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From inputs to interactions: soil stoichiometry and microbiomes as drivers of crop nutrient use efficiency



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Agricultural nutrient-management increasingly recognises soil stoichiometry and microbial biodiversity yet rarely integrates them with crop nutrient demand. Soil microbiomes regulate nutrient availability, recovery and resilience, but depend on balanced elemental resources and supportive management. We argue that sustainable productivity requires synchronised managing of crop demand, soil C:N:P balance and microbial nutrient cycling. Our proposed framework identifies interventions to improve nutrient recovery, reduce environmental losses, and sustain soil fertility and resilience.

Challenges in conventional agriculture

Maintaining food security in a changing world requires local solutions, which mostly depend on intensive agriculture linked with high nutrient inputs resulting in increased synthetic fertiliser demands or nutrient dense livestock slurries. Besides economic constraints due to rising costs for fertilisers and disruptions in global supply chains, intensive agriculture often creates nutrient oversupplies (mainly nitrogen (N) and phosphorus (P)), which negatively impacts soil quality and water resources, accelerates greenhouse gas emissions and leads to soil erosion¹. The overuse of fertilisers is exemplified by the EU's gross N surplus of roughly 50 kg N per hectare and year². As a result, about 40% of N inputs are not used for crop production and may be lost to the environment³. Indeed, over 13% of groundwater monitoring stations in Europe exceeded the nitrate limits of 50 mg/l from 2012–2015⁴ with Germany, Belgium, Netherlands, Spain and Portugal reporting the highest levels⁵. These data have led to more stringent regulations including the reduction of fertiliser application rates by 20%⁶.

Consequently, improving plant nutrient use efficiencies (NUE) represents a key strategy to maintain yields while lowering dependency on mineral fertilisers worldwide. NUE is understood as a plant intrinsic trait that describes how effectively plants acquire nutrients from the soil and convert them into harvestable yield⁷. At the plant level, NUE combines two complementary components: (i) nutrient uptake efficiency, the capacity of roots and associated microorganisms to acquire nutrients from available and poorly accessible soil pools, and (ii) nutrient utilisation efficiency, the amount of biomass or harvestable yield produced per unit nutrient taken up.

Nutrient recovery efficiency is related but distinct, because it quantifies the proportion of an applied nutrient input that is recovered in plant biomass or harvested products and therefore links plant traits to soil retention, microbial immobilisation, and loss pathways. Importantly, NUE is not a static crop characteristic but depends on dynamic plant traits that govern nutrient acquisition throughout the growing season. Key determinants include root system architecture (root depth, lateral branching, root length density, root hair formation), the spatial foraging capacity of roots, the associated microbes that mobilise plant unavailable nutrients, and the regulation of nutrient transporter proteins for ammonium (NH₄⁺) and phosphate (PO₄³⁻) uptake⁸. Crop phenology also plays a major role, as plants must synchronise nutrient uptake with periods of high growth, while minimising nutrient demand during sensitive stress phases⁹. Moreover, NUE depends strongly on internal nutrient use and allocation, such as N remobilisation from leaves and stems into grain (a central trait in cereals), the partitioning of nutrients into harvested organs (nutrient harvest index), and photosynthetic efficiency per unit N invested in leaves. These biological controls imply that improved NUE can be achieved not only by reducing losses from soils, but also through crop breeding and cultivar choice, selecting varieties with superior nutrient acquisition traits and improved nutrient partitioning into yield¹⁰.

Current NUE concepts do not always fully capture microbially mediated nutrient transformations and therefore do not fully explain the mismatch between fertiliser input and plant uptake under field conditions. This disparity is expressed by nutrient recovery efficiency, which measures

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the proportion of applied fertiliser that is taken up by the plant, while the remaining fraction may be retained in soil pools or lost through leaching and gaseous emissions. Microbially mediated nutrient transformations are therefore integral to nutrient recovery, because they can provide access to otherwise plant-inaccessible nutrient pools¹¹. Plant inaccessibility occurs when nutrients are organically bound or secondary minerals are formed. Microbes are capable of unlocking these nutrient resources and transforming them into plant-available forms. Such microbial activities can be influenced through root exudation patterns and selective recruitment of beneficial microorganisms¹². Thus, the supporting role of the soil microbiome is an integral part of NUE. Here, we propose a unifying framework that integrates soil microbial diversity, microbial activity, plant intrinsic traits, and nutrient stoichiometry as interacting control points rather than as separate descriptors. The conceptual advance is to link crop nutrient demand with C:N:P-regulated microbial mobilisation, immobilisation, storage, and loss pathways, thereby identifying management points that can influence not only fertiliser input rates but also the biological fate of nutrients. By aligning microbial nutrient transformations with plant demand, this approach may enhance nutrient recovery efficiency, promote plant nutrient uptake, and reduce environmental losses. Such a framework shifts the focus from input-based management toward the coordinated regulation of biological processes that underpin sustainable nutrient transformation.

Soil microbial diversity as key for functional potentials and resilience of soils

The soil microbiome is a major driver of soil quality and resilience, defined as the capacity of soils to maintain their functions and recover from disturbances such as drought, heavy rainfall, heat waves, or pest outbreaks¹³. High microbial biodiversity can be fundamental to both properties, but diversity should not be equated directly with function. Specific functional groups, keystone taxa, and the expression of nutrient-cycling genes may disproportionately control individual processes, whereas high overall taxonomic diversity can support resilience mainly by increasing functional redundancy and response diversity. Diverse microbial communities harbour a broad range of functional traits and overlapping metabolic capabilities, enabling multiple biogeochemical processes while providing functional redundancy. This ensures that, if certain microbial groups are impaired by environmental stress, others can maintain key soil functions¹⁴. Recent advances in soil metagenomic studies have identified that taxonomic microbial diversity can exceed functional diversity¹⁵. This may allow for a certain level of taxonomic diversity decline without loss of functional diversity. However, this hypothesis is based on the assumption that all microbial functions have been identified (which they have not) and that any loss of diversity would not affect particular microbial clades disproportionately. Therefore, high microbial diversity should be considered an important, but not sufficient, safeguard of functional diversity; its agronomic relevance depends on the presence and activity of microbial groups that perform key nutrient cycling processes under the prevailing soil and management conditions.

A central function of the soil microbiome is the regulation of nutrient mobilisation, immobilisation, and storage. Microbial processes control the mobilisation of nutrients from organic residues, microbial biomass, soil organic matter, and mineral fractions. At the same time, microbial immobilisation represents a key mechanism for nutrient retention, temporarily sequestering nutrients in biomass as transient nutrient pools and thus reducing leaching losses. Through this dynamic balance, the soil microbiome regulates nutrient availability over time and contributes to the establishment and stabilisation of nutrient stocks in soil. Through these processes, the soil microbiome directly regulates nutrient availability and therefore plays a central role in determining plant NUE.

This regulatory role is particularly evident for P that is frequently limiting in soils, because of its high reactivity with the soil matrix. Typically, less than 1% of total soil P is directly plant-available¹⁶, while more than 99% is present in organic forms or bound to calcium, aluminium, and iron

minerals¹⁷. Many soil microorganisms can mobilise these otherwise inaccessible pools through processes such as acidification and enzymatic hydrolysis, releasing P from mineral complexes and organic matter¹⁸. However, mineralisation of organo-P depends on energy/C availability. In the rhizosphere, root exudates may provide such energy sources to microorganisms in exchange for nutrient mobilisation¹⁹. At the same time, microorganisms immobilise P within their biomass, thereby acting as a dynamic reservoir that buffers fluctuations in P availability. Symbiotic associations with mycorrhizal fungi further enhance P acquisition by extending the soil volume explored by roots and increasing the efficiency of P uptake and mineralisation²⁰.

Similarly, microbes catalyse major processes related to N transformation, by linking immobilisation, mobilisation, and loss pathways. Microbial immobilisation converts inorganic N into organic forms through uptake and biomass formation, promoting N retention in the soil system. In contrast, mineralisation releases plant-available inorganic N from organic matter²¹. These transformations regulate whether N is retained within soil organic pools or becomes susceptible to loss. In addition, soil microorganisms mediate key transformations that connect soil N transformation to atmospheric fluxes. Diazotrophic microorganisms fix atmospheric dinitrogen (N₂) into bioavailable forms, providing an important N input, particularly in low-input systems²². Conversely, nitrifying and denitrifying microorganisms can lead to N losses. Nitrification converts ammonium into nitrate and can produce nitrous oxide (N₂O) as a by-product, especially under conditions of high NH₄⁺ availability and fluctuating oxygen levels²³. Denitrification reduces nitrate to gaseous forms (N₂O and N₂) under oxygen-limited conditions, representing a major pathway of N loss²⁴. These processes highlight the dual role of the soil microbiome as both a regulator of nutrient retention and a driver of nutrient loss pathways. Consequently, effective microbial regulation of N transformation is critical for improving nutrient use efficiency and minimising environmental losses, including greenhouse gas emissions and leaching²⁵. Overall, soil microorganisms act as a gatekeeper of nutrient transformation by synchronising nutrient immobilisation and release with plant demand. The capacity to immobilise nutrients during periods of excess and to remobilise them when plant demand is high is essential for reducing nutrient losses and improving nutrient use efficiency²⁶.

Despite the central importance of microbial diversity for these processes, current agricultural management often gives little explicit consideration to its maintenance. Intensive practices are a major driver of soil biodiversity loss and can disrupt microbially mediated nutrient cycling. Frequent and deep tillage disturbs soil structure, breaks up aggregates that protect organic matter, disrupts fungal networks, and accelerates decomposition²⁷, thereby reducing the capacity for nutrient storage and increasing nutrient losses. Monocultures limit the diversity of root-derived carbon inputs, narrowing the range of microbial substrates and constraining functional diversity involved in nutrient transformations²⁸. High rates of synthetic fertilisers can, depending on soil type, crop system, fertiliser timing, and carbon availability, suppress microbial nutrient cycling by reducing plant C allocation to the rhizosphere and favouring fast-growing taxa with potentially lower contributions to stable nutrient storage²⁹. However, the consequences of such community shifts for long-term nutrient retention and resilience are context dependent and mediated by soil structure, organic matter inputs, water availability, and the persistence of functional or keystone taxa. In addition, pesticide and fungicide use can negatively affect non-target soil microorganisms and alter microbial processes linked to nutrient turnover³⁰.

As microbial diversity declines under intensive management, soils lose their capacity to retain and recycle nutrients efficiently. This leads to reduced immobilisation and storage in organic pools, increased reliance on external nutrient inputs, and greater susceptibility to nutrient losses through leaching and gaseous emissions. Consequently, soils become less self-regulating and less resilient to environmental fluctuations³¹. In contrast, management practices that promote microbial diversity and plant-microbe interactions can strengthen nutrient mobilisation-immobilisation dynamics and

enhance nutrient storage. Reduced or no-tillage preserves soil structure, maintains microbial habitats, and protects organic matter-associated nutrient pools³². Diversified crop rotations, particularly those including legumes and deep-rooting species, increase the diversity and continuity of root exudates, supporting a wider range of microbial processes involved in nutrient cycling²⁸. Cover crops maintain continuous plant cover, enhance carbon inputs, capture residual nutrients, and promote their incorporation into microbial biomass and soil organic matter³³. Organic amendments such as compost, manure, or crop residues provide carbon and nutrients that stimulate microbial activity and contribute to the formation of stable organic matter, serving as a long-term nutrient reservoir³⁴. Together, these practices enhance the synchronisation of nutrient release with plant demand, improve nutrient retention, and build soil nutrient stocks, thereby reinforcing soil fertility and resilience.

Translating potentials into activities

The soil microbiome is a major driver of soil quality and resilience and harbours a vast genetic potential for nutrient transformation. However, the expression of this potential into actual biochemical activity—such as enzyme production and nutrient turnover—is not automatic. Instead, activities are tightly regulated by resource availability and the stoichiometric balance of C, N, and P in soil.

To date, agricultural sustainability efforts have largely focused on reducing fertiliser inputs and mitigating nutrient losses. However, the role of soil nutrient stoichiometry in regulating nutrient retention, mobilisation, and long-term soil fertility has received comparatively little attention. The balance and availability of N and P are not determined by fertiliser inputs alone but are strongly mediated by microbial mobilisation-immobilisation processes. Consequently, soil C:N:P stoichiometry shapes microbial nutrient demand³⁵ and determines whether microbial communities act primarily as sinks (through immobilisation) or sources (through mineralisation) of plant-available nutrients. In this way, stoichiometry governs whether microbial genetic potential is translated into nutrient retention or nutrient release. Root exudates play a central role in this regulation by acting as both substrates and signalling molecules that recruit microbial taxa with specific functional traits for biological nutrient acquisition³⁶ to access otherwise unavailable nutrient pools. However, high inputs of synthetic fertilisers can weaken this plant-driven selection, reducing the reliance on microbial nutrient acquisition pathways and diminishing the activity of the soil microbiome³⁷. Such shifts risk transforming soils into systems increasingly dependent on external inputs, with long-term consequences for soil fertility, resilience, and economic sustainability³⁸.

Microbial nutrient transformations are tightly interconnected and co-regulated by resource availability. Functional groups such as nitrogen fixing rhizobia, for example, simultaneously mediate nitrogen transformations and phosphorus mineralisation. For an effective N fixation, a coordinated expression of the N fixation machinery alongside C and P metabolism is required to ensure sufficient energy supply³⁹. This illustrates that microbial functions do not operate independently but respond jointly to C, N, and P availability. Soil nutrient stoichiometry therefore provides a key framework for predicting which metabolic pathways and enzyme systems are activated under given conditions.

Soil microorganisms tend to maintain relatively stable internal C:N:P ratios (approximately 60:7:1), reflecting their elemental requirements, although these can vary with vegetation, soil type, and management⁴⁰. These values should not be interpreted as universal management thresholds, but they provide useful diagnostic reference points for evaluating whether microbial growth is more likely constrained by C, N, or P availability. When external resource stoichiometry deviates from microbial demand, microbes adjust their metabolism and enzyme production accordingly. Under relatively low C:N or C:P resource ratios - such as following high mineral fertiliser inputs - nutrient availability may exceed microbial C supply. In these conditions, microbial growth is carbon-limited, reducing the capacity for nutrient immobilisation and increasing the risk of nutrient losses, particularly

NO₃⁻ leaching⁴¹. In contrast, relatively high C:N and C:P resource ratios resulting from C-rich inputs stimulate microbial growth and promote extracellular enzyme production targeting the acquisition of limiting nutrients. This enhances microbial immobilisation and the incorporation of nutrients into biomass and soil organic matter, although it may also increase competition with plants for available nutrients during periods of high demand⁴². Soil N content is also affected by N-loss through gaseous emissions via microbial nitrification and denitrification as well as input through diazotrophic N-fixation⁴³. The balance among these pathways is strongly governed by substrate availability and C:N:P ratios, linking nutrient cycling directly to environmental outcomes. Microbial activity and gene expression are further influenced by site-specific factors such as soil type, pH, moisture, and temperature⁴⁴, which interact with stoichiometric constraints to regulate microbial activity and enzyme kinetics. This makes the soil microbiome a key leverage point for improving nutrient use efficiency and sustainability when management is adapted to site-specific conditions⁴⁵.

Management strategies that explicitly consider soil stoichiometry can enhance the alignment between microbial activity and plant nutrient demand. Precision fertilisation can reduce periods of nutrient oversupply by matching inputs more closely to crop requirements⁴⁶, while cover crops help to retain nutrients during agronomic production breaks. Improved irrigation management can reduce NO₃⁻ leaching and influence soil redox conditions that regulate microbial transformations⁴⁷. Combining organic and mineral fertilisers provides both rapidly available nutrients and slower-release C sources, improving synchrony between nutrient supply and biological demand⁴⁸, while recycled fertilisers such as struvites can support sustained P availability⁴⁹.

In practice, stoichiometry-guided management will require pragmatic indicators rather than perfect mechanistic measurements. At field scale, soil organic C, total and mineral N, available P, microbial biomass C:N:P, extracellular enzyme activity ratios, crop nutrient removal, residual soil nitrate, and, where feasible, indicators of N₂O emissions or leaching risk can be combined to identify local stoichiometric constraints. Such indicators must be interpreted across seasons and soil zones, because fertiliser bands, root hotspots, wet-dry cycles, and organic amendments create strong spatial and temporal heterogeneity.

Targeted increases in C availability can be effective for enhancing microbial immobilisation and nutrient retention, but the outcome depends on timing, amendment quality, soil moisture, and crop demand. During periods of low plant demand, such as after harvest, the addition of C-rich materials (e.g., crop residues, straw, compost, or other organic amendments) stimulates microbial growth and promotes the incorporation of available N and P into microbial biomass⁵⁰. This can reduce nutrient losses during vulnerable periods and create a temporary nutrient reservoir that can be remobilised during subsequent crop growth. For example, increasing soil C:N and C:P ratios through straw return has been shown to enhance soil organic matter and microbial biomass while reducing off-season nutrient losses^{51,52}. Similar effects have been observed with the application of C-rich organic materials such as green waste compost or paper waste, which can also mitigate N losses under certain conditions⁵³. However, the same immobilisation processes may temporarily reduce nutrient availability for crops if C-rich amendments are applied close to periods of high plant demand, and poorly timed applications under wet conditions may increase gaseous N losses.

In the longer term, soil stoichiometry is closely linked to microbial community dynamics and the accumulation of soil organic matter. Microbial biomass and activity contribute to the formation and stabilisation of soil organic matter, which serves as a key reservoir for nutrients⁵⁴. Fertiliser regimes influence not only immediate nutrient availability but also microbial community composition and function^{55,56} thereby affecting the soil's capacity to retain and recycle nutrients over time. Systems with higher organic inputs, such as organic farming, often exhibit increased microbial biomass and improved C-use efficiency, leading to tighter nutrient cycling and more balanced stoichiometry⁵⁷.

Unifying framework of microbial biodiversity, nutrient stoichiometry and plant nutrient use efficiency for future agricultural practice

Future sustainable agricultural management requires an integrated framework that explicitly links crop NUE, soil nutrient stoichiometry, and microbial biodiversity. The novelty of this perspective is not that these components matter individually, but that their simultaneous consideration turns nutrient management into a set of operational, testable principles: (i) matching nutrient supply with crop demand and NUE should increase recovery only when microbial immobilisation and remobilisation are synchronised with plant phenology; (ii) soil C:N:P balance should predict whether microbial processes primarily retain, mobilise, or release nutrients; and (iii) microbial functional diversity, including keystone taxa and response diversity, should stabilise these processes under environmental stress. This implies that no single management measure is sufficient to promote effective nutrient management, but requires coordinated interventions that target (a) nutrient timing, (b) stoichiometric balance, and (c) microbial habitat and activity. The following principles provide a practical framework (Fig. 1):

Integrative nutrient and stoichiometry management as the central framework for future agriculture

Future agricultural systems must move beyond yield-oriented fertilisation strategies toward integrated nutrient management concepts that explicitly consider soil stoichiometry, microbial nutrient demand, and plant nutrient acquisition as interconnected processes. Although soil stoichiometry and microbial biodiversity are well represented in parts of the literature, they are not yet routinely combined with crop NUE and nutrient recovery efficiency in operational nutrient-management decisions. However, nutrient-use efficiency is not solely determined by fertiliser input, but by the synchronisation between nutrient availability, microbial transformation processes, and crop demand across space and time. In this context, soil C:N:P stoichiometry represents a central regulatory framework that determines whether nutrients are retained within microbial biomass and soil organic matter or lost through leaching and gaseous emissions.

Future management strategies should therefore aim to actively steer stoichiometric balances rather than treating them as passive consequences of fertilisation. This requires combining mineral fertilisers with carbon-rich amendments such as crop residues, composts, recycled organic fertilisers, or cover crop biomass to enhance microbial nutrient immobilisation during periods of nutrient excess. Conversely, periods of strong microbial nutrient immobilisation following high-carbon inputs may require targeted nutrient supplementation or the inclusion of legumes to avoid competition between plants and microorganisms. Such approaches transform nutrient management from a purely chemical intervention into a biologically regulated process that integrates nutrient buffering, microbial storage, and controlled re-mobilisation.

Importantly, stoichiometry-guided management must also become site-specific. Soil texture, pH, hydrology, climatic conditions, legacy nutrient pools, and organic matter content strongly influence microbial nutrient turnover and nutrient losses. Precision agriculture technologies, high-resolution nutrient monitoring, and microbial indicators should therefore be integrated into future nutrient management frameworks to identify local stoichiometric constraints and optimise fertiliser timing, placement, and composition. Practical implementation could combine routine soil testing with biological indicators, including microbial biomass, enzyme activities, residual mineral N after harvest, available P, and crop nutrient removal, to define whether management should prioritise nutrient release, microbial retention, or loss prevention. Integrating these biological and physicochemical dimensions provides an opportunity to substantially improve nutrient recovery efficiencies while simultaneously reducing environmental impacts, greenhouse gas emissions, and dependency on synthetic fertilisers.

Protecting and restoring soil microbial biodiversity as a foundation of resilient nutrient cycling

Microbial biodiversity must be recognised as a core agricultural resource rather than merely a consequence of soil management. However, diversity alone is not a sufficient management target. Diverse microbial communities provide the functional backbone—including functional groups and keystone taxa—for nutrient cycling, nutrient retention, soil organic matter formation, and ecosystem resilience, but the relationship between diversity and function is not linear. High microbial diversity can increase functional redundancy, meaning that key ecosystem functions such as nitrogen mineralisation, phosphorus mobilisation, nitrification, denitrification, and carbon turnover may be maintained even under environmental stress or disturbance. At the same time, the loss or inactivity of specific keystone taxa or functional guilds can impair individual processes even when overall diversity remains high. The loss of microbial functional capacity therefore directly threatens the self-regulating capacity of soils and increases dependency on external nutrient inputs.

Current intensive agricultural systems frequently undermine these functions through deep tillage, monocultures, excessive synthetic fertilisation, pesticide use, and simplified crop rotations. Such practices reduce the diversity of root-derived carbon inputs, disrupt microbial habitats and fungal networks. The short-term influx of available nutrients through high mineral fertiliser deposition can shift microbial communities toward fast-growing opportunistic taxa (*r*-strategists), but the consequences of such shifts for long-term nutrient storage and soil stability depend on carbon availability, soil structure, moisture regimes, crop rotations, and the persistence of slow-growing or keystone taxa. Thus, shifts in community composition should be interpreted together with functional indicators rather than used alone as evidence for reduced resilience. As microbial functional capacity declines, soils become increasingly vulnerable to nutrient losses, drought stress, and reduced resilience under climate change.

Future agricultural management must therefore prioritise the preservation and restoration of microbial habitats and plant–microbe interactions. Reduced or conservation tillage systems should be expanded to maintain soil structure and protect microbial niches. Diversified crop rotations and multispecies cover crop systems should be implemented to increase the diversity and continuity of root exudates that sustain microbial functional diversity. Organic amendments derived from circular-economy approaches should be promoted not only as nutrient sources, but also as drivers of microbial activity and soil organic matter formation. Importantly, microbial diversity should increasingly become part of agricultural monitoring frameworks and soil health assessments, using molecular tools and functional indicators to identify losses in ecosystem functionality before agronomic decline becomes visible.

Maintaining microbial biodiversity is particularly critical under future climate scenarios characterised by more frequent droughts, heat waves, and extreme precipitation events. Soils with diverse and active microbiomes are more capable of buffering such disturbances through stabilised nutrient cycling and improved soil structure. Supporting microbial biodiversity should therefore be viewed as a long-term investment into agricultural resilience, environmental sustainability, and food security rather than as an optional ecological co-benefit.

Maintaining continuous biological activity through plant cover, water management, and biologically informed farming systems

Agricultural systems should increasingly be designed to maintain continuous biological activity in soils throughout the year. Nutrient losses frequently occur during periods when plant nutrient uptake is low while microbial nutrient immobilisation is insufficient to buffer excess nutrients. This is particularly evident after harvest, during fallow periods, or under conditions of excess soil moisture where nitrate leaching and denitrification strongly increase. Maintaining active plant–microbe systems across seasons is therefore essential for improving nutrient retention and stabilising soil functioning.

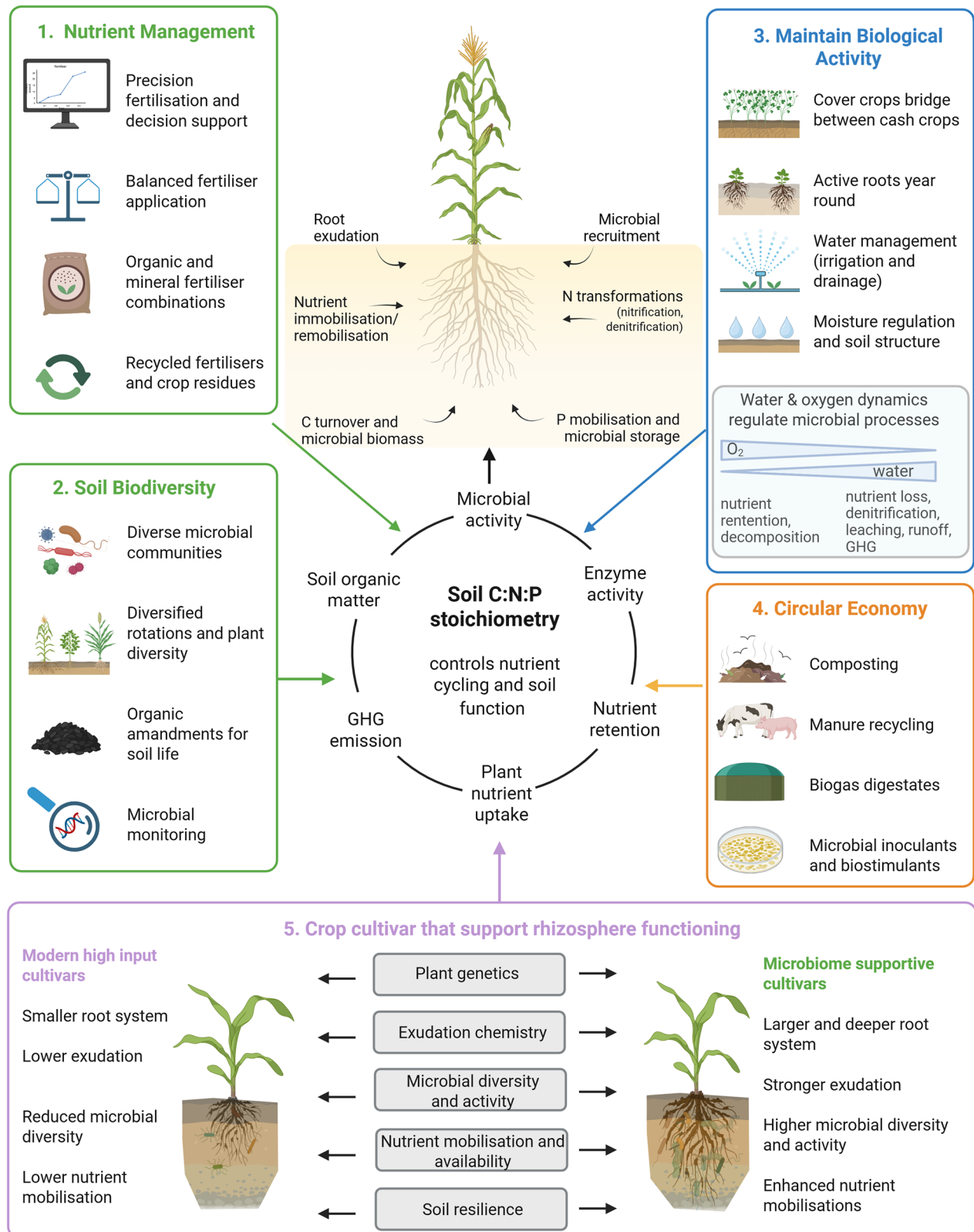


Fig. 1 | Created in BioRender. Schulz, S. (2026) <https://BioRender.com/vemaual>. Conceptual framework linking plant nutrient use efficiency (NUE), soil microbial processes, and nutrient stoichiometry. Plant nutrient acquisition and utilisation (top) interact with microbially mediated nutrient mobilisation, immobilisation, and storage in the rhizosphere (middle), which are regulated by soil C:N:P stoichiometry acting as a central control on microbial activity and enzyme expression. Management practices (bottom) influence these interactions by modifying resource

availability, microbial habitats, and nutrient balances. The framework highlights intervention points and feedback loops whereby management- and climate-driven changes in water availability, carbon inputs, and nutrient loss pathways affect microbial activity and crop nutrient demand. Aligning stoichiometry, microbial processes, and plant demand enhances nutrient recovery efficiency, reduces environmental losses, and supports long-term soil fertility and resilience.

Cover crops represent one of the most effective tools to maintain biological continuity in agricultural soils. They capture residual nutrients, increase carbon inputs into the rhizosphere, stimulate microbial immobilisation, and support the formation of microbial biomass and soil organic matter. Species mixtures combining grasses, legumes, and deep-rooting species can further optimise stoichiometric balance by simultaneously providing carbon inputs, biological nitrogen fixation, and improved nutrient redistribution within soil profiles. Continuous plant cover additionally protects soils against erosion, improves water infiltration, and stabilises soil structure, thereby reducing nutrient runoff. However, cover crops and companion crops can also create trade-offs, particularly in water-limited systems or when termination is poorly timed: they may compete with the main crop for water and nutrients, increase management costs, or delay nutrient release when microbial immobilisation remains high during early crop growth.

Water management must become more tightly integrated with nutrient and microbiome management. Soil moisture directly regulates oxygen availability, microbial metabolism, nitrification, denitrification, and greenhouse gas emissions. Excessive irrigation or poor drainage promotes oxygen limitation and nitrogen losses through denitrification, while drought suppresses microbial activity and nutrient mobilisation. Future farming systems therefore require integrated water and nutrient management approaches that synchronise irrigation regimes with microbial activity and plant nutrient demand. Precision irrigation technologies, improved drainage systems, and adaptive management based on climatic forecasts can substantially reduce nutrient losses while stabilising microbial functions, albeit at additional costs to farmers.

Biologically informed farming systems should further integrate organic amendments, residue management, and recycled nutrient sources into coherent management frameworks. Rather than maximising short-term nutrient availability, future systems should aim to maintain long-term nutrient cycling capacity and biological buffering functions. This requires balancing benefits against practical constraints: slow nutrient release from bio-based and recycled fertilisers can limit short-term agronomic output, nutrient composition may vary among batches, transport and application costs can be substantial, and poorly timed applications may increase leaching or greenhouse gas emissions. Such systems would not only improve nutrient-use efficiency but also increase resilience against climatic variability and external input dependency when embedded in site-specific monitoring and adaptive management.

Advancing circular nutrient economies and biologically active fertilisation strategies

The transition toward sustainable agriculture requires a fundamental shift from linear fertiliser consumption toward circular nutrient economies that integrate biological nutrient retention and recycling processes. Current agricultural systems rely heavily on mineral fertilisers derived from energy-intensive industrial production or finite geological resources, while substantial proportions of applied nutrients are lost to the environment. Circular nutrient strategies provide an opportunity to simultaneously reduce dependency on external inputs, improve nutrient synchrony, and strengthen soil microbial functioning.

Recycled fertilisers such as composts, digestates, manure-derived products, bio-based fertilisers, and phosphorus-recovery products including struvites should become integral components of future nutrient management systems. Compared with highly soluble mineral fertilisers, many recycled products provide slower nutrient release and additional carbon substrates that stimulate microbial immobilisation and soil organic matter formation. This improves synchrony between nutrient availability and plant demand while reducing nutrient losses through leaching and gaseous emissions. At the same time, such approaches strengthen microbial nutrient buffering and contribute to long-term soil fertility.

Future fertilisation concepts should increasingly integrate biological stimulants and soil improvers that enhance rhizosphere processes and microbial activity. Plant biostimulants, microbial inocula, and organic soil

improvers may support nutrient mobilisation, stress resilience, and root development, but their performance under field conditions is often inconsistent. This variability reflects competition with resident microbial communities, low persistence after application, abiotic stress, mismatch between inoculant traits and local soil-crop contexts, and limited understanding of how introduced strains interact with native nutrient cycling networks. Consequently, their future role should not be viewed as isolated products or universal solutions, but as components of integrated biological management systems combining nutrient timing, stoichiometric regulation, microbial activation, plant genotype, and plant-microbe interactions.

To successfully implement circular nutrient economies, substantial advances in monitoring, regulation, and quality control are required. Recycled fertilisers and biological products must be evaluated not only for nutrient content but also for their effects on microbial communities, nutrient cycling dynamics, greenhouse gas emissions, and long-term soil functioning. This will require interdisciplinary research linking microbiology, soil science, agronomy, plant physiology, and systems modelling. Ultimately, circular nutrient management offers a major opportunity to transform agriculture from an input-intensive system into a biologically regulated and resource-efficient production system capable of operating within planetary boundaries.

Breeding and selecting plant cultivars that actively support rhizosphere microbial functioning

Future crop breeding strategies should increasingly consider the capacity of plants to shape beneficial rhizosphere microbiomes, while recognising that this remains an emerging and context-dependent breeding target. Modern breeding has strongly focused on aboveground productivity, harvest index, and responsiveness to mineral fertilisers, often under conditions where nutrient supply was artificially maintained at high levels. This may have contributed to reduced root biomass, simplified root architectures, and lower carbon allocation into the rhizosphere in some modern cultivars. Consequently, the capacity of plants to recruit and sustain diverse microbial communities involved in nutrient mobilisation, nutrient buffering, pathogen suppression, and stress resilience may have been unintentionally reduced, but this hypothesis requires validation across crop species, soils, and management systems.

Forthcoming agricultural systems aiming to improve nutrient-use efficiency and reduce external inputs will require cultivars that actively support microbial life and activity in the rhizosphere through root exudation and beneficial plant-microbe interactions. Root exudates represent key energy and signalling sources that regulate microbial recruitment and functional activity. Plants capable of maintaining diverse and metabolically active rhizosphere communities are likely to achieve improved access to organically bound or mineral-associated nutrient pools while simultaneously stabilising nutrient cycling processes under environmental stress.

Old land races and traditionally bred cultivars may represent valuable genetic resources because they frequently evolved under lower-input conditions and may maintain stronger belowground investment and broader microbial associations. At the same time, emerging breeding technologies including CRISPR/Cas-based genome editing provide new opportunities to target traits linked to rhizosphere functioning, nutrient acquisition, root architecture, exudation chemistry, and microbiome recruitment. Such approaches could enable the development of crop cultivars that are optimised not only for yield performance but also for their capacity to sustain biologically active and resilient soil systems, provided that microbiome-associated traits are reproducible across environments and do not compromise yield stability.

Integrating plant breeding with microbiome science therefore represents a major frontier for sustainable agriculture. Future breeding programmes should increasingly include belowground traits, rhizosphere interactions, and microbial recruitment capacities as measurable selection targets rather than assumed outcomes. Combining advanced genomics, metabolomics, microbiome profiling, and systems biology approaches may ultimately enable the development of crops specifically designed to

cooperate with beneficial soil microbiomes, thereby enhancing nutrient recovery efficiency, reducing fertiliser dependency, and improving long-term soil health and resilience under future environmental conditions. However, the agronomic value of microbiome-informed breeding should be tested across genotype-by-environment-by-management gradients before being translated into broad recommendations.

Overall, improving NUE in future agricultural systems requires moving beyond input-based strategies toward adaptive, biologically informed management. By explicitly managing soil stoichiometry, fostering microbial functional capacity, and selecting crops with favourable nutrient acquisition traits, it is possible to enhance nutrient recovery efficiency, reduce environmental losses, and maintain long-term soil fertility. The framework proposed here should be viewed as a set of testable operational principles rather than a universal prescription: its value will depend on local soils, climates, crop systems, management histories, and the availability of practical indicators. Such integrated, site-specific strategies provide a robust pathway to sustain agricultural productivity while remaining within environmental limits under future climatic and regulatory conditions.

Data availability

No datasets were generated or analysed during the current study.

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Author contributions

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Competing interests

The authors declare no competing interests.

Additional information

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