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Effects of Straw Return on Soil Properties in Legume Fields

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Abstract Straw returning has been widely recognized as an effective agricultural practice for improving soil quality and promoting sustainable crop production. Legume crops play an important role in agroecosystems due to their biological nitrogen fixation capacity and contribution to soil fertility. This review summarizes the effects of straw returning on soil physical, chemical, and biological properties in legume cropping systems. Straw incorporation improves soil structure, enhances aggregate stability, increases water-holding capacity, and reduces soil compaction. Meanwhile, straw-derived organic carbon promotes soil organic matter accumulation, regulates nutrient cycling, and improves the availability of nitrogen, phosphorus, and potassium. In addition, straw returning stimulates microbial activity, alters microbial community composition, and enhances soil enzyme activities involved in carbon, nitrogen, and phosphorus transformations, thereby improving rhizosphere ecological functions and biological nitrogen fixation. Case studies of maize straw returning in soybean fields, wheat straw returning in faba bean systems, and long-term straw management in legume rotations demonstrate its potential for enhancing soil fertility and crop productivity. However, challenges such as slow decomposition, nutrient immobilization, and management optimization remain. Future research should integrate multi-omics approaches and precision management strategies to develop efficient straw returning systems for sustainable legume production.
Keywords Straw returning; Legume cropping systems; Soil properties; Soil microbial community; Sustainable agriculture

1 Introduction

Straw return has become an important strategy for recycling crop residues and promoting sustainable agriculture, particularly as intensive cultivation, residue burning restrictions, and soil degradation have increased pressure to improve soil quality while maintaining crop productivity. Crop straw is a major agricultural biomass resource, and returning it to soil is widely recognized as an environmentally friendly management practice that can enhance nutrient supply, support crop production, and reduce the negative consequences of residue removal or burning (Liu et al., 2024). Across agroecosystems, straw return generally improves key soil properties by increasing soil organic carbon, dissolved and labile carbon pools, total nitrogen, and available nutrients, while also reducing bulk density and improving porosity and water retention. Long-term field studies further show that straw return can substantially increase labile organic carbon fractions, microbial biomass carbon, and multiple extracellular enzyme activities, indicating that it contributes not only to nutrient replenishment but also to the recovery of ecological functions that are often impaired by conventional fertilization and residue mismanagement. In legume fields, these effects are especially meaningful because legumes occupy a distinctive position in agroecosystems through symbiotic and free-living nitrogen fixation, high nitrogen demand during reproductive development, and strong dependence on biologically mediated nutrient cycling. Evidence from maize-soybean residue return shows that straw addition can markedly enhance soil biological nitrogen fixation and increase the abundance of key N-cycling genes such as nifH, nirS, and nosZ, largely through changes in soil organic matter, pH, nitrate, and available potassium. This suggests that in legume-based systems, straw return is not merely a residue disposal practice but a potentially important regulator of soil fertility, microbial nitrogen transformation, and the productive capacity of the soil-plant system. At the same time, responses vary with straw type, application rate, soil conditions, climate, and accompanying practices such as tillage and nitrogen fertilization, so a field-specific evaluation is necessary before general recommendations can be made (Chen et al., 2022; Song et al., 2025).

Current research shows that straw return affects soil ecological processes through interconnected physical, chemical, and biological pathways. Physically, straw incorporation can improve aggregate stability, reduce soil penetration resistance and bulk density, increase macroaggregate-associated carbon, and enhance the soil quality index, all of which create a more favorable habitat for root growth, aeration, and water storage. Chemically, straw return supplies carbon substrates and nutrients, promotes SOC sequestration, and alters nutrient retention and transformation; however, the direction and magnitude of these effects depend on decomposition dynamics and nutrient availability. For example, straw return increased SOC content by 20% in a long-term experiment, while nitrogen fertilization accelerated microbial utilization of straw and increased the contribution of microbial necromass to SOC formation (Meng et al., 2023). Microbially, straw return often increases community diversity, shifts dominant bacterial and fungal groups, stimulates cellulolytic and nutrient-cycling functions, and strengthens microbial network complexity and stability. Multi-year evidence further indicates that straw retention can drive microbial succession, increase fungal biomass, stimulate cellulose-decomposing microorganisms, enhance C- and N-cycling enzymes, and enrich genes involved in nitrification, nitrogen fixation, and carbon metabolism (Jia et al., 2025). Even so, the ecological effects of straw return are not uniformly positive. Meta-analysis shows that although straw return can increase crop yield and soil carbon sequestration, it can also raise ammonia emissions and nitrous oxide emissions in upland systems, revealing trade-offs between soil improvement and reactive nitrogen losses. Short-term or poorly managed return may also slow residue decomposition, temporarily reduce nutrient availability because of the high C/N ratio of straw, or increase the abundance of certain plant pathogens, especially when matching practices for nutrient regulation and disease control are lacking. These findings indicate that the influence of straw return on soil ecological processes is complex, highly management-dependent, and still insufficiently resolved for legume fields, where residue quality, rhizosphere processes, and nitrogen transformations may differ from cereal-dominated systems (Ninkuu et al., 2025).

Against this background, the present study focuses on legume fields to clarify how straw return influences soil properties and related ecological processes under a legume cropping context. Although many studies have examined cereal systems, saline soils, or broad agroecosystem patterns, comparatively fewer have directly addressed the combined physical, chemical, and biological responses of soils in legume fields, especially from the perspective of integrated soil quality improvement and nitrogen-related functions. Therefore, the objectives of this study are to determine the effects of straw return on key soil physicochemical properties in legume fields, including soil organic matter, nutrient status, pH, bulk density, aggregate stability, and moisture-related conditions; to evaluate its effects on soil biological characteristics such as microbial abundance, community composition, enzyme activity, and nitrogen-cycling potential; and to reveal the major pathways through which straw return regulates soil ecological quality in legume production systems. In addition, because management outcomes differ with return method and fertilization regime, this study also considers the practical relevance of coupling straw return with appropriate agronomic measures to improve nutrient-use efficiency and avoid adverse effects such as excessive greenhouse gas emissions or nutrient immobilization. The major contents of the paper therefore include: analysis of the changes in soil physical traits after straw return; assessment of soil chemical fertility and carbon-nitrogen dynamics; characterization of microbial and enzymatic responses associated with residue decomposition and nutrient cycling; and discussion of the implications of these changes for sustainable soil management in legume fields. Overall, this study aims to provide a scientific basis for optimizing straw return practices in legume systems so that residue resources can be more effectively transformed into improvements in soil quality, ecological function, and agricultural sustainability.

2 Straw Returning Practices and Their Effects on Legume Agroecosystems

2.1 Major types and technical approaches of straw returning

Straw returning in agroecosystems mainly includes surface mulching, soil incorporation, burial, compost/manure use, and biochar conversion, and these methods differ in residue placement, soil contact, moisture regulation, and nutrient transformation. Reviews also note that direct straw return, straw biochar return, and combinations with fertilizer are the most widely discussed technical patterns in current field management. In practice, the technical effect of a method depends strongly on depth and placement. Field evidence shows that shallow mixing or burial generally accelerates decomposition and C and N release more than deeper placement, while in saline or dry environments mulching often improves moisture conservation and crop performance more effectively than other methods (Tian et al., 2019). A broader meta-analysis likewise found that straw mulching produced the largest average yield gain, whereas straw incorporation more strongly increased soil organic matter, indicating that no single technique is optimal across all production goals.

For legume fields, method selection should match the ecological needs of legumes, especially their sensitivity to early root-zone aeration, moisture, and available nitrogen. Straw incorporation can strengthen soil-residue contact and favor nutrient turnover, but excessive depth or poorly timed return can delay residue decay and weaken near-surface benefits. By contrast, combining straw return with legume-based cover crops or converting part of the residue to biochar offers a more balanced technical route, because legumes help offset straw-induced N limitation while biochar can improve nutrient retention and reduce environmental loss risks. Biochar-based strategies are increasingly treated as a modified form of straw return rather than a separate pathway, because they retain residue-derived carbon while changing its decomposition behavior and environmental footprint. In rotation systems, converting residues to biochar before incorporation increased yields and nitrogen fertilizer use efficiency, while reducing N2O and CH4 emissions relative to direct straw return (Zhang et al., 2023). Straw combined with a suitable biochar rate also improved ammonium, nitrate, and available phosphorus retention compared with straw alone, suggesting practical value where legume production requires stable rhizosphere nutrient supply.

2.2 Straw decomposition processes and nutrient release mechanisms

Straw decomposition is a stage-dependent biological process controlled by substrate quality, soil environment, and microbial succession. Early decomposition is rapid because easily degradable fractions such as starch, hemicellulose, and cellulose are consumed first, whereas later decomposition slows as lignin-rich and more recalcitrant compounds remain. This general pattern is also reflected in nutrient release dynamics, which tend to follow the order K > P > C > N, showing that nitrogen is usually released more slowly than other major nutrients (Li et al., 2024). The organisms driving decomposition also change over time. Bacteria dominate the initial phase because they exploit labile carbon rapidly, whereas fungi become more important later as straw becomes enriched in structurally resistant compounds. Actinomycetes and specialized decomposer inoculants can further accelerate lignocellulose breakdown by increasing enzymes such as xylanase, laccase, and peroxidase, which is relevant when field residues are coarse or decomposition is otherwise slow (Ninkuu et al., 2025).

Nutrient release from decomposing straw does not translate directly into plant availability, because released elements can be mineralized, immobilized into microbial biomass, stabilized in soil organic matter, or lost through leaching and volatilization. Long-term evidence indicates that straw return raises SOC partly through preserved plant residues and partly through microbial processing, while nitrogen fertilization increases conversion of straw carbon into microbial necromass and thereby changes the pathway of SOC formation (Meng et al., 2023). In legume agroecosystems, decomposition has special significance because straw C/N ratio interacts with biological nitrogen inputs from legumes. Straw alone can impose microbial nitrogen limitation and slow SOC accumulation, but combining straw with legume cover crops improves C/N balance and promotes simultaneous increases in SOC and total N. Experimental evidence further shows that this combined strategy increased both SOC and TN and offers a feasible pathway to facilitate straw decomposition while lowering dependence on synthetic N fertilizer. Decomposition rates also respond to management and stress context. In some soils, native microbes do not decompose returned straw efficiently, and decomposition agents or adequate nitrogen supply are needed to support cellulase activity and straw-derived carbon incorporation. Salinity can further alter decomposition by changing DOC, nitrate depletion, enzyme activity, and the balance between copiotrophic and oligotrophic bacteria, so nutrient release from straw should be interpreted as environment-specific rather than fixed.

2.3 Effects of straw returning on legume rhizosphere environments

Straw return changes the legume rhizosphere environment by altering carbon inputs, nutrient availability, and root-microbe interactions. More broadly, rhizosphere processes are shaped not by straw return alone but by the interaction between residue management and plant selection, meaning that root traits determine how much of the straw effect is expressed near roots. Long-term evidence likewise shows that the interaction of straw return and plant selection can reshape rhizosphere bacterial communities more strongly than either factor alone. A central consequence in legume systems is the stimulation of nitrogen-cycling functions. In soils receiving maize-soybean straw mixtures, biological nitrogen fixation was highest under the mixed-residue treatment, and the abundance of nifH, nirS, and nosZ carriers increased markedly. The same study showed that changes in soil organic matter, pH, nitrate, and available potassium explained much of the increase in BNF, linking residue return directly to the microbial processes that support N supply in legume-centered systems (Duan et al., 2023).

Straw return also reorganizes the broader rhizosphere microbiome. Rhizosphere-focused studies show that straw can increase the relative abundance of nitrogen-associated groups such as Rhizobiales, Bradyrhizobium, and Sphingomonas, while improving microbial network connectivity and nitrogen supply potential. In other cropping systems, straw return has similarly increased the richness of beneficial rhizosphere taxa and improved soil functionality, supporting the view that residue-derived substrates help recruit functionally important microorganisms around roots. These rhizosphere benefits are accompanied by important caveats. Straw retention for several years can enhance fungal biomass, cellulose-decomposing communities, and genes involved in nitrification and N fixation, but it can also increase the abundance of some plant pathogens (Jia et al., 2025). Straw return therefore appears most effective in legume agroecosystems when residue type, return mode, and complementary management are coordinated to strengthen beneficial rhizosphere processes without creating pathogen or nutrient-immobilization risks. Overall, straw returning in legume agroecosystems works through method-dependent residue placement, microbially mediated decomposition, and rhizosphere reassembly. The most suitable approach is the one that couples efficient residue decay with stable nitrogen supply and a favorable rhizosphere microbial environment for legumes (Figure 1).

3 Effects of Straw Returning on Soil Physical Properties in Legume Fields

3.1 Changes in soil structure and aggregate stability

Straw return generally improves soil structure by increasing the formation and persistence of water-stable aggregates, which are the basic physical units governing pore continuity, resistance to slaking, and protection of organic matter. In a winter pea-summer corn rotation, straw return under multiple tillage modes increased larger aggregate fractions and raised R0.25, MWD, and GMD relative to no-tillage without straw, indicating stronger aggregate stability in a legume-containing system (Huang et al., 2024). Similar long-term results from other croplands show that straw addition increases macroaggregate abundance and SOC within large aggregates, with associated gains in MWD of about 26-34%, suggesting that residue-derived organic binding agents consistently promote structural improvement across soils.

The structural benefits of straw return also depend on return method and duration. In Mollisols, straw strip return increased macroaggregate proportion while reducing silt/clay dominance, and this shift raised both MWD and GMD in the 0-20 cm layer, showing that residue placement can alter how aggregates are assembled within the plow layer (Lian et al., 2022). Meta-analytic and validation evidence from black soils further indicates that long-term return, especially beyond five years, produces the largest gains in macroaggregates, whereas short-term return tends to generate weaker or less stable improvements, implying that legume fields are most likely to show durable structural recovery when straw return is maintained over multiple seasons.

3.2 Regulation of soil water retention and aeration properties

Straw return improves soil water retention mainly by modifying surface cover, pore structure, and rainfall capture. In a soybean-growing Mollisol, soil water storage in the 0-60 cm layer increased by 2.8%-10.6% under rotary return and by 15.0%-19.3% under strip mulching compared with straw removal, and the regulating mechanisms were linked to changes in porosity, temperature, and rainfall interception capacity (Xing et al., 2025). Related field evidence shows that straw return can also regulate soil evaporation and create a moisture-conserving surface barrier, thereby sustaining higher water content through sensitive crop growth stages.

Aeration responses reflect the same structural changes. Across long-term field trials, straw mulching, incorporation, and ammoniated incorporation all increased saturated hydraulic conductivity and soil water retention, indicating that improved aggregate organization can simultaneously support water storage and gas exchange. X-ray CT evidence further shows that straw return reconstructs a more intricate pore network: direct incorporation increased porosity and macropore number, whereas biochar-modified return altered pore circularity and strengthened soil moisture memory, demonstrating that different return modes reshape the soil air-water architecture in distinct ways (Wang et al., 2024).

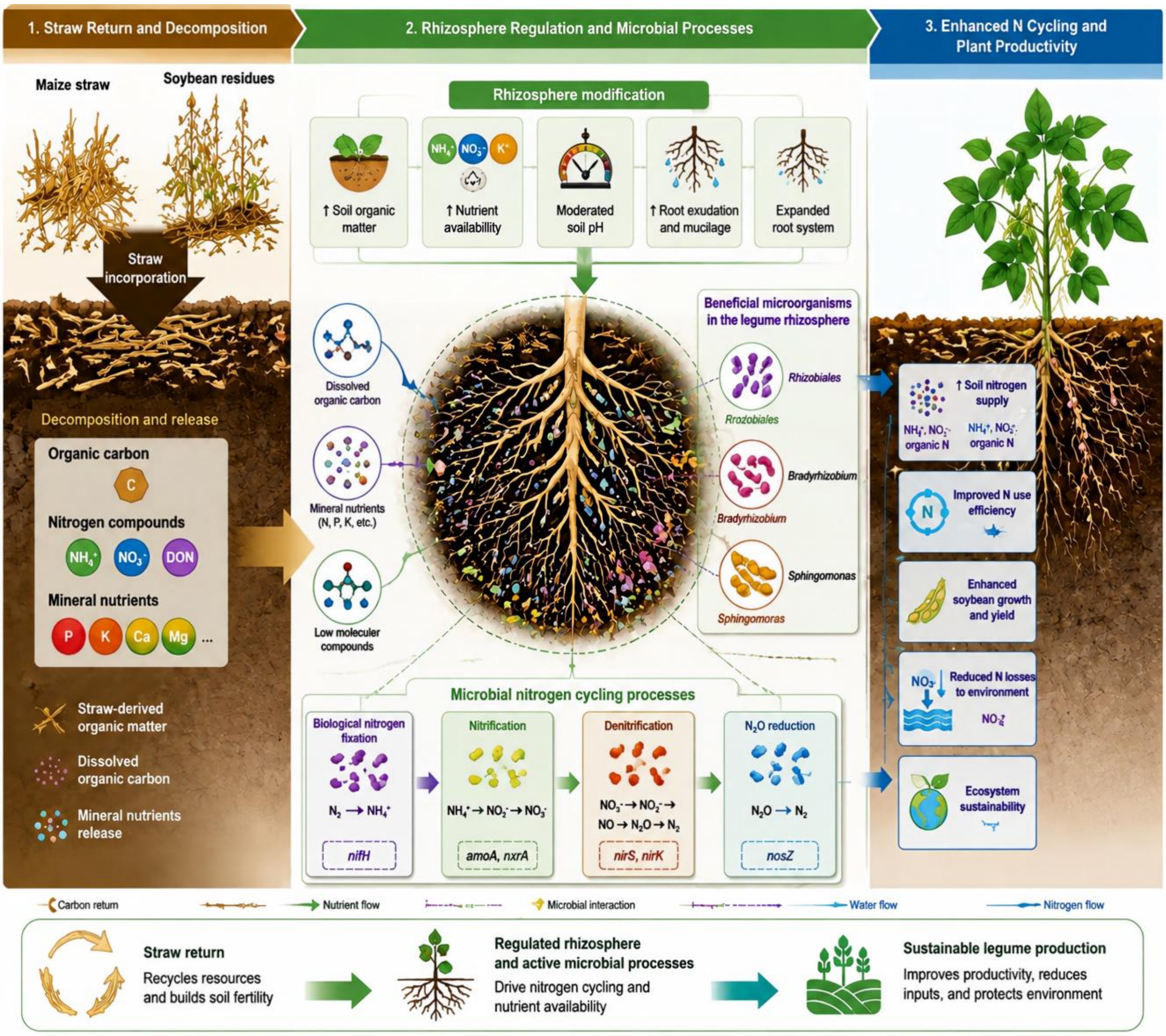

Figure 1 Mechanistic framework illustrating how straw return modifies the legume rhizosphere environment by increasing carbon inputs, improving nutrient availability, restructuring microbial communities, and enhancing nitrogen cycling functions. Straw-derived organic substrates stimulate beneficial rhizosphere microorganisms and functional genes associated with biological nitrogen fixation and nitrogen transformation, ultimately improving nitrogen supply in legume-based agroecosystems

3.3 Effects on soil bulk density and root growth responses

A consistent physical effect of straw return is lower bulk density. In field studies, deep plowing or subsoiling combined with straw return reduced bulk density and increased total porosity within the 15-45 cm layer, whereas repeated shallow or no-tillage return could allow recompaction in some settings, showing that residue return alone is not always sufficient if the subsoil remains mechanically constrained. Other multi-year experiments likewise found significant decreases in bulk density and increases in porosity in both 0-20 and 20-40 cm layers after consecutive straw return, confirming that residue inputs can loosen both topsoil and part of the subsoil when incorporated effectively (Xu et al., 2024).

These density changes matter because they alter the rooting environment of legumes. A review of straw-return effects reports improved root-soil interactions and nutrient assimilation under maize straw mulch without tillage, indicating that better physical contact and lower evaporative stress can translate into more favorable belowground growth conditions. More directly, experiments on straw return with nitrogen management showed that straw reduced bulk density not only in the farming layer but also near the plow pan, and this was accompanied by higher subsoil root length density under moderate nitrogen input; related work also found greater earthworm abundance and more biopores near straw incorporation strips, suggesting that straw can expand biologically accessible rooting channels in compacted profiles (Getahun et al., 2022). Overall, in legume fields, straw return appears to improve physical soil quality by strengthening aggregate stability, increasing water retention and pore continuity, and reducing bulk density in ways that can support deeper and more effective root growth. The magnitude of these benefits depends strongly on return method, duration, and tillage combination, so physical improvement in legume agroecosystems is best understood as a management-dependent response rather than a uniform effect.

4 Effects of Straw Returning on Soil Chemical Properties in Legume Fields

4.1 Changes in soil organic matter and carbon cycling

Straw return generally increases soil organic matter in cropping systems by adding exogenous carbon and promoting the formation of both stable and labile carbon pools. A global meta-analysis found that straw return increased soil organic C by 14.9% on average, together with clear gains in dissolved and labile carbon fractions, indicating that residue return stimulates active carbon turnover as well as longer-term carbon accumulation. In a 15-year soybean-maize system, continuous straw return with mineral fertilization increased SOC by 14.2% and raised microbial biomass C, water-soluble organic C, light-fraction C, readily oxidizable organic C, and particulate organic C, showing that carbon storage in legume-including rotations is accompanied by substantial shifts in SOC composition.

The carbon effect of straw return is not uniform, because sequestration depends on duration, background fertility, and nitrogen balance. A large meta-analysis from China showed that SOC increased by 13.97% overall, but the strongest gains occurred under moderate return duration, suitable climate, and low initial SOC, which means that carbon accumulation after straw return is strongly context dependent. In legume-linked systems, this dependence is partly explained by C/N interactions: combining straw with legume cover crops increased both SOC and total N, whereas straw alone often increased SOC while reducing TN, suggesting that biologically fixed N from legumes can relieve microbial N limitation during residue decomposition (Wang et al., 2025).

4.2 Soil nutrient availability and elemental cycling

Straw return improves nutrient availability because straw itself contains substantial amounts of N, P, and K, and its decomposition transfers part of these elements into plant-available and soil-retained pools. Reviews consistently report that straw return stimulates total N, available N, total P, available P, total K, and available K, while also reducing nutrient loss through improved retention and cation exchange effects (Chen et al., 2022). Across 363 publications, straw return increased total N by 9.8%, available N by 14.1%, available P by 10.4%, and available K by 17.8%, confirming that nutrient enhancement is a broad and reproducible outcome rather than an isolated site response.

Elemental cycling under straw return is mediated by microbial processes and can be especially important in legume agroecosystems, where residue decomposition interacts with biological N inputs. In a 34-year field experiment, long-term straw return increased available P and available K, and it promoted labile and moderately stable P fractions by enriching P-activation genes such as ugpQ, ppk, phoD, and gcd, indicating that residue return changes both nutrient pools and the biochemical machinery controlling their turnover. Legume-based diversification can further strengthen this pathway: soybean intercropping increased total soil N and mineral N, lowered soil and microbial C/N ratio, and accelerated straw decomposition, which in turn favored the transformation of residue-derived carbon into more persistent mineral-associated organic carbon.

4.3 Changes in soil ph and salinity dynamics

The effect of straw return on soil pH is more variable than its effect on SOC or nutrient supply. One global meta-analysis reported no significant overall change in pH, suggesting that pH responses are often small when averaged across cropping systems and management types. More recent syntheses, however, indicate that straw return tends to cause slight acidification overall, with an average decline of 0.030 pH units, and that the direction of change depends strongly on initial soil pH: pH tends to decrease in alkaline soils but can increase in already acidic soils (Guo et al., 2025).

In saline-alkali soils, straw return appears more consistently beneficial because it can reduce salt stress while moderating alkalinity, although the effect depends on return method and companion inputs. A meta-analysis of saline-alkali land showed that straw return increased soil organic matter by 19% and reduced soil salinity by 15%, with straw incorporation performing especially well under severe salinity and high pH conditions (Song et al., 2025). Longer-term field evidence further shows that combining straw with manure and chemical fertilizer reduced soil pH, total salt content, and alkalinity while increasing SOC, total N, and available NPK, suggesting that integrated amendment strategies may be the most effective option where legume fields are constrained by salinity or alkalization. Overall, in legume fields, straw return tends to improve soil organic matter, enhance nutrient cycling, and moderate adverse chemical constraints, but the magnitude and direction of change depend on residue quality, nitrogen balance, initial pH, and whether straw is used alone or in combination with legumes, fertilizers, or other organic amendments.

5 Effects of Straw Returning on Soil Biological Properties in Legume Fields

5.1 Changes in soil microbial community structure

Straw returning generally increases the biological activity and compositional heterogeneity of soil microbial communities by supplying fresh carbon substrates and changing nutrient availability. In field experiments, straw return significantly increased the diversity and composition of bacterial and fungal communities relative to non-return treatments, and these shifts were closely associated with SOC, TN, and sucrose-related enzyme activity (Yang et al., 2022). A large meta-analysis similarly showed that straw return slightly increased bacterial richness overall, with stronger diversity gains under continuous return, low straw input, or higher nitrogen supply, indicating that microbial responses depend on management intensity rather than straw input alone. Changes in community structure are not limited to diversity metrics but include shifts in dominant taxa and ecological strategies. Straw return often enriches Proteobacteria and other copiotrophic groups involved in residue utilization, while changing the balance among decomposers, nutrient cyclers, and stress-tolerant taxa. In soybean rhizosphere soil, different straw-return rates selected distinct bacterial and fungal assemblages, and full-dose return enriched taxa linked to nitrogen cycling, methane-related metabolism, and mycorrhizal functioning, showing that legume fields can generate especially functionally diverse microbial responses.

Microbial succession under continued straw return follows a recognizable temporal pattern. Early after residue input, bacteria respond rapidly because they exploit easily degradable compounds, whereas fungi become more important later as lignin and other recalcitrant substrates accumulate (Jia et al., 2025). Multi-year studies confirm this transition: bacterial biomass increased in the first year of straw retention, while fungal biomass became significantly higher after three to five years, together with greater abundance of cellulose-decomposing communities. Not all microbial changes are uniformly beneficial. Straw return can increase microbial network modularity and stability, but high residue amounts or specific straw types can also favor fungal pathogen accumulation or reduce fungal diversity under some conditions. Long-term rotation studies reported higher abundance of a fungal pathogen under high-rate corn straw return, and short-term straw retention also increased some plant pathogens despite improving the overall microecological environment (Su et al., 2020).

5.2 Regulation of soil enzyme activities and ecological functions

Straw return consistently stimulates soil extracellular enzyme activities that govern carbon, nitrogen, and phosphorus turnover. Across 135 field studies, straw return increased C-acquiring, N-acquiring, P-acquiring, and oxidative enzymes by 26.5%, 20.3%, 17.8%, and 9.1%, respectively, indicating a broad enhancement of microbial investment in residue decomposition and nutrient acquisition. A separate global synthesis focused on hydrolytic carbon-degrading enzymes found a 25% average increase, together with higher dissolved organic carbon, particulate organic carbon, microbial biomass carbon, and SOC, supporting a strong link between enzyme activation and belowground carbon accumulation (Somchanh et al., 2026). Field experiments show that this enzymatic stimulation extends to specific catalytic functions relevant to residue breakdown and nutrient mineralization. In a 14-year rotation, straw return combined with fertilizer increased α-glucosidase, β-glucosidase, cellulase, xylanase, N-acetyl-glucosaminidase, leucine aminopeptidase, and acid phosphatase by roughly 46-113% relative to the control, while also improving microbial diversity and activity. In aggregate-scale soils, straw return increased urease activity by 43.08% in >0.053 mm aggregates, although phosphatase and invertase declined in the same system, showing that enzyme responses can differ among substrates and microhabitats.

The ecological significance of these enzyme shifts lies in their control over nutrient release, microbial metabolism, and soil multifunctionality. Random forest and correlation analyses indicate that cellulolytic, ammoniating, phosphate-solubilizing, and potassium-dissolving microbial groups are major contributors to urease, peroxidase, phosphomonoesterase, and invertase activity under straw return (Guan et al., 2023). In soybean rhizosphere soil, soil multifunctionality was strongly associated with nitrate N, organic carbon, microbial biomass N and P, and invertase activity, and higher fungal and whole-network complexity directly supported multifunctionality (Zhao et al., 2025). These responses remain management- and time-dependent. Enzyme stimulation tends to weaken in experiments lasting ten years or more, and the positive effects on C-and P-acquiring enzymes decline as straw application rate becomes excessive. This suggests that in legume fields, moderate and sustained straw return is more likely than excessive residue loading to support efficient decomposition, nutrient-use efficiency, and stable biological functioning.

5.3 Interactions between legume roots and rhizosphere microorganisms

In legume systems, straw return interacts with a rhizosphere that is already biologically distinctive because legumes recruit symbiotic and associative nitrogen-fixing microorganisms. Large comparative datasets show that legume rhizospheres have lower overall microbial diversity but stronger enrichment of nitrogen-cycling taxa such as Rhizobiaceae, Xanthobacteraceae, and Sphingomonadaceae, together with a higher abundance of nitrogen-fixing genes (Yang et al., 2024). This baseline legume-specific organization means that straw return is likely to modify not only decomposer activity but also the balance between residue turnover and biological nitrogen fixation. Evidence from long-term straw return supports that view. The interaction between straw incorporation and plant selection had a stronger effect on rhizosphere bacterial communities than either factor alone, increasing community differentiation, enhancing network connectance, and elevating the abundance of Rhizobiales, Sphingomonadales, and other groups linked to nitrogen supply. Core genera associated with rhizosphere N supply, including Bradyrhizobium, Sphingomonas, and Pseudolabrys, were enriched under this interaction, and dissolved organic carbon was identified as an upstream regulator of these microbial shifts.

Soybean-specific studies further indicate that straw return can reorganize rhizosphere microbial networks in ways that strengthen ecosystem function. After three years, half-dose straw return significantly increased microbial diversity, while fungal network nodes, edges, and average degree also rose markedly relative to no return. These network changes mattered because microbial network complexity directly drove higher soil multifunctionality, which in turn was positively associated with crop biomass and grain yield in the soybean field. Mechanistically, these effects likely arise from the coupling of residue-derived carbon with legume root signaling and nodulation biology. Legumes form nitrogen-fixing nodules through coordinated rhizobial infection and cortical cell division, and this symbiosis depends on selective recognition of beneficial partners while excluding pathogens. Reviews of soybean straw return therefore argue that legume-specific traits such as biological nitrogen fixation and root-secreted signaling compounds can reshape microbial interaction patterns under straw input, making legume rhizospheres distinct from cereal systems and especially relevant for future validation. Overall, straw return in legume fields tends to enhance microbial turnover, strengthen enzyme-mediated nutrient cycling, and reassemble rhizosphere interaction networks around nitrogen supply. The main uncertainty is not whether biological responses occur, but how strongly they depend on straw rate, return duration, and the distinctive symbiotic ecology of different legume crops.

6 Effects of Straw Returning on Legume Growth, Development, and Yield Formation

6.1 Effects on root growth and physiological characteristics of legumes

In legume fields, straw return tends to improve the root-zone environment and thereby support root growth and physiological activity. In red kidney bean, straw return significantly increased chlorophyll content, photosynthetic traits, and dry matter accumulation across three growing seasons, indicating that improved belowground conditions translated into stronger whole-plant physiological performance. More generally, straw return helps maintain soil moisture and air circulation favorable for crop growth, which provides a plausible physical basis for better legume root functioning under residue retention. The effect is not purely structural; it also involves root functional activation. In long-term field studies outside legumes, straw return increased root length, surface area, volume, root-shoot ratio, bleeding intensity, and nitrate and amino acid concentrations in bleeding sap, supporting a root-centered pathway from improved absorption to higher photosynthesis and biomass accumulation (Guan et al., 2025). Similar long-duration evidence shows that straw return can delay root senescence and increase deep-soil root activity later in the season, which is relevant to legumes because sustained root vitality is closely tied to prolonged nutrient uptake and nodule functioning.

Straw-return effects on root morphology also depend on return mode and dosage. In maize, straw return alone promoted root thickening, whereas combining straw with fertilizer increased total root number and root nitrogen concentration, showing that residue return can alter root architecture differently depending on nutrient context. This management dependence is consistent with cotton evidence showing that straw incorporation and especially straw-derived biochar increased root biomass, root activity, soluble protein, and antioxidant enzyme activity, while reducing malondialdehyde and delaying premature root decline (Jin et al., 2024). Legume responses are therefore likely to be strongest when straw return avoids early-stage inhibitory effects and maintains a balanced nutrient supply. Rice studies show that poorly matched straw placement can temporarily suppress new root growth and root enzyme activity early after planting, even when later-season effects become positive. For legume crops, this suggests that the agronomic value of straw return lies less in residue addition alone than in choosing a method and complementary fertilization regime that supports continuous root activity from establishment through reproductive growth (Figure 2).

6.2 Effects on nutrient uptake and biological nitrogen fixation capacity

Straw return can enhance nutrient uptake in legume systems by increasing nutrient recycling from residues and improving the soil environment for acquisition. In red kidney bean, straw return combined with nitrogen fertilizer significantly improved yield components across three years, and the treatment ranking showed that nutrient-supplied straw return outperformed straw return without nitrogen, indicating that stronger nutrient acquisition was a central part of the response. This pattern aligns with broader evidence that straw return improves soil quality and nitrogen supply, and that higher plant N uptake is linked to greater soil organic carbon, microbial biomass, and inorganic N availability. Phosphorus acquisition appears especially responsive to long-term straw addition. Straw-amended systems showed higher root exudate phosphatase and β-glucosidase activity, greater recruitment of phosphate-mobilizing microbes, and stronger rhizosphere P mobilization, with crop P uptake under straw addition driven primarily by rhizosphere functional gene abundance rather than root morphology alone. Although these data come from maize-based systems, they are relevant to legumes because legume productivity is often co-limited by P availability, and faba bean data show very high grain P uptake and strong responsiveness of N and P uptake traits even when yield itself changes little (Klippenstein et al., 2021).

The interaction between straw return and biological nitrogen fixation is particularly important in legume agroecosystems. Combining straw with legume-based cover crops increased both SOC and TN, whereas straw alone often raised SOC while reducing TN, indicating that biologically fixed N can offset the microbial N limitation created by high-C/N residues. Direct evidence from maize-soybean straw mixtures further shows that mixed straw return sharply increased soil BNF, with the highest treatment reaching 2.51 $\mu g \cdot g^{-1}$ DW and strongly increasing nifH, nirS, and nosZ abundance. Legume crops themselves already contribute large amounts of fixed N to the system, so straw management influences not only the current crop but also subsequent nutrient cycling. Faba bean shows a very high N fixation potential, with about 88% N derived from the atmosphere in controlled conditions and around 230 kg·N·ha^{-1} accumulated in aboveground biomass in field experiments. Residue studies also show that faba bean roots and straw can return 29-43 kg·ha^{-1} of fixed N to soil and support higher N recovery by following cereals than wheat residues, which underscores why straw return in legume systems has implications beyond a single season (Siczek et al., 2026).

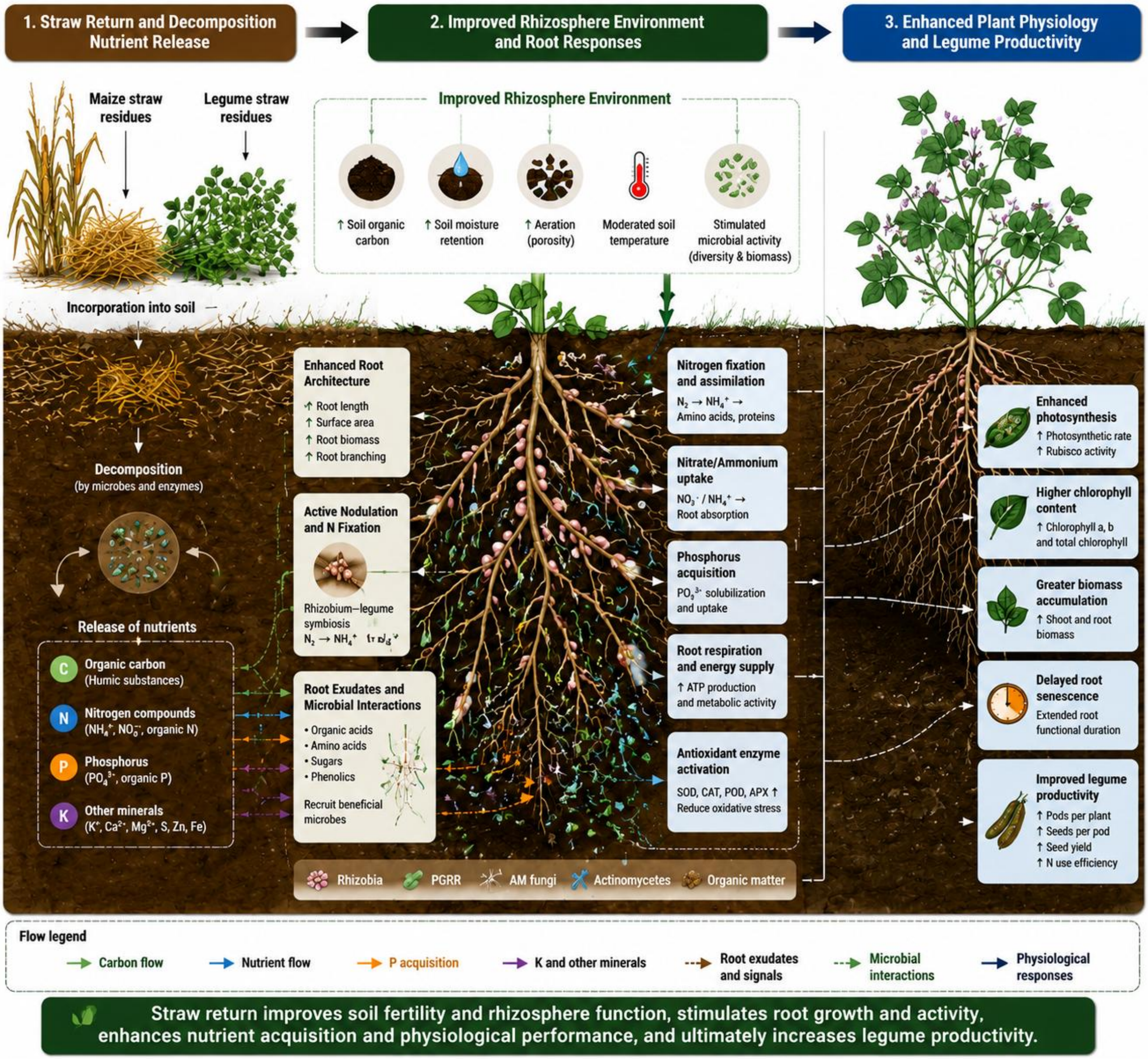

Figure 2 Mechanistic framework illustrating how straw return enhances root growth and physiological activity in legume agroecosystems

6.3 Effects on yield formation and quality improvement

Straw return generally improves yield formation in legumes when paired with appropriate nutrient management. In red kidney bean, straw return increased chlorophyll content, photosynthetic rate, transpiration, dry matter accumulation, and final yield, with the ST+N135 treatment producing the highest values for all major traits across three seasons. The same experiment showed clear gains in pods per plant, 100-seed weight, seeds per pod, and yield, with yield increasing by 17.08-21.05% under ST+N135 compared with the control. Mechanistically, straw return appears to improve yield through a root-photosynthesis-biomass pathway. Evidence from physiological field studies shows that root nitrate transport, bleeding intensity, root length, root volume, and chlorophyll status are key yield-driving traits, and structural equation models indicate that straw return enhances yield primarily by improving root morphology and bleeding traits, which then promote canopy photosynthesis and biomass production. This pathway is consistent with long-term agronomic syntheses showing that yield benefits from straw return are closely tied to improvements in soil structure, soil organic carbon, and nutrient availability, and are strongest under deep tillage, irrigation, and adequate fertilization (Islam et al., 2022).

Quality improvement under straw return is less well documented in legumes than in cereals, but the available evidence points in the same direction. Meta-analysis across major grain crops found that straw return increased protein content, total amino acids, and grain phosphorus content overall, while field experiments with straw return plus potassium increased grain protein and other quality traits together with yield stability. These results are not legume-specific, but they support the expectation that better nutrient mobilization under straw return can improve both legume seed filling and compositional quality when nutrient supply is balanced. The main caveat is that yield benefits are management-dependent rather than automatic. Meta-analyses consistently show that straw return has little benefit without sufficient fertilizer and that yield gains peak under suitable return duration and locally adapted tillage strategies. In addition, improper straw return can increase disease risk or create temporary N immobilization, which may offset gains in sensitive legume systems if return rate, placement, and nutrient supplementation are not well matched (Ninkuu et al., 2025). Overall, in legume fields, straw return most often promotes growth, development, and yield formation by sustaining active roots, increasing nutrient capture, and reinforcing biological nitrogen pathways. Its greatest value appears when straw return is integrated with legume-specific nitrogen ecology and with management practices that prevent early stress while supporting later reproductive demand.

7 Case Studies: Effects of Different Straw Returning Practices on Soil Improvement in Legume Systems

7.1 Case study of maize straw returning for improving soil quality in soybean fields

In soybean-centered systems, maize straw return improves soil quality mainly by increasing organic inputs, stabilizing aggregates, and stimulating biological activity. In a maize-soybean intercropping study, straw return increased water-stable aggregates under both crops, and the combined treatment of intercropping plus straw return produced the strongest overall efficiency gains, indicating that maize residue can enhance the physical basis of soil quality in the soybean root zone. The same system also showed markedly higher rhizosphere microbial biomass carbon and enzyme activities under straw return, with MBC rising by 59.10% and urease, sucrase, catalase, and acid phosphatase all increasing, which supports a concurrent improvement in biological fertility around soybean roots.

The agronomic effect depends on how maize straw is returned. Across rotation studies, straw incorporation combined with suitable tillage increased soil organic C, total N, and available nutrients in deeper layers while reducing bulk density and improving water retention, which helps explain why soybean fields often benefit most when maize residues are incorporated rather than left unmanaged. In Mollisols, the strongest gains in soil quality index and crop yield occurred under inversion tillage plus straw return, and the physical soil property index contributed more to yield than chemical or microbial indices, suggesting that in soybean fields the main benefit of maize straw return may begin with restoration of soil structure and pore conditions.

7.2 Case study of wheat straw returning regulating soil ecological processes in faba bean fields

Wheat straw return regulates soil ecological processes in legume rotations by changing nitrogen-cycling microbiota, residue decomposition conditions, and pathogen balance. In a 3-year wheat-soybean rotation, wheat straw return increased soil total N and enriched nitrogen-cycling bacterial genera such as Bradyrhizobium and Rhizobium, showing that returned wheat residue can promote a rhizosphere environment more favorable to biologically mediated N turnover before or during the soybean phase (Yang et al., 2019). More broadly, straw return is reported to maintain soil moisture, moderate the soil microenvironment, and support fungal diversity, bacterial activity, and functional genes involved in N fixation, nitrification, denitrification, and P and K mineralization, which are the core ecological processes likely to matter in faba bean fields as well (Ninkuu et al., 2025).

The ecological outcome is not uniformly positive, and this is the main caution for wheat-straw management in legumes. Some rotation studies found that straw return lowered the relative abundance of several pathogenic fungal genera, suggesting that moderate return rates can improve ecological balance rather than simply amplify disease risk (Yang et al., 2019). Yet other evidence shows that wheat straw return can increase the abundance of pathogenic Fusarium in some seasons, while broader straw-return research warns that return rate and residue type strongly shape disease pressure, so wheat straw regulation in faba bean systems should be viewed as rate- and context-dependent rather than inherently beneficial.

7.3 Case study of long-term straw returning for enhancing sustainability of legume-based rotation systems

Long-term straw return enhances the sustainability of legume-based rotation systems by steadily improving soil carbon, nitrogen, and yield stability. In a wheat-maize-soybean rotation monitored over decades, straw incorporation increased soil humus, total N, and SOC in the 0-30 cm layer by 4.2%, 3.8%, and 11.3%, respectively, while grain yield rose by an average of 8.4 ± 4.5% with greater stability than under straw removal (Jaćimović et al., 2023). That rotation study concluded that long-term straw return combined with mineral fertilization is an economically viable and environmentally acceptable strategy, making it one of the clearest direct models for sustainable soil management in legume-based systems.

The broader long-term literature shows that sustainability depends on duration, nutrient balance, and return intensity. Meta-analysis indicates that SOC commonly increases under continuous straw return, with an average gain of 13.97%, but the strongest response is typically observed within about 6-9 years, after which benefits can plateau or weaken if management is not adjusted. Other long-term studies show that straw return coupled with optimized N fertilizer or decomposer inoculants can further improve aggregate stability, nutrient stoichiometry, carbon-nitrogen sequestration, and yield, whereas excessive residue inputs may cause transient nutrient immobilization or greater pathogenic risk, so the most sustainable legume-rotation strategy is a moderated, locally adapted straw-return program rather than maximum residue loading (Guo et al., 2024). Overall, these case studies show that straw return improves legume-system soils through structure building, nutrient cycling, and ecological regulation, but the best outcomes come from matching residue type, return method, duration, and fertilizer support to the specific legume rotation.

8 Constraints and Optimization Strategies for Straw Returning Application

8.1 Challenges associated with straw returning practices

One major constraint of straw returning is the mismatch between slow residue decomposition and the immediate nutrient demand of crops. Straw has a relatively high C:N ratio, so its decomposition often induces nitrogen limitation in soil microorganisms and intensifies competition for N between microbes and plants, especially during early growth. This problem is agronomically important because slow mineralization limits the in-season use of returned straw, and rapid forced decomposition can further reduce soil N effectiveness while increasing organic acids, CO_2, and phenolics that are unfavorable for seedlings. A second challenge is that straw return does not produce uniform outcomes across straw types, soils, climates, and management modes. The nutrient composition and mineral release pattern depend on straw species and whether residues are mulched or buried, making it difficult to develop a universal decomposition model or single best-return method for all systems (Ninkuu et al., 2025). This heterogeneity helps explain why straw return sometimes shows negative effects on nutrient availability or crop response, and why long-term locally specific testing is still needed before broad recommendations are made for legume regions.

Straw return can also increase ecological risk when it is poorly managed. Direct return without pretreatment can aggravate pest incidence because dormant pathogens and insect eggs may proliferate under favorable decomposition conditions, and this risk becomes more serious when large residue loads are left near the soil surface. Beyond biotic risk, straw return can create trade-offs with greenhouse gas emissions and nutrient loss, since it may improve SOC and yield while also increasing N_2O or CH_4 depending on crop and hydrological context. Finally, important methodological constraints still limit the precision of straw-return management. Current research still lacks enough quantitative tracking of nutrient release, transformation, and loss pathways during decomposition, even though these processes determine whether returned C, N, P, and K are retained, mineralized, or lost from the system. Several field studies also remain short in duration or narrow in scope, which makes it difficult to assess long-term interactions among straw return, soil biology, yield stability, and environmental losses under legume-based rotations (Liu et al., 2024).

8.2 Optimization strategies for straw returning technologies

The first optimization principle is to match return method to site conditions rather than treating all straw-return technologies as interchangeable. Meta-analysis shows that the yield and SOC effects of straw return vary strongly with tillage and fertilization combinations, with no-tillage plus balanced fertilization performing better in dry, erosion-sensitive areas and deep tillage plus balanced fertilization performing better in humid double-cropping regions (Islam et al., 2024). At the field scale, deep plowing and subsoiling combined with straw incorporation can also mitigate nitrogen competition, improve subsoil structure, and expand the effective rooting zone, which is particularly relevant where compaction limits legume root development. A second strategy is to optimize nitrogen coordination under straw return. Straw return and nitrogen application interact significantly, and moderate N reduction under continuous straw incorporation can maintain yield, enhance nitrogen use efficiency, and lower the effective threshold for fertilizer input. In long-term N-management work, deep-plowed straw return sustained soil fertility, yield, and NUE even with a 15-20% reduction in N input, showing that rational N optimization is more effective than simply increasing fertilizer to overcome immobilization (Figure 3).

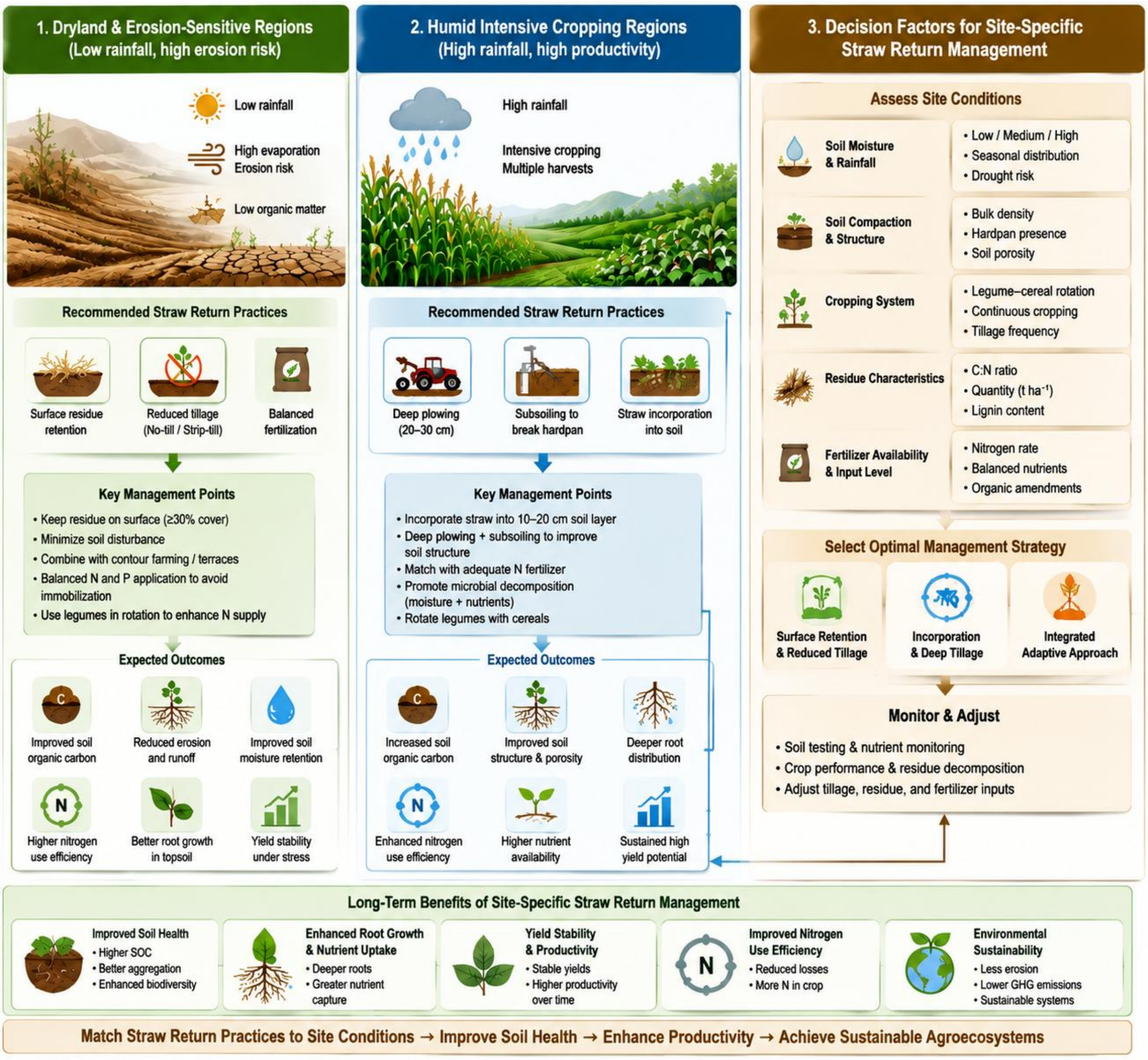

Figure 3 Site-specific optimization framework showing how straw-return strategies should be matched with regional soil and climate conditions. Different combinations of tillage practices, residue placement, and fertilization regimes determine the effectiveness of straw return in improving soil organic carbon, root development, and crop productivity

A third strategy is to improve straw quality or transformation before field return. Straw-derived biochar is often more effective than direct straw for nutrient retention because it increases soil carbon stock, cation exchange capacity, and nutrient adsorption while releasing nutrients more steadily over time. Periodic rather than annual biochar return also appears practical: one 7-year study found that applying straw-derived biochar every five years increased yield and SOC, reduced greenhouse gas intensity, and maintained economic returns in dryland agriculture (Chang et al., 2025). Optimization also includes timing, quantity, and duration. Meta-analysis suggests that the best management windows differ among crops, with recommended return durations of 5-10 years for maize and rice but shorter durations for wheat, indicating that benefits do not increase indefinitely with continuous residue input. Machine-learning analysis likewise found that nitrogen input was the strongest driver of yield response and that straw-return benefits stabilized after about 13 years, reinforcing the need for adaptive rather than fixed long-term management.

8.3 Integrated management approaches for sustainable agriculture

The most effective sustainable approach is to combine straw return with balanced fertilization rather than applying straw alone. In a 14-year field experiment, straw return plus chemical fertilizer increased labile carbon fractions, enzyme activities, and microbial diversity more strongly than either no input or straw alone, indicating that integrated nutrient support improves both decomposition and soil ecological functioning. Long-term rotation evidence from a wheat-maize-soybean system similarly showed that continuous straw return with adequate mineral N increased yield stability and improved humus, TN, and SOC, whereas straw return without N reduced yield. In legume-based systems, integration with legume cover crops is especially promising because it directly addresses the N limitation created by high-C residues. Straw return combined with legume cover crops increased both SOC and TN, whereas straw alone or straw with grasses tended to increase SOC while reducing TN to varying degrees. This approach appears particularly useful for sustainable agriculture because legume-assisted straw decomposition can reduce dependence on external N fertilizer while strengthening carbon and nitrogen accumulation in soil (Wang et al., 2025).

Integrated management should also extend beyond fertilizer to multi-amendment systems where soil constraints are severe. In saline farmland, combining straw, manure, and chemical fertilizer reduced pH, salinity, and alkalinity while increasing SOC, TN, available N, P, and K, and it also improved microbial community structure more than simpler amendment regimes. This kind of synergistic design matters because single-input strategies often show limited efficacy under stressed soils, whereas coupled amendments improve both abiotic and biotic regulation pathways (Duan et al., 2025). At the system level, sustainability depends on integrating straw return, tillage, fertilizer reduction, and crop rotation into a locally adapted package. In wheat-soybean rotation, straw retention with reduced fertilization improved aggregates, porosity, field water capacity, SOC storage, microbial biomass, total yield, profit, and emergy sustainability compared with both no-straw and conventional fertilization treatments. More broadly, integrated straw-return and tillage strategies produced the largest long-term gains in system productivity and sustainable yield index when residue management was coordinated across crops within the rotation rather than optimized for only one season. Overall, the main constraints on straw returning in legume fields are slow decomposition, N immobilization, ecological risk, and strong context dependence. The most effective optimization pathway is an integrated one that matches straw type, tillage, nitrogen management, legume inclusion, and amendment strategy to local soil and rotation conditions.

9 Conclusions and Future Perspectives

Straw return improves soil properties in legume systems first by increasing carbon inputs and stimulating the formation of active and stable organic matter pools. Across global agroecosystems, straw return increased soil organic C by 14.9%, while long-term incorporation in a wheat-maize-soybean rotation increased SOC, TN, and humus in the topsoil, showing that residue-derived carbon accumulation remains one of the most consistent outcomes of the practice. Mechanistically, this carbon gain is not only direct residue retention; long-term studies show that straw accelerates decomposition, increases enzyme activity, and supports the conversion of residue C into both plant-derived and microbial-derived SOC fractions, especially when nitrogen supply is adequate. A second mechanism is the strengthening of coupled nutrient and microbial cycling in the rhizosphere and bulk soil.

Straw return supplies C, N, P, and K substrates and tends to increase available N, P, and K, while microbial activity and extracellular enzymes accelerate the mineralization and transformation of these elements into more plant-available forms. In legume-linked systems, this process is further reinforced when straw is combined with biologically active partners such as legumes or intercropping, because legume-associated N inputs relieve microbial N limitation and increase microbial biomass, enzyme activity, and soil multifunctionality more effectively than straw alone.

Current research limitations are mainly system specificity, incomplete mechanism resolution, and uneven experimental timescales. Much of the direct evidence still comes from cereal-based systems or mixed rotations rather than dedicated legume monocultures, and several reviews explicitly note that responses differ strongly among soils, climates, crops, and management combinations, which limits how confidently broad conclusions can be transferred to all legume fields. Even in legume-relevant rotations such as wheat-soybean, field studies show that straw return alters microbial diversity and nitrogen-cycling taxa, but the overall community response remains moderate and context dependent, indicating that mechanistic understanding is still incomplete. Another major limitation is that benefits often coexist with trade-offs and operational constraints. Straw return can increase SOC and crop productivity, but global evidence shows that it can also raise NH3 emissions and upland N2O emissions, so carbon sequestration does not automatically imply improved whole-system environmental performance. In addition, implementation quality remains a practical bottleneck, because recent engineering reviews identify poor chopping quality, uneven residue distribution, and high energy consumption as major constraints to reliable field adoption of straw-return machinery.

Future research should move from documenting average effects to identifying optimized, legume-specific management pathways. Reviews consistently argue that the next step is to resolve how straw return alters N, P, and K transformations across different soils, climates, and crops, especially under combined tillage and fertilization strategies rather than straw addition in isolation. Regionally adapted optimization is likely to be essential, because machine-learning and meta-analytic work shows that nitrogen input is the strongest driver of yield response and that the benefits of straw return stabilize over time rather than increasing indefinitely. A second priority is to design integrated residue systems that better match the biological characteristics of legumes. Combining straw with legumes or green manures appears especially promising because mixed residue inputs improve SOC sequestration efficiency, reduce microbial N limitation, and strengthen microbial carbon-pump pathways compared with straw alone. For legume systems specifically, future experiments should therefore compare straw type, return depth, residue proportion, inoculation, cover-crop pairing, and machinery quality within long-term rotations, so that recommendations can target sustainable soil improvement without increasing pathogen pressure, gaseous N losses, or short-term nutrient immobilization. Overall, straw return improves soil properties in legume systems through carbon accumulation, nutrient recycling, and microbial regulation, but its full value depends on better mechanistic resolution and more precise field management. Future progress will come from long-term, legume-centered experiments that integrate biology, environment, and machinery into one management framework.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Chang F., Yue S., Li S., Wang H., Chen Y., Yang W., Wu B., Sun H., Wang S., Yin L., and Deng X., 2025, Periodic straw-derived biochar improves crop yield, sequesters carbon, and mitigates emissions, European Journal of Agronomy, 164: 127516.
https://doi.org/10.1016/j.eja.2025.127516

Chen L., Sun S., Yao B., Peng Y., Gao C., Qin T., Zhou Y., Sun C., and Quan W., 2022, Effects of straw return and straw biochar on soil properties and crop growth: a review, Frontiers in Plant Science, 13: 986763.
https://doi.org/10.3389/fpls.2022.986763

Duan F., Peng P., Yang K., Shu Y., and Wang J., 2023, Straw return of maize and soybean enhances soil biological nitrogen fixation by altering the N-cycling microbial community, Applied Soil Ecology, 192: 105094.
https://doi.org/10.1016/j.apsoil.2023.105094

Duan H., Gao R., Liu X., Zhang L., Wang Y., Jia X., Wang X., Zheng S., and Jing Y., 2025, The coupling of straw, manure and chemical fertilizer improved soil salinity management and microbial communities for saline farmland in Hetao Irrigation District, China, Journal of Environmental Management, 380: 124917.
https://doi.org/10.1016/j.jenvman.2025.124917

Getahun G.T., Kätterer T., Munkholm L.J., Rychel K., and Kirchmann H., 2022, Effects of loosening combined with straw incorporation into the upper subsoil on soil properties and crop yield in a three-year field experiment, Soil and Tillage Research, 223: 105466.
https://doi.org/10.1016/j.still.2022.105466

Guan C., Ma T., Miao M., Chen J., Bao Z., Chen B., Lu J., Liu F., Wang N., Wang H., and Zhang Z., 2025, Physiological mechanisms underlying maize yield enhancement by straw return in the thin-layer mollisol region of the Songnen Plain, Plants, 14(21): 3331.
https://doi.org/10.3390/plants14213331

Guan Y., Wu M., Che S., Yuan S., Yang X., Li S., Tian P., Wu L., Yang M., and Wu Z., 2023, Effects of Continuous Straw Returning on Soil Functional Microorganisms and Microbial Communities, Journal of Microbiology, 61(1): 49-62.
https://doi.org/10.1007/s12275-022-00004-6

Guo Y., Zhang Z., Liang F., Cao W., Wang Y., Chen J., and Guo J., 2025, Meta-analysis reveals that returning crop straw to arable land causes soil acidification at the global scale, European Journal of Agronomy, 164: 127511.
https://doi.org/10.1016/j.eja.2025.127511

Guo Z., Liu Y., Meng X., Yang X., Chai H., Li H., Ding R., Nazarov K., Zhang X., and Han Q., 2024, The long-term nitrogen fertilizer management strategy based on straw return can improve the productivity of wheat-maize rotation system and reduce carbon emissions by increasing soil carbon and nitrogen sequestration, Field Crops Research, 317: 109561.
https://doi.org/10.1016/j.fcr.2024.109561

Huang C., Huang H., Huang S., Li W., Zhang K., Chen Y., Yang L., Luo L., and Deng L., 2024, Effects of straw returning on soil aggregates and its organic carbon and nitrogen retention under different mechanized tillage modes in typical hilly regions of Southwest China, Agronomy, 14(5): 928.
https://doi.org/10.3390/agronomy14050928

Islam M., Guo Z., Jiang F., and Peng X., 2022, Does straw return increase crop yield in the wheat-maize cropping system in China? A meta-analysis, Field Crops Research, 285: 108447.
https://doi.org/10.1016/j.fcr.2022.108447

Islam M., Jiang F., Halder M., Barman A., Liu S., and Peng X., 2024, Quantitative assessment of different straw management practices on soil organic carbon and crop yield in the Chinese upland soils: a data-driven approach based on simulation and prediction model, European Journal of Agronomy, 157: 127092.
https://doi.org/10.1016/j.eja.2024.127092

Jaćimović G., Aćin V., Mirosavljević M., Brbaklić L., Vujić S., Dunđerski D., and Šeremešić S., 2023, Effects of combined long-term straw return and nitrogen fertilization on wheat productivity and soil properties in the wheat-maize-soybean rotation system in the Pannonian Plain, Agronomy, 13(6): 1529.
https://doi.org/10.3390/agronomy13061529

Jia S., Li Y., Qu H., Li B., Juan Y., Xing Y., Liu Y., Bao H.-J., and Sun W., 2025, Straw retention drives microbial community succession to improve soil C/N cycling: insights from a multi-year rice-based system, Frontiers in Microbiology, 16: 1590788.
https://doi.org/10.3389/fmicb.2025.1590788

Jin W., Liu Z., Cheng Z., Wang Q., Hu W., Chen B., Meng Y., and Zhou Z., 2024, The trade-off between root growth redundancy and premature senescence under different straw returning modes affects boll formation and seedcotton yield, European Journal of Agronomy, 156: 127175.
https://doi.org/10.1016/j.eja.2024.127175

Klippenstein S., Khazaei H., Vandenberg A., and Schoenau J., 2021, Nitrogen and phosphorus uptake and nitrogen fixation estimation of faba bean (*Vicia faba* L.) in Western Canada, Agronomy Journal, 114(1): 811-824.
https://doi.org/10.1002/agj2.20945

Li H., Li J., Jiao X., Jiang H., Liu Y., Wang X., and Chen C., 2024, The fate and challenges of the main nutrients in returned straw: a basic review, Agronomy, 14(4): 698.
https://doi.org/10.3390/agronomy14040698

Lian H., Wang Z., Li Y., Xu H., Zhang H., Gong X., Qi H., and Jiang Y., 2022, Straw strip return increases soil organic carbon sequestration by optimizing organic and humus carbon in aggregates of Mollisols in Northeast China, Agronomy, 12(4): 784.
https://doi.org/10.3390/agronomy12040784

Liu R., Borjigin Q., Gao J.L., Yu X.F., Hu S.P., and Li R.P., 2024, Effects of different straw return methods on soil properties and yield potential of maize, Scientific Reports, 14(1): 28682.
https://doi.org/10.1038/s41598-024-70404-8

Meng X., Zhang X., Li Y., Jiao Y., Fan L., Jiang Y., Qu C., Filimonenko E., Jiang Y., Tian X., Shi J.L., and Kuzyakov Y., 2023, Nitrogen fertilizer builds soil organic carbon under straw return mainly via microbial necromass formation, Soil Biology and Biochemistry, 188: 109223.
https://doi.org/10.1016/j.soilbio.2023.109223

Ninkuu V., Liu Z., Qin A.-G., Xie Y., Song X., and Sun X., 2025, Impact of straw returning on soil ecology and crop yield: a review, Heliyon, 11(2): e41651.
https://doi.org/10.1016/j.heliyon.2025.e41651

Siczek A., Becher M., Kalembasa S., and Kalembasa D., 2026, The uptake of nitrogen biologically fixed by faba bean by cereals grown as succeeding crops, European Journal of Agronomy, 174: 127952.
https://doi.org/10.1016/j.eja.2025.127952

Somchanh S., Li Y., Yang L., Wei R., Zhang Y., Liu B., Jiang Q., and Yang Q., 2026, Keystone roles of carbon-degrading enzyme activities in mediating carbon in soils subjected to straw return: a global meta-analysis, Frontiers in Microbiology, 17: 1739110.
https://doi.org/10.3389/fmicb.2026.1739110

Song Y., Gao M., and Li Z., 2025, Impacts of straw return methods on crop yield, soil organic matter, and salinity in saline-alkali land in North China, Field Crops Research, 322: 109752.
https://doi.org/10.1016/j.fcr.2025.109752

Su Y., Yu M., Xi H., Lv J., Zhou Z., Kou C., and Shen A., 2020, Soil microbial community shifts with long-term of different straw return in wheat-corn rotation system, Scientific Reports, 10(1): 6360.
https://doi.org/10.1038/s41598-020-63409-6

Tian P., Sui P., Lian H., Wang Z., Meng G., Sun Y., Wang Y., Su Y., Qi H., and Jiang Y., 2019, Maize straw returning approaches affected straw decomposition and soil carbon and nitrogen storage in Northeast China, Agronomy, 9(12): 818.
https://doi.org/10.3390/agronomy9120818

Wang J., Sun C., Zhang Y., Xiao J., Jiang Y., Jiang J., and Zhang L., 2024, Straw return rearranges soil pore structure improving soil moisture memory in a maize field experiment under rainfed conditions, Agricultural Water Management, 306: 109164.
https://doi.org/10.1016/j.agwat.2024.109164

Wang M., Liu C., Zhang Y., Yan F., Liao Z., and Wang E., 2025, Straw returning in cooperation with legume-based cover crops: a potential path to promote both soil organic carbon and total nitrogen, Land Degradation & Development, 37(3): 811-825.
https://doi.org/10.1002/ldr.70143

Xing S., Zhang G., Zhang N., Zhang Y., and Zhang Y., 2025, Effects of straw returning methods on seasonal variation in soil moisture and water storage in Mollisols with different degradation degrees, Agricultural Water Management, 319: 109796.
https://doi.org/10.1016/j.agwat.2025.109796

Xu J., Song F., Wang Z., Qi Z., Liu M., Guan S., Sun J., Li S., and Zhao J., 2024, Effects of different straw return methods on the soil structure, organic carbon content and maize yield of black soil farmland, Agronomy, 14(9): 2011.
https://doi.org/10.3390/agronomy14092011

Yang H., Rong Z., Zeng D., Wang Y., Hu S., Ye W., and Zheng X., 2019, Wheat straw return influences nitrogen-cycling and pathogen associated soil microbiota in a wheat-soybean rotation system, Frontiers in Microbiology, 10: 1811.
https://doi.org/10.3389/fmicb.2019.01811

Yang L., Muhammad I., Chi Y., Wang D., and Zhou X., 2022, Straw return and nitrogen fertilization to maize regulate soil properties, microbial community, and enzyme activities under a dual cropping system, Frontiers in Microbiology, 13: 823963.
https://doi.org/10.3389/fmicb.2022.823963

Yang Y., Xu N., Zhang Z., Lei C., Chen B.A., Qin G., Qiu D., Lu T., and Qian H., 2024, Deciphering microbial community and nitrogen fixation in the legume rhizosphere, Journal of Agricultural and Food Chemistry, 72(11): 5659-5670.
https://doi.org/10.1021/acs.jafc.3c09160

Zhang S., Ren T., Yang X., Zhou X., Li X., Cong R., and Lu J., 2023, Biochar return in the rice season and straw mulching in the oilseed rape season achieve high nitrogen fertilizer use efficiency and low greenhouse gas emissions in paddy-upland rotations, European Journal of Agronomy, 148: 126869.
https://doi.org/10.1016/j.eja.2023.126869

Zhao H., Lu Z., Cheng M., Wei S., Fang J., Cao W., Shi H., Zhang W., Zhang X., Qu Y., Liu L., Zhang D., and Zhao X., 2025, How straw returning impacts microbial-interaction-network-mediated improvements in soil multifunctionality, Frontiers in Microbiology, 16: 1710232.
https://doi.org/10.3389/fmicb.2025.1710232