration, thereby influencing nutrient transport and uptake. Well-structured soils provide interconnected pores that facilitate drainage and aeration while retaining plant available water, whereas compaction restricts root exploration and the movement of water and dissolved nutrients (21, 32). Water availability affects nutrient acquisition through root activity and the transport of dissolved nutrients. Water deficits can reduce root growth, nutrient transport, microbial activity and nutrient uptake, whereas waterlogging limits oxygen availability and alters redox sensitive nutrient transformations. Thus, both drought and excess water can impair nutrient acquisition without necessarily changing total soil nutrient concentrations (21, 32). Soil organic matter supports these processes by improving aggregation, water retention and microbial activity. However, the magnitude of these effects depends on soil texture, climate, organic matter quality, management history and soil disturbance; improvements in structure should therefore be considered within the broader soil system rather than as direct predictors of crop nutrient density (8, 21).

Soil organic matter and carbon-nutrient dynamics

The SOM is an important reservoir of carbon and nutrients and regulates their cycling through microbial decomposition. Nutrients released by mineralisation may alternatively be temporarily immobilised in microbial biomass, determining the timing and magnitude of nutrient availability to crops (8, 24). The C: N ratio of organic inputs is particularly important. High C: N materials can promote temporary N immobilisation, whereas lower C: N materials generally release N more rapidly. Nutrient synchronisation with crop demand depends on residue quality, decomposition rate, temperature, moisture, microbial activity and application timing. Combining organic inputs with mineral fertilisers can therefore provide complementary nutrient release patterns when appropriately managed (24, 25). The SOM also contributes to nutrient retention through interactions with mineral surfaces and aggregates and provides substrates for microbial nutrient transformations involving N, P, S and micronutrients (8, 15). However, increased soil carbon does not necessarily produce immediate increases in plant available nutrients because carbon accumulation and nutrient release occur on different timescales. Nutritional effects should therefore be evaluated over appropriate periods rather than inferred solely from changes in SOM (24, 25).

Soil pH, salinity and nutrient bioavailability

Soil pH regulates nutrient solubility, retention, microbial activity and plant uptake, although responses are nutrient and soil specific. For many agricultural soils, nutrient availability is broadly favourable under moderately acidic to near neutral conditions, but crop-specific optima vary (22, 33). Phosphorus illustrates this dependence: in strongly acidic soils it may be associated with Fe and Al containing minerals, whereas in alkaline soils it can form relatively insoluble Ca phosphate phases. Micronutrients such as Fe, Zn, manganese (Mn) and copper (Cu) generally become less soluble as pH increases, although acidic conditions may increase their availability while also increasing risks of aluminium (Al) or Mn toxicity (22, 33). Consequently, pH management should be based on the specific nutrient, soil chemistry and crop requirement rather than a universal target. Salinity reduces soil water potential and can disrupt nutrient balance, while sodicity can impair structure and infiltration through clay dispersion. These chemical and physical constraints can interact with water stress and further restrict crop growth and nutrient acquisition.

Macronutrient and micronutrient availability

Crop nutritional quality depends on the availability and physiological utilisation of both macro and micronutrients. The N, P and K availability is governed by interactions among mineral and organic pools, microbial transformations, soil moisture, pH, root activity and nutrient inputs rather than total soil concentrations alone (14, 23).

Nitrogen availability reflects SOM decomposition, biological fixation, mineralisation, immobilisation, nitrification and denitrification. Adequate N supports protein accumulation and photosynthetic

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activity, whereas severe deficiency restricts growth and reproductive development. Excessive N inputs, however, can increase nutrient losses and environmental impacts without proportionate improvements in crop nutritional quality (15, 23). Phosphorus availability depends on mineral associations and microbial and root mediated mobilisation, including the activities of phosphate solubilising microorganisms and mycorrhizal fungi. Potassium availability depends on exchange processes and release from non-exchangeable and mineral pools, with microbial weathering contributing under some conditions (17, 27, 28).

Micronutrients are particularly sensitive to pH, organic matter, redox conditions, mineralogy and microbial activity. Geospatial evidence from cereal producing regions of Ethiopia and Malawi showed substantial variation in grain calcium (Ca), Fe, selenium (Se) and Zn concentrations, with soil and environmental variables contributing to this variation (34). These findings support linking soil micronutrient mapping with crop composition and nutritional data while recognising that soil conditions are only one determinant of crop nutrient density.

Nutrient density, bioactive compounds and yield-nutrition trade offs

Crop nutritional quality includes minerals as well as proteins, vitamins, fatty acids, phenolic compounds, flavonoids, carotenoids and other bioactive constituents. Soil conditions can influence these components through nutrient supply, water relations, plant growth and metabolism, but responses vary among crops and environments (4, 9). Yield increases can sometimes dilute nutrient concentrations when biomass accumulation exceeds nutrient accumulation. This effect has been documented particularly for mineral nutrients under elevated atmospheric CO_2, although its magnitude varies with crop, genotype, nutrient and environment (35, 36). Conversely, improved nutrient availability or physiological efficiency may maintain or increase nutrient concentrations without compromising yield.

Nutritional performance should therefore be evaluated using both nutrient concentration and nutrient yield per unit area. A lower concentration accompanied by a sufficiently large yield increase may increase total nutrient production per hectare, whereas higher nutrient concentration with substantial yield loss may not improve overall nutrient supply (36). The nutritional significance of soil management interventions also depends on crop genotype, environment, harvest maturity, post-harvest handling and dietary bioavailability. Consequently, changes in soil indicators alone cannot establish improvements in nutritional quality (34, 37).

Soil contamination, crop uptake and food safety

Potentially toxic elements such as cadmium (Cd), arsenic (As), lead (Pb), chromium (Cr) and nickel (Ni) can enter agricultural soils through industrial emissions, mining, wastewater irrigation, atmospheric deposition, contaminated amendments and some agricultural inputs. Their persistence can create long-term food safety risks when they become available for plant uptake (5, 7). Transfer to crops depends on chemical form and interactions with soil pH, organic matter, CEC, mineral surfaces, redox conditions and competing ions. For example, acidification can increase Cd availability in some systems, whereas liming may reduce Cd uptake; however, management effects are contaminant specific. Water management can likewise produce contrasting effects on Cd and As availability in flooded rice systems (6, 38, 39).

Crop species and cultivar further influence accumulation through differences in uptake, translocation, sequestration and tissue distribution. Food safety assessment should therefore consider both soil contamination and crop-specific accumulation potential (5, 7). Risk reduction should prioritise pollution prevention, safe irrigation water management and appropriate regulation of agricultural inputs. Where contamination exists, liming, organic amendments, biochar, water management practices, phytoremediation and low accumulating cultivars may reduce risk depending on the contaminant and cropping system (6, 7). Their effectiveness should be assessed using contaminant bioavailability and crop uptake rather than total soil concentrations alone.

Soil management practices and crop nutritional quality

Organic amendments and nutrient cycling

Organic amendments, including compost, manure, crop residues and other organic materials, modify soil physical, chemical and biological properties by increasing carbon inputs, improving aggregation and water retention, supplying nutrients and supporting microbial activity. Their effects depend on amendment composition and maturity, application rate, soil properties, climate and management history (40, 41). The principal soil management practices discussed in this review and their potential relevance to crop nutritional quality are summarised in Table 3.

Compost and stabilised amendments generally provide gradual nutrient release, whereas fresh materials with high C: N ratios may temporarily immobilise N; more decomposed materials tend to reduce this short term effect (24, 25). Organic inputs may improve crop nutritional quality through enhanced soil structure, water retention, microbial activity and nutrient availability, although responses vary with crop, nutrient status, amendment characteristics and environment (37, 40). Comparisons between organic and conventional systems should therefore be interpreted cautiously. A meta-analysis of 343 publications reported higher concentrations of some antioxidant compounds and lower Cd concentrations and pesticide residue occurrence in organically

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produced crops, whereas differences in individual minerals and vitamins were more variable (42). Other reviews have found substantial overlap in nutrient composition between production systems (4). Thus, nutritional outcomes are better attributed to specific soil and crop management practices than to production labels alone.

Crop diversification, rotations and cover crops

Crop rotations, intercropping, cover crops and legumes influence soil health through changes in carbon inputs, rooting patterns, nutrient cycling and microbial communities. Contrasting rooting systems distribute resource acquisition across soil zones, cover crops maintain living roots between main crops and legumes contribute biologically fixed N (11, 30). Cover crops can reduce erosion and nutrient losses, improve aggregation and alter soil water dynamics. They may capture residual mineral N during fallow periods, while subsequent decomposition returns nutrients to the soil; however, residue C: N ratio and decomposition timing determine whether nutrients are released or temporarily immobilised (24, 43). Diversification also alters root exudates and microbial habitats and can interrupt pathogen and pest cycles, indirectly supporting root health and nutrient acquisition (44). Nutritional benefits are not universal. Cover crops may compete for water under dry conditions, while high biomass residues can temporarily immobilise N. Outcomes therefore depend on climate, soil type, crop sequence, residue management and nutrient release timing. Nevertheless, diverse rotations, cover crops, organic amendments and reduced tillage are consistently associated with improvements in several soil health indicators in organically managed systems (20, 45).

Tillage, residue retention and conservation management

Tillage affects soil structure, aggregate stability, organic matter turnover, water dynamics, erosion and biological communities. Intensive disturbance can disrupt aggregates, accelerate organic matter decomposition and increase erosion, whereas reduced or non-inversion tillage can preserve surface residues, soil structure, biological habitat and water infiltration. Responses vary with soil, climate, crop and equipment (20, 21). Residue retention supplies carbon and nutrients, protects soil against erosion and water loss and supports microbial activity and aggregate formation. However, high C residues may temporarily immobilise N, while residue retention can alter soil temperature and moisture and may be constrained where residues are required for livestock feed or fuel (24). Conservation practices may therefore support crop nutrition indirectly by improving conditions for roots and nutrient cycling. Their effects on specific nutrient concentrations in edible tissues are less consistent than their effects on soil physical and biological properties; they should consequently not be regarded as direct methods for increasing crop micronutrient concentrations (20, 46).

Table 3. Soil management practices and their potential effects on crop nutritional quality

Management practice	Principal soil effects	Potential nutritional relevance	Key references
Organic amendments	Increase organic matter inputs, nutrient retention, aggregation and microbial activity	Can improve nutrient availability and, under some conditions, increase concentrations of selected minerals	(37, 40)
Crop rotation and diversification	Increase diversity of rooting patterns and carbon inputs and modify nutrient cycling and microbial communities	Can improve nutrient use efficiency and nutrient acquisition; effects depend on crop sequence and environment	(20, 45)
Cover crops and residue retention	Reduce erosion and nutrient losses, maintain soil cover and increase carbon inputs	Can improve nutrient retention and subsequent nutrient supply, although high C residues may temporarily immobilise N	(20, 24)
Reduced/ conservation tillage	Preserve soil structure and surface residues and reduce physical disturbance; effects on SOC vary among systems	May support root growth, water availability and nutrient acquisition indirectly	(20, 46)
Integrated nutrient management	Combines organic and mineral nutrient sources to improve nutrient synchronisation and use efficiency	Can improve nutrient acquisition and productivity while maintaining soil fertility	(23, 47)
Biological/ microbial management	Modifies rhizosphere processes, nutrient cycling and plant–microbe interactions	Can enhance acquisition of selected nutrients, particularly where microbial activity is limiting	(17, 27)

SOC: soil organic carbon; C: carbon; N: nitrogen.

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Integrated nutrient management and nutrient use efficiency

Integrated nutrient management (INM) combines mineral fertilisers, organic amendments, crop residues, biological nutrient inputs and site-specific management to synchronise nutrient supply with crop demand while maintaining soil fertility. Its objective is to improve nutrient use efficiency and productivity rather than simply reduce mineral fertiliser use (47). Mineral fertilisers provide readily available nutrients, whereas organic inputs can supply slower release nutrients, improve retention and support microbial activity and soil structure. Evidence from broadacre cropping systems indicates that combining compost with fertiliser can improve nutrient use efficiency and productivity while addressing low organic matter, poor structure and limited nutrient retention (47). Balanced nutrient supply can influence protein and mineral concentrations in edible tissues, but excessive N, P, or micronutrient application can increase environmental losses and create nutrient imbalances (23). The INM should therefore be based on soil testing, crop requirements, nutrient budgets and the characteristics of available nutrient sources. Optimal combinations vary among soils, crops, climates and farming systems (20, 47).

Microbial and biological management

Soil management practices influence crop nutrition partly through their effects on microbial biomass, community composition, enzyme activity and rhizosphere interactions. Organic inputs, diverse rotations, living roots, reduced disturbance and appropriate nutrient management can affect nutrient mineralisation, P mobilisation, micronutrient availability, root development and disease suppression (15, 44). Targeted microbial interventions include plant growth promoting bacteria and AMF, which may contribute through N fixation, P solubilisation, siderophore production, root growth modulation and stress tolerance. Their performance, however, depends strongly on soil properties, native microbial communities, crop genotype, nutrient status and environmental conditions (17, 27).

Microbial management should therefore complement broader soil health practices rather than be viewed as a universally effective intervention. Living roots, organic inputs and habitat diversity can support indigenous microbial functions, whereas inoculants may be beneficial when appropriately matched to crop and soil conditions. Current evidence does not support if microbial products consistently increase yield or nutrient density across field environments (15, 27). This context dependence also applies to “regenerative” and “biological” systems, which combine multiple practices and therefore make individual effects difficult to isolate. Long-term controlled field comparisons are needed to distinguish individual and interactive effects (20, 37).

Integrated management and crop nutritional outcomes

The greatest improvements in soil function are likely to result from complementary practices rather than isolated interventions. Organic amendments increase C inputs and nutrient retention; diversified rotations provide continuous root derived carbon and biological N; cover crops reduce nutrient losses; reduced tillage preserves soil structure; and balanced nutrient management synchronises nutrient supply with crop demand (11, 20, 47). Improved soil health does not, however, guarantee higher concentrations of all nutrients or bioactive compounds. Crop nutritional composition depends on soil nutrient supply, genotype, physiology, environment, yield level and the timing and form of nutrient availability. An intervention may improve water regulation or microbial activity without immediately increasing a particular nutrient, such as grain Zn (34, 37).

Evidence comparing farming systems reflects this complexity: organic production has been associated with higher concentrations of some antioxidants and lower concentrations of certain contaminants, whereas differences in major nutrients and minerals are smaller or inconsistent (4, 42). Management should therefore be evaluated according to specific nutritional outcomes rather than assumed to produce universally superior food. Future assessments should integrate soil properties, crop yield, nutrient concentrations, nutrient use efficiency, contaminants and, where possible, nutrient bioavailability and dietary relevance. Such integrated evaluation provides a stronger basis for determining whether improvements in soil functioning translate into meaningful gains in food nutritional quality and safety (37).

Soil health and crop nutrient density

Soil health as a determinant of crop nutritional composition

Soil health influences crop nutritional composition through nutrient availability, root development, water relations, microbial activity and plant metabolism. However, this relationship is not linear: crop genotype, climate, soil mineralogy, nutrient and water supply, management and yield level can modify nutritional responses. Thus, improved soil health may support crop nutritional quality without increasing every nutrient in edible tissues (2, 37). Soil pH, organic matter, redox conditions, microbial activity and accessible nutrient pools determine the chemical forms and availability of elements, while physical properties affect root exploration and water mediated nutrient transport (22, 33). Consequently, nutrient density reflects interactions among soil nutrient supply, plant uptake and allocation. Total soil nutrient content alone does not predict crop nutrient concentration because nutrients may be poorly available, inaccessible to roots, or inadequately transported to edible tissues (23, 34).

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Macronutrients and crop nutritional quality

Nitrogen, P, K, Ca, magnesium (Mg) and S support essential plant functions, including protein synthesis, energy metabolism, osmotic regulation, photosynthesis and structural development. Soil health can affect their composition through nutrient cycling, root development, water availability and nutrient use efficiency. Organic matter and favorable soil structure can support root activity and microbial mineralisation, potentially improving synchronization between nutrient release and crop demand, particularly for N under limiting conditions (23, 24). However, effects of soil management on macronutrient concentrations are generally less consistent than effects on soil physical and biological properties. Yield increases can also alter nutrient concentrations because biomass and nutrient accumulation may not increase proportionally. Therefore, neither higher yield nor higher nutrient concentration alone necessarily indicates greater nutritional output.

Micronutrients: Iron, zinc, selenium, calcium and other essential elements

Micronutrient density is particularly sensitive to pH, organic matter, mineralogy, redox conditions and microbial processes. The Fe and Zn are especially important because their deficiencies affect both plant performance and human nutrition. Differences in soil micronutrient status can contribute to geographical variation in mineral concentrations of edible crops (33, 34). Selenium illustrates the importance of soil geochemistry. Its mobility and plant availability depend on chemical form, pH, redox conditions, organic matter, mineral interactions and microbial processes, resulting in substantial spatial variation in crop Se concentration and influencing the potential for agronomic biofortification (48). Calcium and Mg availability likewise depends on pH and cation exchange processes, while plant uptake and translocation are influenced by transpiration and internal nutrient interactions (33). Thus, relationships between soil status and crop nutrient density are element specific.

Evidence from regenerative and soil-health-oriented systems suggests that selected practices can increase particular micronutrient concentrations. A scoping review reported potential increases under combinations of organic inputs, cover crops, rotations, reduced tillage, biostimulants and irrigation management; increased grain Zn was reported in 15 of 16 studies of rice receiving greater organic inputs. However, substantial variation occurred among crops, practices, locations and study designs (37). Similarly, geospatial studies in cereal producing regions of Ethiopia and Malawi found substantial variation in grain Ca, Fe, Se and Zn concentrations associated partly with soil and environmental factors (34). These findings support integrating soil micronutrient information with crop composition data while recognising that soil is only one determinant of crop nutrient density.

Vitamins, phytochemicals and other bioactive compounds

Crop nutritional quality also includes vitamins and bioactive compounds such as phenolic acids, flavonoids, carotenoids and anthocyanins, which contribute to plant defence, signalling, pigmentation and stress responses. Soil conditions may influence their synthesis through nutrient supply, water status, microbial interactions and plant stress physiology, but responses vary with crop species, cultivar, developmental stage, environment and management. A systematic review and meta-analysis of 343 publications reported higher concentrations of several antioxidant polyphenols in organically produced crops, together with lower Cd concentrations and pesticide residue occurrence, whereas differences in individual vitamins and minerals were less consistent (42). These findings demonstrate that production practices can influence crop composition but do not establish that organic production universally produces nutritionally superior crops. Accordingly, changes in phytochemicals should be evaluated using compound specific measurements and, where relevant, bioavailability and dietary exposure rather than assuming direct human health benefits.

Nutrient dilution, yield and nutrient yield per unit area

Nutrient density can decline when biomass accumulation exceeds nutrient accumulation, a phenomenon known as nutrient dilution. Elevated atmospheric CO_2 provides a well-established example: meta analyses have reported reductions in Zn, Fe and protein concentrations in several C_3 crops, with responses modified by crop type, water availability and N supply (35, 49). These findings also demonstrate that changes in crop nutritional composition can arise from environmental change independently of soil degradation. Nutritional performance should therefore be evaluated using both nutrient concentration and nutrient yield per unit area:

Nutrient yield = Crop yield × Nutrient concentration

A higher concentration accompanied by substantial yield loss may not increase total nutrient production per hectare, whereas a modest concentration decline may be offset by a sufficiently large yield increase. Interpretation should therefore reflect whether the objective is food nutrient density, nutrient production per unit land area, or dietary nutrient supply.

Agronomic biofortification and the soil-crop nutrition interface

Agronomic biofortification can increase crop concentrations of selected micronutrients through soil or foliar application of Zn, Fe, Se and other nutrients. Mycorrhizal fungi and selected plant growth promoting bacteria may further influence nutrient acquisition and translocation. Its effectiveness depends on soil pH, organic matter, nutrient interactions, moisture, nutrient form and, in the case of Se speciation and redox conditions (50, 51). Biofortification should therefore complement soil fertility and soil health management rather than function as an isolated input. Excessive

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application can cause environmental losses, phytotoxicity or nutrient imbalance, making appropriate rates, application methods, crop-specific recommendations and monitoring essential (50). Importantly, improved soil or crop nutrient concentrations do not directly equate to improved human nutritional status. The ultimate nutritional benefit depends on dietary patterns, nutrient bioavailability, food processing and consumption. Soil and crop nutrient concentrations should therefore be interpreted as intermediate outcomes within the broader soil–crop–diet pathway.

Soil health, food safety and human health

The soil-crop-diet-health continuum

Human health is connected to soil through interacting environmental and nutritional pathways. Soil properties influence plant growth, nutrient availability, contaminant mobility and microbial processes, which affect the quantity, composition and safety of food entering the diet. These effects are subsequently modified by food choice, processing, cooking, nutrient bioavailability, dietary interactions and individual characteristics. Soil should therefore be viewed as an upstream determinant within a broader soil-crop-food-health system rather than as a direct determinant of human health (52, 53). The strength of this pathway varies with dietary dependence on locally produced foods. In subsistence and smallholder systems, locally grown staples may constitute a large proportion of dietary intake, making soil and crop mineral status particularly relevant. In diversified and globally connected food systems, foods from multiple regions can weaken the relationship between a particular soil and an individual's nutrient intake (52). Evidence from farming communities in Jharkhand, India, illustrates this complexity: associations among soil, rice and human mineral indicators were reported, but agronomic practices, food preparation, water sources, socioeconomic conditions and other factors could contribute to the observed relationships (52). Such evidence supports soil-crop-human connections while cautioning against interpreting observational associations as direct causation.

Soil micronutrients, dietary quality and hidden hunger

Soil micronutrient availability can influence crop composition and therefore represents one component of strategies addressing micronutrient malnutrition. However, not all human micronutrients are essential for plants and soil concentrations do not necessarily predict their concentration or bioavailability in edible tissues. For Zn and Fe, crop uptake depends on soil concentration and chemical form, pH, organic matter, competing nutrients, root physiology, microbial interactions and crop genotype. Even adequate soil nutrient concentrations may not produce sufficient concentrations in edible tissues, while correcting a soil deficiency does not automatically improve human nutritional status because processing, dietary composition, absorption and physiological requirements also influence nutrient status (34, 53).

Potential soil-based approaches include balanced fertilisation, organic amendments, improved nutrient management, microbial interventions and agronomic biofortification. These should complement rather than replace dietary diversification, food fortification, supplementation and other public health interventions (54). Research from rural India has reported associations between soil mineral availability and population level nutritional indicators, including relationships between soil Zn availability and childhood linear growth and between soil Fe availability and hemoglobin. However, these observational findings do not establish that changing soil mineral availability alone will produce equivalent improvements in human nutritional status (53).

Soil contamination, food safety and human exposure

Soil contamination provides a relatively direct pathway from soil condition to human health because potentially toxic elements can enter crops and subsequently the human diet. Cadmium, Pb, As, chromium (Cr) and mercury (Hg) are important concerns because chronic exposure can cause adverse health effects. Dietary exposure depends on contaminant concentration and speciation, soil properties, crop type and edible tissue, food processing and dietary intake (55). Transfer to crops is governed by bioavailability rather than total soil concentration alone. Soil pH, SOC, CEC, mineral composition, redox conditions, competing ions, crop species and genotype influence contaminant uptake and translocation. Consequently, a single soil concentration threshold cannot reliably predict food safety risk across all crops and environments (55, 56).

Rice provides an important example because flooded conditions can alter As and Cd mobility and uptake. Soil-plant transfer models indicate that soil pH, SOC and crop genotype can substantially affect the transfer of potentially toxic elements into rice grain. Soil safety assessments for rice should therefore consider both soil properties and crop-specific transfer characteristics rather than relying solely on total contaminant concentrations (55). Risk management should prioritise contamination prevention through appropriate irrigation water management, control of industrial and agricultural sources, safe amendment uses and monitoring. Where contamination exists, liming, organic amendments, water management, phytoremediation and low accumulating cultivars may reduce exposure in suitable systems. Their effectiveness is contaminant and site-specific and should be evaluated using contaminant bioavailability and crop concentrations.

Soil biodiversity and the soil-plant-human microbiome axis

Soil microorganisms provide another potential connection between soil ecosystems and human health. They contribute to nutrient cycling, plant health, decomposition, contaminant transformation and ecosystem functioning and form part of the environmental microbial reservoir considered within the

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One Health framework (26). Soil microbiomes may influence human health indirectly by altering crop nutritional composition and safety through effects on nutrient mobilisation, plant defence and root development. Microorganisms may also move among environmental compartments, although the extent and health significance of such transfers remain incompletely understood (26).

The proposed soil-plant-human gut microbiome axis suggests that microbial communities and functions may interact across these environments. However, evidence for direct transmission of specific soil microorganisms to the human gut and subsequent beneficial health effects remains limited. Soil microbiomes are therefore best considered potential contributors to a broader environmental microbiome network rather than established direct determinants of gut health (26). This distinction is important because microbial diversity can have both beneficial and harmful implications. Diverse communities may support pathogen suppression and ecosystem stability, while soils can also harbor pathogens, antimicrobial resistance determinants and contaminants. Greater soil biodiversity should therefore not automatically be equated with improved human health without considering microbial identity, function, exposure route and environmental context (26).

Soil health, environmental resilience and indirect health benefits

Healthy soils support human well-being through ecosystem functions beyond the nutrient composition of individual crops. Improved soil structure and organic matter can enhance water infiltration and retention, reduce erosion and support agricultural productivity under variable conditions, while microbial activity supports nutrient cycling and decomposition and SOC contributes to broader ecosystem and climate regulation (2, 26). These functions can indirectly support human health through food availability, water quality and agricultural resilience. For example, improved water retention can stabilise production during drought, while reduced erosion can conserve fertile topsoil and associated nutrients. Such benefits contribute to food system stability without necessarily increasing the nutrient concentration of every crop.

From soil indicators to human health outcomes

A major challenge in establishing soil-human health relationships is the long causal chain connecting soil properties with health outcomes. Crop composition is additionally influenced by cultivar, climate, management, harvest timing, storage, processing, cooking, dietary diversity and nutrient interactions, while human nutritional status depends on age, sex, disease, socioeconomic conditions, absorption efficiency and overall dietary intake (52, 53). Soil health indicators such as SOC, microbial biomass, nutrient availability, pH and contaminant concentrations should therefore not be interpreted as direct proxies for human health. Population level assessment requires additional measurements, including crop nutrient profiles, dietary intake, nutrient biomarkers, contaminant exposure and relevant health outcomes. Future research should integrate soil properties, crop composition, food consumption, nutrient bioavailability and human health indicators in longitudinal and multi-site studies. Such designs can better distinguish causal pathways from correlations and identify which soil management interventions produce measurable nutritional or health benefits.

Overall, the evidence supports a meaningful but pathway dependent connection between soil condition and human well-being. The most established pathway is:

soil → nutrient/contaminant availability → crop composition → dietary exposure

whereas the soil-plant-human microbiome pathway remains comparatively exploratory. Maintaining this distinction is essential for a scientifically rigorous interpretation of soil-health relationships.

Soil degradation, climate change and nutritional security

Soil degradation as a threat to food and nutritional security

Soil degradation involves deterioration of physical, chemical and biological functions supporting crop production and ecosystem services. Major processes include erosion, organic matter loss, nutrient imbalance or depletion, salinisation, acidification, compaction, contamination, biodiversity loss and declining soil water function. Approximately one third of the world's soils are estimated to be moderately to highly degraded, with these processes threatening agricultural productivity and soil function (1). Degradation can reduce nutrient retention, water infiltration, root exploration and microbial activity, while salinity and sodicity restrict water uptake and create ionic imbalances. Acidification can alter nutrient availability and increase the solubility of potentially toxic elements such as Al and Mn (21, 33). However, degraded soils do not inevitably produce nutrient deficient crops because crop genotype, physiological adaptation and external nutrient inputs can partially compensate for declining soil function. Nutritional effects should therefore be assessed using soil properties together with crop nutrient composition and yield.

Erosion, salinisation and nutrient depletion

Erosion removes topsoil, organic matter, fine particles and associated nutrients and can progressively reduce rooting depth and water holding capacity. Because soil formation is much slower than agricultural soil loss, severe erosion can produce persistent declines in soil function. Global modelling suggests that erosion may increase under several future climate and socioeconomic scenarios, although impacts vary among regions and management systems (57, 58). Salinisation is particularly important in irrigated and arid and semi-arid systems. Excess salts reduce soil water potential

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and cause ionic and nutritional imbalances, while sodicity can further impair structure and infiltration. Management therefore requires appropriate irrigation quality, drainage, salt balance and crop selection rather than fertiliser adjustment alone. Nutrient depletion occurs when nutrient removal through harvest, erosion and leaching persistently exceeds replenishment. Continuous cultivation without adequate replacement can reduce nutrient stocks and organic matter, while imbalanced fertilisation can create deficiencies despite high inputs of other nutrients. Maintaining soil fertility therefore requires balanced nutrient management based on crop removal, soil nutrient pools, nutrient losses and crop demand (23).

Climate change and soil nutrient dynamics

Climate change modifies soil processes through changes in temperature, precipitation, atmospheric CO_2, drought, flooding and other stresses. These factors interact with existing soil constraints: drought can reduce microbial activity and nutrient diffusion, whereas intense rainfall can increase erosion and nutrient losses; warming may accelerate decomposition, while altered moisture can constrain microbial activity and change biogeochemical processes (1). The relationship is bidirectional. Degraded soils with low organic matter, weak structure and poor water holding capacity are more vulnerable to climatic extremes, while climate stresses can accelerate erosion, organic matter loss, salinity and disruption of nutrient cycling. These feedback can reduce the capacity of agricultural systems to withstand subsequent climate stress (59). Climate change can also alter crop nutritional composition independently of soil degradation. Elevated CO_2 can increase biomass in some crops while reducing Zn, Fe and protein concentrations in several C_3 crops, although responses vary with crop, genotype, N availability, water status and experimental conditions (35, 49). Such nutritional changes should therefore not be attributed exclusively to declining soil health. The interacting effects of soil degradation and climate change on soil processes, crop nutritional quality, food systems and nutritional security are summarised in Fig. 3.

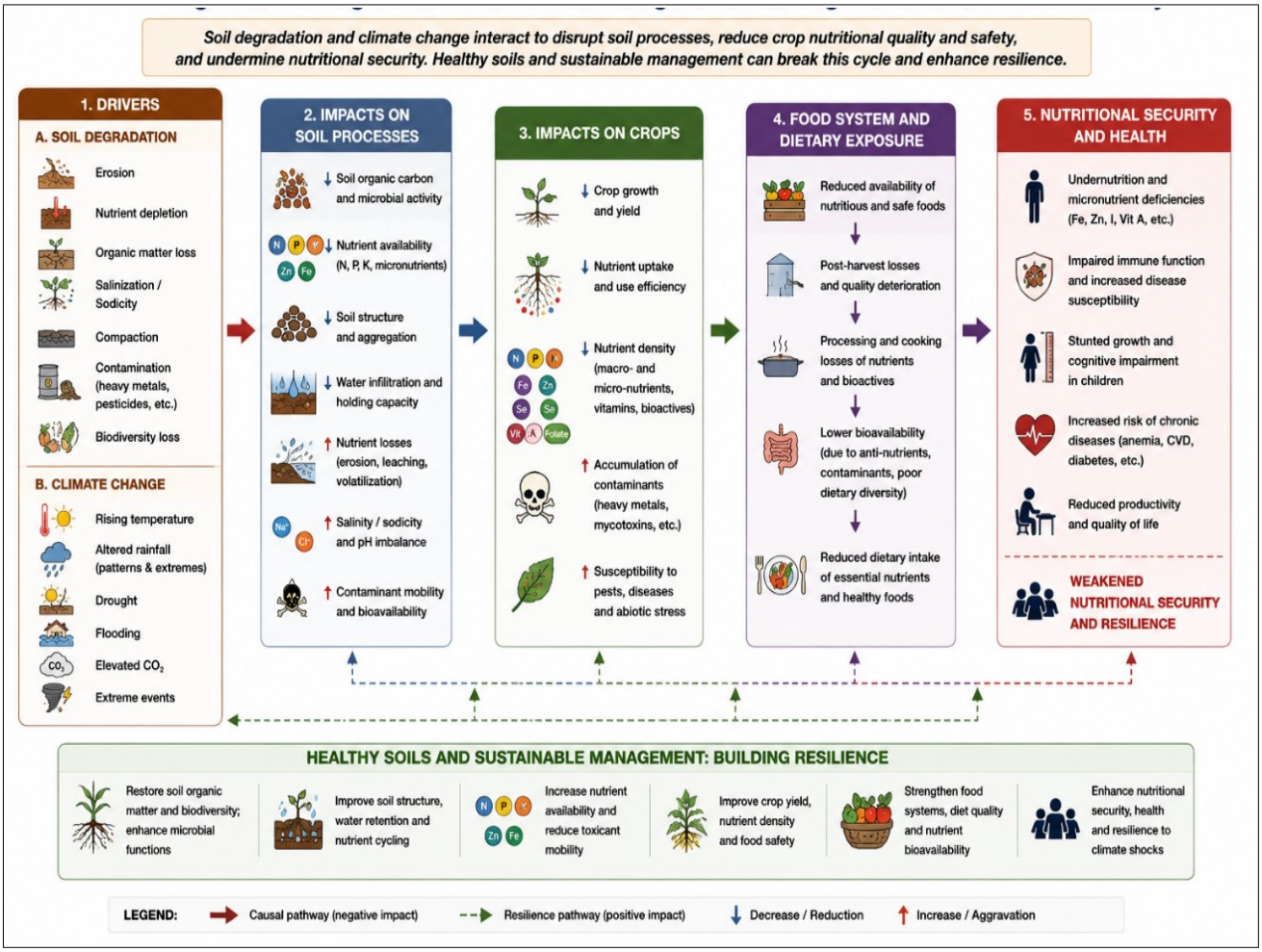


Fig. 3. Soil degradation and climate change as interacting threats to nutritional security.

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Climate stress, nutrient dilution and nutritional quality

Climate related changes in biomass production and nutrient acquisition can produce nutrient dilution when crop growth increases faster than nutrient accumulation. This is particularly important for staple crops that contribute substantially to dietary nutrient intake. Elevated CO_2 has been associated with reductions in Zn, Fe and protein concentrations in several C_3 crops, although field responses vary among cultivars, nutrient supply, rooting conditions and experimental systems (35, 49). Nutritional consequences should therefore be evaluated using nutrient concentration alongside yield, nutrient yield, edible biomass, dietary dependence and nutrient bioavailability. A decline in grain Zn concentration, for example, does not necessarily represent an equivalent decline in Zn production per hectare or dietary intake. These effects may be particularly relevant where diets depend heavily on staple cereals and legumes. However, population level nutritional outcomes are also influenced by dietary diversity, food availability, fortification, supplementation and other interventions (35).

Soil health, climate resilience and nutritional security

Healthy soils can increase agricultural resilience by improving water retention, infiltration, aggregation, nutrient retention and biological functioning. Residue retention, cover crops, diversified rotations, organic amendments, reduced disturbance and integrated nutrient management can address several constraints simultaneously, although their effectiveness depends on climate, soil, crop system and management capacity (20, 59). These practices can reduce sensitivity to environmental variability: organic matter improves water retention, stable aggregates reduce erosion, diversified rotations distribute nutrient demand and rooting activity and balanced nutrient management reduces depletion of individual nutrients. However, none is universally beneficial; residue retention may temporarily immobilise N, cover crops can compete for water under dry conditions and reduced tillage produces context dependent outcomes (20). Nutritional resilience therefore requires maintaining not only production but also food nutritional quality and safety under environmental stress. This requires integration of soil conservation, nutrient management, crop diversification, climate adaptation and nutrition sensitive interventions.

Implications for nutritional security and sustainable food systems

Soil degradation and climate change can jointly increase food system vulnerability through declining productivity, nutrient losses, changes in crop nutrient density, contaminant risks in some environments and greater production variability. Risks are likely to be greatest where severe soil constraints, climatic stress, rainfed dependence and limited access to external inputs coincide (1, 57). Nutritional security extends beyond calorie availability to adequate intake of essential micronutrients and other components of a healthy diet. Soil management can contribute by maintaining nutrient availability, supporting crop diversity, reducing contaminant transfer and improving resilience, but it is only one component of a broader strategy that includes crop breeding, dietary diversification, biofortification, fortification, supplementation, food safety regulation and equitable access to nutritious foods. Monitoring should therefore integrate soil indicators, crop yield, nutrient concentrations, contaminants and dietary outcomes to identify where declining soil function is associated with deterioration in food quality and to guide targeted soil restoration and nutrition interventions. Overall, soil restoration cannot eliminate nutritional insecurity by itself, but maintaining soil function preserves important upstream conditions for productive, diverse, safe and nutritionally adequate food systems.

Knowledge gaps and future research directions

From associations to causal soil-crop-health relationships

Evidence increasingly links soil condition with crop nutritional quality, food safety and human health, but the strength of evidence varies among pathways. Most studies examine individual relationships, such as soil properties and crop nutrient concentrations or soil contamination and crop uptake, rather than the complete pathway from soil condition to dietary exposure and health. Future research should distinguish association from causation using longitudinal, experimental, or quasi experimental designs where feasible and account for confounders including crop genotype, climate, irrigation, fertiliser use, dietary patterns and socioeconomic conditions. Integrating soil properties, crop composition, dietary intake and nutritional or exposure biomarkers would provide stronger evidence of when changes in soil function translate into meaningful health outcomes (60, 61).

Long-term, multi-site and integrated research

Many soil health studies are short term or site-specific, although changes in soil organic matter, microbial communities, nutrient pools and structure often occur over longer timescales. Future research should therefore combine long-term field experiments with coordinated multi-site studies across contrasting soils, climates, crops and management systems. Standardised measurements should include soil physical, chemical and biological indicators; crop yield and nutritional composition; bioactive compounds; and contaminant concentrations. Where human health implications are examined, dietary intake and appropriate nutritional or exposure biomarkers should also be included. Such integrated designs would improve comparability and establish whether nutritional effects persist over time (60, 61).

Functional soil microbiomes and the soil-plant-human microbiome axis

Soil microorganisms regulate nutrient cycling, organic matter transformation, plant health and contaminant dynamics, but their contribution to the soil-crop-human health continuum remains incompletely understood. Research should move beyond microbial richness and

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taxonomy toward functional approaches, including metagenomics, meta transcriptomics, metabolomics, functional gene analysis and stable isotope tracing, to identify microbial processes involved in nutrient mineralisation, P mobilisation, micronutrient acquisition, C transformation and contaminant immobilisation. The soil-plant-human gut microbiome axis remains particularly promising but exploratory. Evidence that soil associated microorganisms directly alter human gut microbiota or health is limited. Future studies should determine whether relevant microorganisms reach edible tissues, survive processing and gastrointestinal passage, interact with the gut microbiome and produce measurable physiological effects, while also assessing potential risks from pathogens and antimicrobial resistance determinants (26, 60).

Integrated soil-nutrition-health indicators

Current soil health assessments emphasise soil function, agricultural productivity and ecosystem services but do not necessarily indicate whether soil conditions produce nutritionally adequate and safe food. Future frameworks should therefore connect soil nutrient availability, biological activity, physical condition and contaminant risk with crop nutritional composition and dietary or health outcomes. Standardised protocols are needed because studies differ in indicators, sampling depth, analytical methods, crop tissues, nutrient units and definitions of nutritional quality. Harmonised and validated indicators would improve cross study comparisons and strengthen links between soil health assessment, food quality and nutritional outcomes (60, 61).

Scaling evidence into monitoring, management and policy

Digital soil mapping, remote sensing, geospatial analysis, molecular diagnostics and data driven modelling offer opportunities to monitor spatial and temporal variation in soil and crop conditions. However, remotely sensed and modelled indicators should be validated against field observations before being used to infer crop nutritional or human health outcomes. Future policies should evaluate soil management interventions using outcomes beyond yield, including crop nutrient density, contaminant exposure, nutrient use efficiency and long-term soil function. The One Health framework provides a useful perspective because soil processes connect environmental, plant, animal and human systems (26). However, interventions should remain evidence based rather than if improvement in one component will automatically improve others. Overall, research should progress from isolated measurements of soil quality or crop composition toward integrated, longitudinal, multi-site investigations of soil-crop-food-health relationships. Such approaches are needed to determine when improvements in soil health translate into better food quality, reduced contaminant exposure, greater nutritional resilience and measurable human health benefits.

3. Conclusion

Soil health is an important upstream component of sustainable food systems because its physical, chemical and biological properties collectively influence crop productivity, nutrient acquisition, food safety and environmental resilience. Soil organic matter, nutrient availability, pH, structure, water dynamics and biological activity regulate nutrient acquisition and allocation in crops, while soil contamination can increase the transfer of potentially toxic elements into food. These processes provide a mechanistic basis for linking soil condition with crop nutritional quality and dietary exposure. Soil management practices, including organic amendments, crop diversification, reduced soil disturbance, residue retention and integrated nutrient management, can improve multiple dimensions of soil function. However, their effects on crop nutrient density are variable and depend on crop genotype, soil properties, climate, nutrient status and management history. Soil health improvement should therefore not be assumed to increase all nutrients or bioactive compounds uniformly; nutritional outcomes should be evaluated alongside yield, nutrient yield per unit area, bioavailability and dietary relevance.

The most clearly supported pathway linking soil to human health is soil condition → nutrient or contaminant availability → crop composition and safety → dietary exposure. Soil degradation and climate change can disrupt this pathway by altering nutrient availability, crop composition, contaminant dynamics and the resilience of food production systems. The soil-plant-human microbiome axis represents an important emerging area, but current evidence remains insufficient to establish direct causal effects on human health. Future progress requires long-term, multi-site research integrating soil indicators, crop nutritional profiles, food safety, dietary intake and appropriate nutritional or health biomarkers. Functional characterisation of soil microbiomes and standardised soil-nutrition indicators may further clarify the mechanisms linking soil processes with food quality. Overall, maintaining and restoring soil health cannot by itself resolve global nutritional or public health challenges, but it can strengthen an essential upstream foundation for safe, productive, resilient and nutritionally adequate food systems.

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Authors' contributions

SG wrote the manuscript. PCNM provided guidance on writing the manuscript. RMJ, PK, TS, SR and SAA reviewed the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Grammarly and ChatGPT to improve language and clarity. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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