CJES
Caspian Journal of Environmental Sciences
Online ISSN: 1735-3866
Print ISSN: 1735-3033

Interrelationship between soil quality and biodiversity: Implications for environmental sustainability

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ABSTRACT

Sustainable farming systems like Conservation Agriculture, regenerative farming, and organic farming offer alternatives to conventional practices that negatively impact soils and biodiversity. A review of 26 articles analyzing soil-biodiversity relationships under these systems identified key patterns. Sustainable practices improved soil physical properties (stable aggregates +38-47%, sediment loss reduced 20-fold), soil organic carbon (up to +8.4 g kg^{-1}), and microbial biomass (up to +293%). Three patterns emerged: "Win-Win-Win" in perennial systems, "Trade-off" systems like organic vineyards (increased biodiversity, -16% yields), and "Context-specific" systems dependent on local conditions. Microbial responses included compositional changes and richness increases. However, most studies are short-term, neglect transition costs (potentially 10-15% yield loss), and overlook biotic interactions. While sustainable practices can positively impact soil and biodiversity, achieving this "golden triangle" depends on crop type, initial soil conditions, and socio-economic factors. Scaling up faces challenges without policies to offset transition costs.

Keywords: Soil quality, Biodiversity, Conservation agriculture, Regenerative farming, Trade-offs, Critical analysis, Ecosystem services, Sustainability.
Article type: Review Article.

INTRODUCTION

Soil degradation is a critical 21st-century challenge impacting food security, ecosystem services, and climate change. Intensive agriculture, including tilling, excessive synthetic fertilizer and pesticide use, monoculture, and inadequate crop residue management, accelerates soil degradation by reducing soil organic matter, stability, and nutrient cycling (Usharani *et al.* 2019; Bonfante *et al.* 2020; Franzluebbers 2022). This leads to erosion, compaction, crusting, hardpan formation, reduced infiltration, and increased drought risk, exacerbated by climate change (Ennaji W 2018; Bonfante *et al.* 2020). Furthermore, the loss of soil biodiversity across trophic levels impairs essential ecosystem services (Zhou 2019; Guarderas *et al.* 2022; Teng *et al.* 2024). Sustainable intensification methods are increasingly being studied as a way to counteract or reverse soil degradation. Alternatives like conservation tillage, regenerative agriculture, organic production, legume-based systems, cover cropping, prairie strips, and low-input biofertilizers aim to restore soil health without yield loss (Fenster *et al.* 2021; Saurabh 2021; Kumar *et al.* 2023). These methods typically minimize soil disturbance, maintain soil cover, diversify crop rotations, retain organic residues, and promote biological processes (Salomé 2016; Franzluebbers 2022). Studies show improved soil physical properties under these systems. For example, zero tillage with residue retention can improve macro-aggregate stability by up to 47%, increase available water capacity, and reduce bulk density (Saurabh 2021). Regenerative management of perennial crops has increased water-stable aggregates by 38%, reduced bulk density, and significantly increased infiltration rates (Fenster *et al.* 2021; Torrús-Castillo 2026). Prairie strips can reduce runoff by 1.6 times and sediment loss by 20 times (Schulte *et al.* 2017), and permanent cover in vineyards improves bulk density and field capacity (Salomé 2016). These improvements are mainly attributed to increased organic matter, reduced disturbance, and enhanced biological activity, leading to greater aggregate stability. Regenerative and conservation agriculture (CA) practices rapidly increase microbial biomass and activity. Studies show significant increases in microbial biomass carbon and nitrogen (up to 213-293%), dehydrogenase activity (210%), and acid phosphatase activity (49%) with targeted CA practices (Choudhary *et al.* 2018). Regenerative olive practices increased basal respiration, average well color development (AWCD), functional diversity, and arbuscular mycorrhizal fungi (AMF) biomass (Torrús-Castillo 2026), while biodynamic practices maintained higher microbial respiration and AMF biomass even during simulated drought (Kundel *et al.* 2020). Macrofauna, such as earthworms, accelerate litter decomposition by 14-15%, enhancing nutrient release (Pant 2017), and cover crop traits influence microbial nutrient acquisition and enzyme activities (Zhang 2022). These biological shifts drive enhanced nutrient turnover, aggregate formation, and stress resistance (Chamorro-Martínez 2022). Biodiversity responses are also evident at higher trophic levels. Prairie strips significantly increased native plant species richness (7.8-fold), insect species (2.6-fold), and avian diversity (approximately 2-fold; Schulte et al. 2017). Full CA systems boosted earthworm density to 1,024 m^{-3} compared to 343 m^{-3} in conventional systems (Kumar et al. 2023). Forest land use types exhibited greater macrofauna genus richness (22 vs. 8 in monocultures/pastures) with predator-dominated communities (Guarderas et al. 2022). Acquisitive cover crops and permanent plant covers also increased nematode abundance and trophic diversity. The strong correlation between mesofauna and organic matter ($r = 0.87$) highlights the crucial role of organic matter in supporting faunal communities (Chamorro-Martínez 2022). Shifts in microbial community composition also occur. Conservation agriculture (CA) scenarios increased Proteobacteria and Actinobacteria while decreasing Firmicutes, alongside higher Shannon and Chao1 indices. Organic cocoa management, particularly agroforestry, enhanced bacterial and fungal richness with distinct indicator taxa (Lori *et al.* 2022; Kumar *et al.* 2023). Regenerative shifts increased microbial and AMF biomass, correlating with soil organic matter (SOM) and aggregate stability. Organic vineyards improved β-glucosidase activity and multitrophic diversity. These compositional changes are linked to soil chemistry and management intensity (Beaumelle 2023; Kumar *et al.* 2023; Lekberg 2024). These changes enhance ecosystem services. Prairie strips achieved substantial sediment retention (20-fold), reduced phosphorus loss (4.3-fold), and improved habitat (Schulte *et al.* 2017). Regenerative olive systems increased regulating services by 165% and cultural services threefold (Torrús-Castillo 2026). Organic practices enhanced pest predation (+93%) without fertility decline. Full CA attained the highest soil quality index (0.55) and strong carbon sequestration potential. Macrofauna-mediated decomposition minimized nutrient losses (Beaumelle 2023; Kumar *et al.* 2023). Production and economic outcomes are context-dependent. Zero-tillage with residue maximized rice yields, positively correlated with the soil quality index ($R^2 \approx 0.47$; Saurabh 2021). Regenerative almond orchards doubled profitability despite similar yields (Fenster *et al.* 2021). Organic vineyards had a 16% yield reduction but better pest control and no biodiversity–production trade-off (Beaumelle 2023). Prairie strips slightly reduced catchment revenue but provided significant environmental benefits (Schulte *et al.* 2017). Legume rotations and CA sustained high nutrient-use efficiency and resilience, despite initial challenges (Singh 2020; Abbasi 2025). Sustainable agriculture, when appropriately planned, enhances soil quality, biodiversity, and ecosystem services while sustaining agricultural productivity, as evidenced by research across diverse agro-ecosystems. However, promoting it requires addressing trade-offs, knowledge gaps, policy issues, and transition risks. This review of 26 primary studies describes the mechanisms underlying sustainable agriculture, quantifies its impacts, and explores opportunities to improve agricultural system resilience and biodiversity.

MATERIALS AND METHODS

We searched Web of Science, Scopus, and Google Scholar for studies published between 2025 and 2026. Our search combined terms related to soil quality (soil health, soil organic matter, aggregate stability, microbial biomass), biodiversity (soil biodiversity, microbial diversity, macrofauna, trophic levels), and sustainable agricultural practices (conservation agriculture, regenerative farming, organic farming, cover crops, prairie strips, bio-inputs). The initial search yielded 847 records, which were screened by title and abstract. We included original, peer-reviewed field studies with at least two years of data that simultaneously measured at least one soil quality and one biodiversity indicator, clearly compared a sustainable practice to a conventional baseline, and were available in full-text English. Reviews, meta-analyses, conference abstracts, and laboratory incubations were excluded. After full-text assessment, 26 studies met all criteria and were selected for review. This review extracted data on study location, duration, agroecological context, sustainable practice type, and various indicators (soil physical, chemical, and biological; biodiversity across trophic levels; yield; economic; and ecosystem services). It also captured reported mechanisms and trade-offs. Due to heterogeneity in indicators, methodologies, and reporting, a thematic synthesis was used instead of meta-analysis. This approach focused on identifying recurrent outcomes (e.g., divergent microbial responses, distinct economic trajectories), trade-offs, and critical gaps (limitations, missing data, understudied variables). Context dependency was mapped by examining how soil type, climate, crop system, and socio-economic factors influenced outcomes. The goal was to understand the conditions under which sustainable practices achieve desired outcomes and their associated costs, rather than simply reporting successful practices.

Improvements in soil physical properties

Many sustainable agricultural practices enhance soil structure and water dynamics, though the magnitude of improvement is highly context-dependent. Conservation agriculture (CA) systems, including zero tillage with residue retention, increased macro-aggregate stability by up to 47% and available water capacity compared with conventional tillage (Saurabh 2021). In regenerative olive and almond orchards, water-stable aggregates rose by 38%, bulk density was reduced (e.g., from 1.33 to 1.16 g cm^{-3} in almond systems), and infiltration rates increased more than sixfold (Fenster *et al.* 2021; Torrús-Castillo 2026). Prairie strips integrated into row-crop landscapes reduced runoff by 1.6 times and sediment loss by 20 times (Schulte et al. 2017). However, these improvements are not universal: permanent plant covers in vineyards showed stronger effects in non-calcareous soils, while calcareous soils exhibited muted responses (Salomé 2016). This soil-type dependency suggests that physical improvements require context-specific targeting rather than uniform application. Additionally, most studies report short-term gains (<10 years); long-term trajectory and potential plateauing of physical improvements remain underexplored (Lekberg 2024). The primary mechanisms—increased organic matter inputs and reduced soil disturbance—are well-established, but their relative contribution varies by system.

Enhancements in soil chemical and nutrient status

While organic amendments and diversified rotations often improve chemical fertility indicators, the extent varies. For example, a Punjab organic farm saw a 50% soil organic matter increase (Abbasi 2025), likely due to initially poor soil. CA-based systems reached 8.4 g kg^{-1} organic carbon (Choudhary *et al.* 2018), and legume rotations achieved a soil quality index of 0.844 (Singh SR 2020); however, soil quality indices are difficult to compare across studies (Hannam 2025). Regenerative systems improved multiple nutrient levels and reduced aluminum (Fenster *et al.* 2021; Lori *et al.* 2022), with organic fertilization effects differing by soil type (Salomé 2016). Fermented plant juices mainly aided microbial solubilization rather than direct nutrient provision (Sulok et al. 2021). A key question remains: Do these chemical improvements negate the need for external fertilizers, or are they merely supplementary?

Advances in soil biological indicators

Regenerative and conservation agriculture (CA) practices enhance biological activity, but literature reveals two response patterns: some systems exhibit substantial increases in microbial biomass carbon and nitrogen (up to 213–293%) and enzyme activities (DHA +210%, APA +49%), along with elevated basal respiration, AWCD, and functional diversity. Other studies report compositional shifts without richness increases, indicating biomass-independent microbial community restructuring. Biodynamic wheat soils demonstrate higher basal respiration and AMF abundance, even under simulated drought, suggesting resilience benefits. Macrofauna exclusion experiments show earthworms accelerate litter decomposition by 14–15 percentage points, but macrofauna-microbe interactions remain unclear. Cover crop strategies modulate microbial nutrient limitations and enzyme activities, demonstrating plant functional trait-mediated biological responses. A key knowledge gap remains: the impact of microbial compositional changes on higher trophic levels lacks network analysis.

Effects on soil biodiversity and macrofauna

The benefits from sustainable practices are often substantial but vary across species and contexts. For example, native prairie strips significantly boosted native plant richness (7.8-fold), insect taxa (2.6-fold), and bird diversity (approximately 2-fold). Conservation agriculture systems show increased earthworm densities compared to conventional systems (1,024 m^{-3} vs. 343 m^{-3}). Forest land also exhibits greater macrofauna genus richness compared to monocultures or pastures (22 vs. 8). However, organic vineyards demonstrate that biodiversity responses are not uniform, with some groups increasing (spiders, foliage arthropods) while others decrease (earthworms, beetles). Cover crops and permanent plant covers enhance nematode abundance and trophic group diversity. The strong positive correlation between soil fauna and organic matter ($r = 0.87$ for mesofauna) highlights the importance of organic inputs, although the causal relationship remains unclear.

Impacts on microbial community composition and diversity

Sustainable management shifts microbial communities toward beneficial taxa, but patterns vary. In CA scenarios, bacterial Shannon and Chao1 diversity increased, with Proteobacteria and Actinobacteria enriched and Firmicutes reduced. Organic cocoa systems, particularly agroforestry, exhibited higher bacterial richness/Shannon diversity and fungal richness, with indicator taxa like Nitrospirales and Pedomicrobium. Regenerative management altered bacterial and fungal composition without significant richness changes, while increasing microbial and AMF biomass correlated with SOM and aggregate stability (Lori *et al.* 2022; Kumar *et al.* 2023; Lekberg 2024). This suggests functional redundancy may allow compositional shifts without diversity loss. Organic vineyards enhanced glucosidase activity and litter stabilization, supporting greater multitrophic diversity (Beaumelle 2023). Critically, whether these taxonomic shifts enhance ecosystem functions requires further demonstration.

Ecosystem services and environmental benefits

Multiple ecosystem services frequently improve simultaneously, though quantification methods vary widely. Prairie strips achieved 20-fold sediment reduction, 4.3-fold lower P loss, improved water quality, and support for pollinators and birds. Regenerative olive groves scored much higher in regulating services (45 vs. 17 points), with 165% greater overall ecosystem service delivery and tripled cultural services. However, these scores are semi-quantitative and may not reflect absolute biophysical flows. Organic systems boosted pest predation (e.g., 93% higher on model caterpillars) and litter stabilization without compromising soil fertility (*Schulte et al.* 2017; Beaumelle 2023; Torrús-Castillo 2026). Full CA systems attained the highest soil quality index (0.55) and strong carbon sequestration potential. Trade-off consideration: While sediment reduction and water quality benefits are well-documented, their economic valuation is rarely integrated into farm-level decision-making (Schulte *et al.* 2017; Kumar *et al.* 2023).

Yield, economic performance, and sustainability trade-offs

Production outcomes reveal three distinct patterns that challenge one-size-fits-all recommendations:

Table 1. Three Distinct Patterns of Production and Economic Outcomes Across Sustainable Practices.

Pattern	Example	Soil Quality	Biodiversity	Yield	Profit	Key Condition
Win-Win-Win	Regenerative almond (Ref 11)	↑↑	↑↑	↔	↑↑	Perennial, value-added markets
Trade-off	Organic vineyard (Ref 7)	↑	↑	↓16%	?	Annual, premium market absent
Context-specific	Prairie strips (Ref 21)	↑↑	↑↑	↔ field; ↓ catchment	↓ catchment	Landscape position matters

Studies showed that zero-tillage with residue retention maximized rice-equivalent yield and positively correlated with soil quality ($R^2 \approx 0.47$; Saurabh 2021). Regenerative almond orchards maintained yields (Table 1) while doubling profitability via value-added products and cost reductions. Organic vineyards had 16% lower yields but better pest control, without a clear biodiversity–production trade-off (Fenster *et al.* 2021; Beaumelle 2023). Prairie strips led to a small revenue decrease (~\$88–124 ha^{-1}) but significantly improved water quality and habitat, benefiting ~40% of Iowa's erosion-prone cropland (Schulte *et al.* 2017). A key gap is the limited quantification of transition costs—initial 10–15% yield declines and 3–5 year adaptation—reported in only two studies (Schulte *et* *al.* 2017; Abbasi 2025). This poses adoption risks for smallholders without supportive policies. Furthermore, profitability often excludes unpaid family labor and ecosystem service valuation, potentially inflating returns.

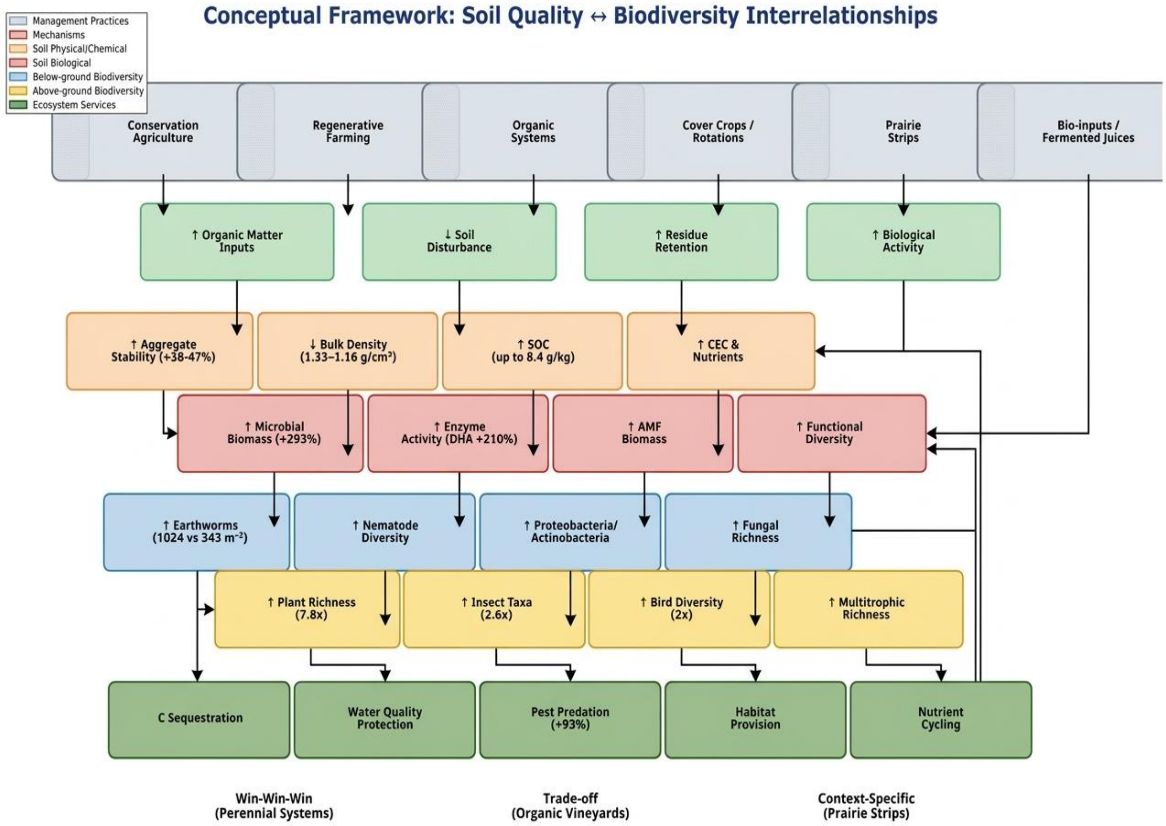

Fig. 1. Mechanistic pathways and three outcome patterns in sustainable agriculture.

Tables 2. Summary table of key soil health outcomes across practices.

Practice Category	Soil Physical Gains	Chemical Fertility	Biological Activity	Biodiversity Response	Yield/ Economic	Ecosystem Services	Main Supporting Refs
CA / Zero Tillage + Residue	↑ Macro-aggregate stability up to 47%, ↑ AWC, ↓ Bulk density (in rice-wheat)	↑ SOC (up to 8.4 g kg^{-1}), ↑ available N/P/K/Mn/Zn/Cu (full CA scenarios)	↑ MBC up to +293%, ↑ enzymes (DHA +210%, APA +49%, FDA hydrolysis 1.4–1.6×), ↑ bacterial diversity indices	↑ Earthworm density (~1024 vs 343 m^{-3}), ↑ bacteria/fungi/actinomycetes, ↑ Proteobacteria & Actinobacteria	Highest system rice equivalent yield (SREY) under ZT + good residue	Highest SQI (0.55), ↑ carbon sequestration potential	(Choudhary *et al.* 2018; Kumar *et al.* 2023; Schulte *et al.* 2017)
Regenerative / Organic	↑ WSA +38%, ↓ Bulk density (e.g. 1.33→1.16 g/cm³ in almond), ↑ infiltration (e.g. >6× in almond), ↑ water content	↑ OM/SOM (up to +50% in Punjab organic, up to 7.3% in olive, 3.88% vs 2.39% in almond), ↑ CEC, nutrients (P, Ca, S, etc.), ↓ Al	↑ Microbial biomass/respiration/AUCAWCD, ↑ AMF biomass, ↑ functional diversity, ↑ enzyme activities (e.g. glucosidase)	↑ Multitrophic richness, ↑ plant species/cover, ↑ invertebrate biomass/diversity, ↑ microbial richness (bacterial/fungal in cocoa/organic), mixed macrofauna	Similar yields (olive, almond), ↓16% yield (vineyard), ↑ profitability (~2× in almond, +187% net income in olive)	↑ Regulating services +165%, cultural ×3, supporting +82%, ↑ pest predation +93%, ↑ C sequestration	(Abbasi 2025; Beaumelle 2023; Fenster *et al.* 2021; Lekberg 2024; Lori *et al.* 2022; Torrús-Castillo 2026)

Prairie Strips	↓ Runoff 1.6×, ↓ sediment loss 20×	↓ N loss 3.3× (surface), ↓ nitrate 3.6× (groundwater), ↓ total P 4.3×	Not directly measured	↑ Native plant cover & richness 13× & 7.8×, ↑ insect taxa 2.6× (incl. pollinators & natural enemies), ↑ bird richness/abundance ~2–2.6×	No change in cropped-area yield; catchment net revenue ↓ (~$88–124/ha)	Major water quality improvement, habitat for wildlife & pollinators	(Schulte *et al.* 2017)
Plant Covers / Rotations	↑ Water retention/field capacity, ↓ Bulk density (in some vineyard groups)	↑ CEC, ↓ C/N ratio, ↑ SOC & MBC with permanent cover	↑ MBC & MBC/SOC (longer plant cover), ↑ nematode density & ecological indices	↑ Nematode abundance & trophic groups (acquisitive cover), strong nematode food web response	Stable yields (vineyard context)	Improved nutrient cycling, biological activity	(Salomé 2016; Zhang 2022)
Fermented Juices / Bio-inputs	Not directly measured / Indirect structure	Low macro-/micro-nutrients; microbial solubilization of P & K	17 beneficial microbes (Bacillus, Lactobacillus, Aspergillus dominant); 9 isolates solubilize P & K	Indirect microbial enhancement	Not measured (focus on potential)	Potential ↑ nutrient cycling, N fixation, pathogen suppression, soil biodiversity	(Sulok *et al.* 2021)

Table 3. Integrated analysis of how sustainable practices enhance soil-biodiversity interrelationships.

Practice Category	**Primary Mechanism (s) Linking Soil Quality ↔ Biodiversity**	**Key Soil Quality Gains (Selected Indicators)**	**Key Biodiversity Gains (Selected Taxa/Groups)**	**Main Ecosystem Services Enhanced**	**Notable Trade-offs / Context Dependency**	**Supporting Refs.**
CA / Zero Tillage + Residue	↑ SOM → ↑ aggregate stability → ↑ microbial habitat + food	↑ SOC to 8.4 g kg^{-1}, ↑ MBC up to +293 %, ↑ macro-aggregates +47 %	↑ Earthworms (~1024 vs 343 m^{-3}), ↑ Proteobacteria & Actinobacteria	↑ C sequestration, ↑ nutrient cycling, ↓ erosion/runoff	Initial adaptation period; best in cereal systems	(Choudhary *et al.* 2018; Kumar *et al.* 2023; Saurabh 2021)
Regenerative / Organic	↑ Ground cover & OM → ↑ microbial biomass & AMF → ↑ faunal habitat	↑ SOM up to +50 %, ↑ CEC, ↑ WSA +38 %, ↓ bulk density	↑ Multitrophic richness, ↑ AMF, ↑ plant/invertebrate diversity	↑ Regulating +165 %, ↑ pest predation +93 %, ↑ cultural ×3	Yield penalty in some systems (e.g. –16 % vineyard)	(Abbasi 2025; Beaumelle 2023; Fenster *et al.* 2021; Lekberg 2024; Lori *et al.* 2022; Torrús-Castillo 2026)
Prairie Strips	Plant diversity → ↑ habitat heterogeneity → ↑ trophic support	↓ Runoff 1.6×, ↓ sediment 20×	↑ Plants 7.8×, ↑ insects 2.6×, ↑ birds ~2×	Water quality protection, habitat provision, pollination	Modest catchment revenue ↓ (~$88–124 ha^{-1})	(Schulte *et al.* 2017)
Plant Covers / Rotations	Root traits & residue → ↑ resource availability → ↑ fauna	↑ CEC, ↓ C/N, ↑ field capacity	↑ Nematode abundance & trophic groups, ↑ food-web complexity	Nutrient cycling, biological pest control	Soil-type modulation of response	(Salomé 2016; Zhang 2022)
Fermented Juices / Bio-inputs	Microbial inoculation → ↑ solubilization & antagonism	Indirect P/K availability via microbes	Indirect microbial community enhancement	Potential pathogen suppression, ↑ biological activity	Limited direct nutrient supply; supplementary role	(Sulok *et al.* 2021)

DISCUSSION AND CONCLUSION

This review of 26 studies demonstrates that targeted sustainable agricultural practices—including conservation agriculture, regenerative farming, organic management, legume-based rotations, cover crops, prairie strips, biodynamic approaches, and bio-inputs—effectively restore soil quality and enhance biodiversity across trophic levels (Tables 2-3). These improvements are mechanistically linked to organic matter accrual, reduced disturbance, increased residue, and enhanced biological activity, promoting ecosystem service delivery and resilience (Ennaji 2018; Firth 2020; Franzluebbers 2022; Chamorro-Martínez 2022; Abbasi 2025). Soil physical restoration is a consistent outcome, with zero tillage and residue retention significantly increasing macro-aggregate stability (up to 47%) and available water capacity, while lowering bulk density in rice-wheat systems. Regenerative perennial systems (olive, almond) increased water-stable aggregates by 38%, reduced bulk density (e.g., 1.33 → 1.16 g cm^{-3}), and greatly accelerated infiltration rates (Fenster *et al.* 2021; Saurabh K 2021; Torrús-Castillo 2026). Integrating prairie strips significantly reduces runoff (1.6-fold) and sediment loss (20-fold). Permanent vineyard cover crops improve field capacity and reduce bulk density, with soil-type-dependent effects (Salomé 2016; Fenster *et al.* 2021; Zhang 2022). These physical improvements stem from SOM-mediated aggregate stabilization, which reduces crusting, compaction, hardpan formation, and erosion risks common in conventional systems (Lekberg Y 2024). Chemical fertility also improves, though magnitudes vary. Organic transition in Punjab increased SOM by 50%, neutralized pH, and improved nutrient bioavailability (Abbasi 2025), likely due to degraded initial conditions. Conservation agriculture rice-wheat-mungbean systems increased SOC to 8.4 g kg^{-1} and enhanced N, P, and K availability (Choudhary *et al.* 2018). Legume rotations yielded the highest soil quality index (0.844) through increased SOC, WHC, and nutrients, although index comparisons are limited by methodological differences (Singh 2020; Hannam 2025). Regenerative almond and cocoa systems improved WEOM, total/inorganic P, Ca, S, CEC, and micronutrients while decreasing Al (Fenster *et al.* 2021, Lori *et al.* 2022). Organic fertilization narrowed C/N ratios and increased CEC and MBC/SOC ratios in vineyards, with soil-specific variations. Fermented juices indirectly support nutrient solubilization by microbes (Salomé 2016; Sulok *et al.* 2021). These improvements reflect organic carbon's role in nutrient storage, pH buffering, and CEC enhancement, mitigating nutrient depletion and acidification associated with intensive management (Usharani *et al.* 2019). Surges in biological activity drive ecosystem function, exhibiting two main patterns. Some systems show increased microbial biomass (213–293% C and N) and enzyme activity (DHA +210%, APA +49%) (Choudhary *et al.* 2018). Regenerative management can also elevate respiration, AWCD, functional diversity, and AMF biomass, even during drought (Kundel *et al.* 2020; Torrús-Castillo 2026). Conversely, other studies indicate compositional shifts without richness gains (Lekberg 2024), suggesting functional redundancy enables community restructuring independent of diversity. Macrofauna, like earthworms and invertebrates, accelerate litter decomposition (14–15%) and nutrient release. Cover-crop traits influence microbial nutrient limitation and enzyme profiles (Pant 2017; Zhang 2022). These biological responses correlate with SOM content, aggregate stability, and CEC, creating positive feedback that maintains nutrient cycling and soil structure (Chamorro-Martínez 2022; Lekberg 2024). Biodiversity generally increases across scales and trophic levels, though responses vary by taxon and are often non-linear. For example, prairie strips increased native plant richness 7.8-fold, insect taxa 2.6-fold, and bird diversity ~2-fold (Schulte *et al.* 2017). Full CA elevated earthworm density significantly (Kumar *et al.* 2023), while forests supported greater macrofauna richness (Guarderas *et al.* 2022). However, organic vineyards showed mixed results, with increased spiders but decreased beetles (Ref 7). Soil fauna–OM correlations ($r = 0.87$) confirm organic inputs as key drivers (Chamorro-Martínez 2022). Microbial communities also shift favorably, with CA enriching Proteobacteria/Actinobacteria, organic cocoa increasing fungal richness, and regenerative management raising AMF biomass, enhancing drought resilience (Lori *et al.* 2022; Kumar *et al.* 2023; Lekberg 2024; Kundel *et al.* 2020). The impact of these changes on ecosystem functions requires further study. Ecosystem services improve concurrently: prairie strips drastically reduce sediment and P loss (Schulte *et al.* 2017); regenerative olive systems increase regulating services substantially (Torrús-Castillo 2026); organic practices boost pest predation significantly (Beaumelle 2023); and full CA achieves a high SQI with strong C sequestration potential (Kumar *et al.* 2023). These improvements suggest a way to address the externalities of industrial agriculture (Franzluebbers 2022). Production outcomes show varied patterns. Zero-tillage maximized yield (Saurabh 2021). Regenerative almond doubled profit with comparable yields (Fenster *et al.* 2021). Organic vineyards experienced a yield loss for improved pest control (Beaumelle 2023). Prairie strips reduced catchment revenue but offered substantial environmental benefits (Schulte *et al.* 2017). Legume rotations initially faced a yield decline (Singh 2020; Abbasi 2025).

Key limitations. Include peak gains within 5–10 years or in low-SOM soils (Lekberg 2024), persistent yield penalties in some organic systems (Beaumelle 2023), and rarely quantified transition costs (Schulte *et al.* 2017; Abbasi 2025). Soil type and climate are also important factors (Salomé 2016; Ennaji 2018), and a network analysis of biotic interactions is lacking. In conclusion, these 26 studies show that well-implemented sustainable practices can restore degraded soil functions, conserve biodiversity, and enhance ecosystem services. However, this is not universally achievable and depends on crop type, initial soil conditions, socio-economic context, and prioritized outcomes. Combining multiple principles yields the strongest synergies. Scaling these approaches requires context-adapted strategies, participatory research, policy incentives, mechanisms to buffer transition costs, and continued quantification of long-term trajectories. With appropriate support, these shifts offer a pathway to resilient, multifunctional, and climate-smart agriculture, but only with honest communication and deliberate management of heterogeneous outcomes and trade-offs.

REFERENCES

Abbasi, NM 2025, Organic farming and soil health: strategies for long term agricultural sustainability. *Agricultural Innovation and Sustainability Journal*, 1: 25-32.

Beaumelle, L, Giffard, B, Tolle, P, Winter, S, Entling, MH, Benítez, E, Zaller, JG, Auriol, A, Bonnard, O, Charbonnier, Y & Fabreguettes, O 2023, Biodiversity conservation, ecosystem services and organic viticulture: A glass half-full. *Agriculture, Ecosystems & Environment*, 351: 108474.

Bonfante, A, Basile, A & Bouma, J 2020, Targeting the soil quality and soil health concepts when aiming for the United Nations Sustainable Development Goals and the EU Green Deal. *Soil*, 6: 453-466.

Chamorro-Martínez, Y, Torregroza-Espinosa, AC, Pallares, MI, Osorio, DP, Paternina, AC & Echeverría-González, A 2022, Soil macrofauna, mesofauna and microfauna and their relationship with soil quality in agricultural areas in northern Colombia: ecological implications. *Revista Brasileira de Ciência do Solo*, 46: e0210132.

Choudhary, M, Jat, HS, Datta, A, Yadav, AK, Sapkota, TB, Mondal, S, Meena, R, Sharma, PC & Jat, ML 2018, Sustainable intensification influences soil quality, biota, and productivity in cereal-based agroecosystems. *Applied Soil Ecology*, 126: 189-198.

Ennaji, W, Barakat, A, El Baghdadi, M, Oumenskou, H, Aadraoui, M, Karroum, LA & Hilali, A 2018, GIS-based multi-criteria land suitability analysis for sustainable agriculture in the northeast area of Tadla plain (Morocco). *Journal of Earth System Science*, 127(6): 79.

Fenster, TLD, Oikawa, PY & Lundgren, JG 2021, Regenerative Almond Production Systems Improve Soil Health, Biodiversity, and Profit. *Frontiers in Sustainable Food Systems*, 5.

Firth, AG, Baker, BH, Brooks, JP, Smith, R, Iglay, RB & Davis, JB 2020, Low external input sustainable agriculture: Winter flooding in rice fields increases bird use, fecal matter and soil health, reducing fertilizer requirements. *Agriculture, Ecosystems & Environment*, 300: 106962.

Franzluebbers, AJ & Martin, G 2022, Farming with forages can reconnect crop and livestock operations to enhance circularity and foster ecosystem services. *Grass and Forage Science*, 77(4): 270-281.

Guarderas, P, Trávez, K, Boeraeve, F, Cornelis, J-T & Dufrêne, M 2022, Native forest conversion alters soil macroinvertebrate diversity and soil quality in tropical mountain landscapes of northern Ecuador. *Frontiers in Forests and Global Change*, 5.

Hannam, JA, Hughes, M, Deeks, L, Hoskins, H, Hutchison, J, Withers, AJ, Harris, JA, Way, L & Rickson, RJ 2025, Developing a multifunctional indicator framework for soil health. *Ecological Indicators*, 175: 113515.

Kumar, R, Choudhary, JS, Naik, SK, Mondal, S, Mishra, JS, Poonia, SP, Kumar, S, Hans, H, Kumar, S, Das, A, Kumar, V, Bhatt, BP, Chaudhari, SK, Malik, RK, Craufurd, P, McDonald, A & Sherpa, SR 2023, Influence of conservation agriculture-based production systems on bacterial diversity and soil quality in rice-wheat-greengram cropping system in eastern Indo-Gangetic Plains of India. *Frontiers in Microbiology*, 14.

Kundel, D, Bodenhausen, N, Jørgensen, HB, Truu, J, Birkhofer, K, Hedlund, K, Mäder, P & Fliessbach, A 2020, Effects of simulated drought on biological soil quality, microbial diversity and yields under long-term conventional and organic agriculture. *FEMS Microbiology Ecology*, 96.

Lekberg, Y, McLeod, M, Bullington, LS, DuPre, ME, De la Roca, G, Greenbaum, S, Rousk, J & Ramsey, PW 2024, Substantial and rapid increase in soil health across crops with conversion from conventional to regenerative practices. *Sustainability*, 16(13): 5509.

Lori, M, Armengot, L, Schneider, M, Schneidewind, U, Bodenhausen, N, Mäder, P & Krause, HM 2022, Organic management enhances soil quality and drives microbial community diversity in cocoa production systems. *Science of the Total Environment*, 834: 155223.

Pant, M, Negi, GC & Kumar, P 2017, Macrofauna contributes to organic matter decomposition and soil quality in Himalayan agroecosystems, India. *Applied Soil Ecology*, 120: 20-29.

Salomé, C, Coll, P, Lardo, E, Metay, A, Villenave, C, Marsden, C, Blanchart, E, Hinsinger, P & Le Cadre, E 2016, The soil quality concept as a framework to assess management practices in vulnerable agroecosystems: A case study in Mediterranean vineyards. *Ecological Indicators*, 61: 456-465.

Saurabh, K, Rao, KK, Mishra, JS, Kumar, R, Poonia, SP, Samal, SK, Roy, HS, Dubey, AK, Choubey, AK, Mondal, S & Bhatt, BP 2021, Influence of tillage based crop establishment and residue management practices on soil quality indices and yield sustainability in rice-wheat cropping system of Eastern Indo-Gangetic Plains. *Soil and Tillage Research* 206: 104841.

Schulte, LA, Niemi, J, Helmers, MJ, Liebman, M, Arbuckle, JG, James, DE, Kolka, RK, O'Neal, ME, Tomer, MD, Tyndall, JC, Asbjornsen, H, Drobney, P, Neal, J, Van Ryswyk, G & Witte, C 2017, Prairie strips improve biodiversity and the delivery of multiple ecosystem services from corn-soybean croplands. *Proceedings of the National Academy of Sciences USA*, 114: 11247-11252.

Singh, SR, Yadav, P, Singh, D, Tripathi, MK, Bahadur, L, Singh, SP, Mishra, A & Kumar, S 2020, Cropping systems influence microbial diversity, soil quality and crop yields in Indo-Gangetic plains of India. *European Journal of Agronomy*, 121: 126152.

Sulok, KMT, Ahmed, OH, Khew, CY, Zehnder, JAM, Jalloh, MB, Musah, AA & Abdu, A 2021, Chemical and biological characteristics of organic amendments produced from selected agro-wastes with potential for sustaining soil health: A laboratory assessment. *Sustainability*, 13: 4919.

Teng, Z, Chen, L, Li, S, Pan, K, Liu, D, Gu, Z, Wang, Y, Huang, L & Chen, Y 2024, Assessing the efficacy of natural soil biotin on soil quality, microbial diversity, and Rhododendron simsii growth for sustainable landscape architecture. *Frontiers in Microbiology*, 15.

Torrús-Castillo, M, Moreno, G, Landa, BB & Gómez, JA 2026, Effect of regenerative agriculture on soil health, ecosystem services and economic performance in a commercial olive orchard in Southern Spain. *Soil Use and Management*, 42(1): e70181.

Usharani, K, Roopashree, K & Naik, D 2019, Role of soil physical, chemical and biological properties for soil health improvement and sustainable agriculture. *Journal of Pharmacognosy and Phytochemistry*, 8: 1256-1267.

Zhang, C, Xue, W, Xue, J, Zhang, J, Qiu, L, Chen, X, Hu, F, Kardol, P & Liu, M 2022, Leveraging functional traits of cover crops to coordinate crop productivity and soil health. *Journal of Applied Ecology*, 59(10): 2627-2641.

Zhou, X, Wang, W, Niu, K & Du, G 2019, Realistic loss of plant species diversity decreases soil quality in a Tibetan alpine meadow. *Agriculture, Ecosystems & Environment*, 279: 25-32.