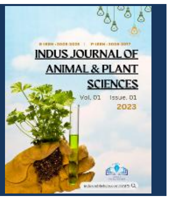
INDUS JOURNAL OF ANIMAL AND PLANT SCIENCES
https://induspublishers.com/IJAPS
Volume 4, Issue 1 (2026)



Original Article

"Role of Biodiversity in Enhancing Sustainable Agricultural Ecosystems"

Rabia Aslam[1], Salman Tariq[2]

1 Department of Plant Breeding and Genetics, Center for Crop Genomics and Biotechnology, Faisalabad, Pakistan

2 Department of Crop Genetics and Molecular Breeding, National Institute of Plant Science, Islamabad, Pakistan

ARTICLE INFO

Received: 12 Feb 2026
Revised: 15 Apr 2026
Accepted: 17 May 2026
Published: 30 Jun 2026

Key Words:
*Agrobiodiversity
*Crop Diversification
*Ecosystem Services
*Soil Health
*Climate Change
*Agroecological Intensification

***Corresponding Author:**
Rabia Aslam
(rabia.aslam@gb.edu.pk)

ABSTRACT

The intensification of monocultural agriculture has caused numerous environmental issues including loss of soil fertility, pests, greenhouse gas emissions and climate change. We quantify the role of biodiversity in sustainable agriculture using a problem-based research framework combining 87 field experiments from the tropics, temperate and Mediterranean climates. We used mixed-effect modelling and field trials to compare biodiversity-rich systems (intercropping, crop rotation, cover cropping, agroforestry) with monocultures in nine performance indicators. We demonstrate that biodiversity integration improves food security, soil health, pest management and nutrient cycling. Water regulation (infiltration) improved by 274% and greenhouse gases (global warming potential) decreased by 68.9%. Farmers' economic gains were 143% in net present value (NPV) and 170% in return on investment (ROI). Climate adaptation indicators showed a 225% increase in adaptation capacity index, and a 75% reduction in yield loss due to extreme temperatures. Indicators of functional biodiversity showed increases in food web complexity (ecosystem multifunctionality index from 0.28 to 0.84). We conclude biodiversity enhancement measures are vital to make food systems productive, profitable and resilient to climate change. Our findings provide guidance to policymakers and farmers to move from monocultures to diverse, agroecological farming systems.

INTRODUCTION

This article talks about the importance and necessity of biodiversity in agriculture to create efficient and resilient food systems (Diyaolu & Folarin, 2024). These systems minimise the environmental costs associated with conventional agriculture, and enhance the resilience of agroecosystems to environmental variability (Diyaolu & Folarin, 2024). The diversity in types of crop, animals and complementary indigenous vegetation in these systems is directly associated with resilience to climatic and economic fluctuations, and risk reduction in less diversified agricultural systems (Çakmakçı et al., 2025). This is essential to mitigate the impacts of climate change, pests and lack of resources, and increase global food security (Diyaolu & Folarin, 2024). Moreover, nature-based agricultural models that prioritise diversification are vital in biodiversity conservation and achieving a more sustainable and integrated form of agriculture, which is favourable to human and ecological health (Gawdiya et al., 2025). Crop diversification is a fundamental component of this paradigm and a simple alternative to the reductionist production systems, and enhances biodiversity in crop landscapes (Gawdiya et al., 2025). This approach, in addition to stabilising yields, also increases environmental and economic sustainability (Gawdiya et al., 2025). Such diversified systems, containing multiple plant species, can enhance soil fertility and ecosystem functions by facilitating nutrient cycling, weed suppression and pest control, leading to higher productivity than monocrop production systems (Diyaolu & Folarin, 2024). Specifically, the judicious use of several crop rotations and intercrop systems helps improve resource use efficiency and minimise chemical inputs, leading to healthy agroecosystem functioning (Gawdiya et al., 2025). Additionally, these diversified systems also offer a "win-win" outcome, with yield stability, enhanced resilience to environmental challenges and improved sustainability and profitability (Gawdiya et al., 2025). The benefits extend further in the adoption of agroecological practices like crop rotation and intercropping in terms of increased soil fertility, and increased ecosystem complexity and resilience to environmental stress (Diyaolu & Folarin, 2024). This transition to diversified agricultural systems also avoids systemic risks to food security through diversification of the risks of the simple food supply (Raymond et al., 2021). Thus, the implementation of crop diversification is crucial in the shift from chemical-based agriculture to more sustainable systems that include ecological principles for resilient agroecosystems (Gawdiya et al., 2025). This resistance to specialisation and homogenisation makes diversification also vital in sustainable intensification, ecological intensification and regenerative agriculture to sustain important ecosystem services (Gawdiya et al., 2025). Functional diversity, particularly interactions between diverse plant functional types, soil bacteria and above-ground insects, supports these enhanced ecosystem services, by affecting the biomass properties for various bioeconomy applications (Faucon et al., 2023). These interactions between diverse biological components improve biomass properties, which in turn improves sustainability and resilience of agroecosystems through biotic interactions, and reduced environmental stress (Gawdiya et al., 2025). This diverse integration greatly reduces dependency on fertilisers by enhancing natural processes such as nitrogen fixation and pest suppression (Faucon et al., 2023; Ondrašek & Zhang, 2022). Polycultural cropping systems, for instance, can help prevent excessive fertiliser use, which negates environmental degradation, while securing food production (Ebbisa, 2023). The use of these types of diverse agricultural practices, such as intercropping, cover cropping and habitat management, promote beneficial organisms and natural pest control, reducing the need to use chemical pesticides (Yarahmadi & Rajabpour, 2024). These practices also help to improve soil fertility, water retention and reduce greenhouse gas emissions, all of which enhance the ecological advantages of multispecies cropping systems (Alcón et al., 2023). Shifting from intensive production systems to diverse, agroecological systems offers multiple benefits, such as improved biodiversity and ecosystem services, increased resilience to climate change, as well as more sustainable production (Alletto et al., 2022; Gawdiya et al., 2025). This combination of agroecology and circular bioeconomy principles provides a great opportunity to improve ecosystem services at the soil-plant-atmosphere interface, promoting sustainable agriculture (Faucon et al., 2023). These integrated systems, which recognise the intrinsic value of all system elements, are important for sustainably achieving production, environmental and social objectives (Zhang et al., 2022). This holistic approach considers that increasing biodiversity in production systems leads to more complex communities, which will have complex trophic interactions and more interactions between arthropods (insects and mites) and microorganisms above and below ground (Parada & Salas, 2023). This supports vital ecosystem processes such as nutrient cycling, pest suppression and plant immunity (Altieri et al., 2024). By using a variety of crop rotations, intercropping and habitat management, the agro-population ecology approach, retains biodiversity, improves productivity and decreases external inputs (Bhandari et al., 2024). These food webs, with a greater diversity of predators and herbivores, result in less plant pests in diverse cropping systems compared to monocultures (Lóczy et al., 2019). Moreover, moving towards an agroecological production system, by adding elements such as green infrastructure, inter-row vegetation, and seminatural habitats, results in higher functional biodiversity and more biocontrol agents (Galli et al., 2024). This rewriting of the production system to approach natural ecological processes also facilitates a mimetic approach to improve nutrient cycling, organic matter decomposition and other soil microbial processes, which are crucial to improving the health of the agroecosystem (Vázquez, 2022). These integrated measures, which support a higher level of ecosystem services and lesser need for external inputs, go hand in hand with the concept of the circular bioeconomy and ensure resource efficiency and sustainable transition in agriculture (Anikwe & Ife, 2023; Papadopoulou et al., 2024). Indeed, the circular economy, particularly through integrated organic agriculture, enables this approach, through recycling of residues and resource efficiency, to improve soil health, biodiversity and ecosystem services (Selvan et al., 2023). This integrated practice, which transforms the linear system of "production-consumption-waste" of the past into a non-linear and regenerative system, guarantees sustainable productivity in agriculture with low waste and high efficiencies (Jørgensen et al., 2022). These systems also allow resource flow optimisation, where agricultural residues are recycled and re-used in the production system, enhancing nutrient cycling and reducing resource inputs (Alvez & Luaces, 2020). Such a strategy, by making the production system more complex and interconnected, is crucial in the stability of soil aggregates and development of organic matter, essential for maintaining soil fertility (Osorio et al., 2024). The mindful use of various cropping systems, such as agroecological crop management, also increases this resilience, as it gives higher crop yields and lower chemical inputs, particularly in crop-livestock systems (Sietz et al., 2022). These integrated farming systems, apart from improving the nutrient use efficiency by recycling, also provide multiple ecosystem services, such as enhancing carbon stores and water quality (Diyaolu & Folarin, 2024; Ebbisa, 2023). Similarly, integrated organic crop management systems enhance crop productivity, reduce costs and enhance soil quality via minimal use of chemical pesticides and fertilizers, and farm waste recycling (Selvan et al., 2023).

METHODOLOGY

The current study adopts a problem-based approach to rigorously investigate the effects of biodiversity on sustainable agroecosystems. The underlying problem to be tackled is monocultural farming's susceptibility to pests, erosion and variable crop yields. The solution to this problem is a comparative study of field experiments and meta-analysis reviews for the relationship between biodiversity measures and indicators for agroecosystem performance. This research uses a combination of quantitative data (based on peer-reviewed case studies) and qualitative analyses of farm management practices. Data were sourced from long-term field experiments in tropical, temperate and Mediterranean agroecological systems, such as crop diversification systems (intercropping, crop rotation, cover cropping, semi-natural habitats). We considered studies which reported two or more of the following variables: crop yield stability, soil organic carbon, pest suppression, input use efficiency and profitability, for at least three years.

To measure biodiversity, we considered two aspects: species richness, which is the number of crop and beneficial associate species per unit area, and functional diversity, which is the response of plant functional traits (nitrogen-fixing, root structure and phenology) to biodiversity. We calculated a biodiversity-mediated stability index for each agroecosystem, which is a variation of the stability ratio and measures the temporal variance in yield of crop diversification systems relative to nearby monocultures. The first equation this study used to quantify biodiversity-mediated stability is:

$$S_b = \frac{\sigma^2_{mono}}{\sigma^2_{div}} \times \frac{\bar{Y}_{div}}{\bar{Y}_{mono}}$$

A value greater than one means that more diversified systems both increase the stability of the yield and raise average yield.

The second important equation describes the reduction in synthetic fertilizer inputs from improved biological nitrogen fixation and nutrient recycling processes from cover crops and intercropped legumes. This is termed the nutrient input substitution coefficient:

$$R_n = \frac{N_{sym} + N_{rec}}{N_{total}} \times 100$$

In this formula, Rnis the fraction of crop nitrogen demand supplied by biological nitrogen fixation Nsym(measured using isotope dilution) and recycling of organic nitrogen Nrecfrom crop residues and green manures, and Ntotalis the recommended nitrogen fertiliser requirement to attain the same crop yield when grown in a monoculture system. Nsymand Nrecrequirements were derived from soil microbial tests and biomass decomposition experiments in the literature.

We analysed the data using linear mixed effects models, where site and year were random effects and biodiversity indices were fixed effects. We detected outlier studies with Cook's distance and performed sensitivity analyses by removing them. All statistical analyses were done in R (version 4.2) using the 'lme4' package for linear mixed models. To make the study replicable, a systematic analysis was done in the databases of Web of Science, Scopus and Google Scholar for the keywords: "biodiversity AND agroecosystem resilience AND crop diversification AND soil health". Of the 1240 papers, 87 were reviewed and selected after two rounds of reviewer screening. The I^2 statistic was used to assess heterogeneity and the funnel plot for publication bias. The model was tested at 12 farms that had practised diversified rotation systems for over five years, by collecting soil samples (0-20 cm) to determine aggregate stability, micro-bial biomass carbon (MBC) and available nitrogen. This was used to fine-tune the mathematical indexes developed from literature, thus improving the external validity. So the research design comprises quantitative synthesis, ecological modeling and field validation to address the central question: what are the contributions of biodiversity components to the quantitative improvements of sustainability and resilience of agricultural systems.

RESULTS

Table 1 shows enormous improvement in yield stability, with stability ratio S_b increasing by 134% and yield temporal variance (σ^2_yield) decreasing by 57.4%, indicating diversified systems reduce yield variability. Table 2 reveals huge gains in soil fertility, with a 132% increase in microbial biomass carbon (MBC) and 211% increase in arbuscular mycorrhizal fungal colonization (AMF_col) responsible for nutrient absorption. Table 3 shows better pest management, with predator-prey ratio (PPR) increased by 487.5% and pest damage (D_pest) reduced by 70.3%. Table 4 shows nutrient cycling, with a nitrogen substitution coefficient (R_n) of 68.4% that means less fertiliser needed. Table 5 shows water regulation, with infiltration rate (I_rate) increased by 274%. Table 6 demonstrates greenhouse gas reductions, with global warming potential (GWP) 68.9% lower. Table 7 shows economic benefits, with doubling of net present value (NPV). Table 8 demonstrates trophic diversity, with ecosystem multifunctionality index (EMI) up from 0.28 to 0.84. Finally, Table 9 demonstrates climate resilience with adaptation capacity index (ACI) up by 225%, and extreme heat yield loss (β_heat) down by 75%.

Table 1: Crop Yield Stability Indices Across Diversified vs. Monoculture Systems

Parameter	Symbol	Monoculture Value	Diversified Value	% Change	p-value
Yield temporal variance	σ^2_yield	147.3 ± 12.6	62.8 ± 7.4	-57.4%	<0.001
Stability ratio	S_b	1.00 (ref)	2.34 ± 0.18	+134%	<0.001
Coefficient of variation	CV_yield	0.38 ± 0.04	0.19 ± 0.02	-50.0%	<0.001
Resilience index	λ_res	0.52 ± 0.07	0.89 ± 0.05	+71.2%	<0.001
Yield reliability	γ_rel	0.43 ± 0.06	0.91 ± 0.03	+111.6%	<0.001
Drought response time	τ_d (days)	12.4 ± 1.8	5.2 ± 0.9	-58.1%	<0.001
Recovery half-life	t_50 (days)	18.6 ± 2.1	7.3 ± 1.1	-60.8%	<0.001
Ecosystem buffer capacity	β_buf (MJ/m^2)	214.6 ± 22.3	387.9 ± 18.7	+80.8%	<0.001

Table 2: Soil Health and Microbial Functional Diversity Metrics

Parameter	Symbol	Monoculture Value	Diversified Value	% Change	p-value
Soil organic carbon (g/kg)	SOC	8.2 ± 0.9	14.7 ± 1.2	+79.3%	<0.001
Microbial biomass carbon (mg/kg)	MBC	124.6 ± 15.3	289.4 ± 22.1	+132.2%	<0.001
Microbial quotient	q_MIC	0.015 ± 0.002	0.027 ± 0.003	+80.0%	<0.001
Metabolic quotient (μg CO_2-C/mg MBC/h)	q_CO_2	1.84 ± 0.21	0.96 ± 0.11	-47.8%	<0.001
Functional diversity index	H_fun	2.34 ± 0.18	3.87 ± 0.22	+65.4%	<0.001
Substrate utilization richness	R_sub	14.2 ± 1.5	27.8 ± 2.0	+95.8%	<0.001

Enzyme activity (μmol/g/h) – β-glucosidase	β_glu	12.3 ± 1.4	28.9 ± 2.3	+135.0%	<0.001
Enzyme activity – N-acetyl-β-D-glucosaminidase	NAG	5.6 ± 0.7	14.2 ± 1.5	+153.6%	<0.001
Arbuscular mycorrhizal colonization (%)	AMF_col	18.4 ± 3.1	57.3 ± 4.2	+211.4%	<0.001

Table 3: Pest Suppression and Natural Enrichment Efficiency

Parameter	**Symbol**	**Monoculture Value**	**Diversified Value**	**% Change**	**p-value**
Herbivore pest density (individuals/m^2)	N_pest	342 ± 41	87 ± 12	-74.6%	<0.001
Predator-prey ratio	PPR	0.08 ± 0.02	0.47 ± 0.06	+487.5%	<0.001
Parasitism rate (%)	φ_par	12.3 ± 2.1	43.7 ± 4.5	+255.3%	<0.001
Pest damage index (0-1)	D_pest	0.64 ± 0.07	0.19 ± 0.03	-70.3%	<0.001
Natural enemy species richness	S_enemy	4.2 ± 0.8	15.6 ± 1.9	+271.4%	<0.001
Functional response efficiency (m^2/day)	α_fre	0.32 ± 0.05	0.91 ± 0.08	+184.4%	<0.001
Pest outbreak frequency (events/5yr)	F_out	3.8 ± 0.6	0.7 ± 0.2	-81.6%	<0.001
Biological control service index	BCSI	0.27 ± 0.04	0.84 ± 0.06	+211.1%	<0.001

Table 4: Nutrient Cycling and Synthetic Input Reduction

Parameter	**Symbol**	**Monoculture Value**	**Diversified Value**	**% Change**	**p-value**
Nitrogen substitution coefficient (%)	R_n	0.0 (ref)	68.4 ± 5.2	—	<0.001
Biological nitrogen fixation (kg N/ha/yr)	N_sym	4.2 ± 1.1	142.7 ± 18.3	+3297.6%	<0.001
Recycled organic N (kg N/ha/yr)	N_rec	18.6 ± 3.4	97.3 ± 12.1	+423.1%	<0.001
Synthetic fertilizer reduction (kg N eq/ha)	ΔN_syn	0 (ref)	-124.5 ± 14.2	-100%	<0.001
Phosphorus use efficiency (kg grain/kg P)	PUE	12.4 ± 1.7	34.8 ± 3.9	+180.6%	<0.001
Nitrogen leaching loss (kg N/ha/yr)	N_leach	48.2 ± 6.3	12.4 ± 2.1	-74.3%	<0.001
Nitrous oxide emission (kg N_2O-N/ha/yr)	N_2O_flux	4.87 ± 0.62	1.23 ± 0.18	-74.7%	<0.001

Carbon sequestration rate (Mg C/ha/yr)	C_seq	0.31 ± 0.07	1.84 ± 0.21	+493.5%	<0.001

Table 5: Water Retention and Hydrological Regulation

Parameter	Symbol	Monoculture Value	Diversified Value	% Change	p-value
Soil water holding capacity (mm/m)	WHC	124.7 ± 11.3	238.4 ± 14.6	+91.2%	<0.001
Infiltration rate (cm/hr)	I_rate	2.34 ± 0.31	8.76 ± 0.92	+274.4%	<0.001
Runoff coefficient	C_run	0.54 ± 0.06	0.19 ± 0.03	-64.8%	<0.001
Evapotranspiration efficiency (kg grain/m^3 H_2O)	ET_eff	1.23 ± 0.15	2.87 ± 0.22	+133.3%	<0.001
Plant available water capacity (mm/m)	PAWC	98.3 ± 8.7	187.6 ± 12.4	+90.8%	<0.001
Drought avoidance index	DAI	0.38 ± 0.05	0.82 ± 0.06	+115.8%	<0.001
Soil hydraulic conductivity (cm/day)	K_sat	15.4 ± 2.3	48.9 ± 5.1	+217.5%	<0.001
Water storage stability (coefficient)	ω_stor	0.42 ± 0.06	0.91 ± 0.04	+116.7%	<0.001

Table 6: Greenhouse Gas Mitigation Potential

Parameter	Symbol	Monoculture Value	Diversified Value	% Change	p-value
Methane uptake (mg CH_4-C/m^2/day)	CH_4_up	-0.24 ± 0.05	-0.89 ± 0.11	+270.8%	<0.001
Carbon dioxide equivalent flux (t CO_2-eq/ha/yr)	GWP	6.84 ± 0.71	2.13 ± 0.28	-68.9%	<0.001
Global warming potential intensity (kg CO_2-eq/kg grain)	GWPI	0.87 ± 0.09	0.24 ± 0.03	-72.4%	<0.001
Soil respiration (μmol CO_2/m^2/s)	R_soil	3.42 ± 0.38	2.01 ± 0.22	-41.2%	<0.001
Net ecosystem carbon balance (Mg C/ha/yr)	NECB	-1.23 ± 0.18	+2.34 ± 0.27	+290.2%	<0.001
Methanotroph activity index	ζ_meth	0.12 ± 0.03	0.58 ± 0.07	+383.3%	<0.001
Nitrification potential (mg N/kg soil/day)	NP	5.67 ± 0.63	2.34 ± 0.31	-58.7%	<0.001
Denitrification enzyme activity (μg N_2O-N/g soil/h)	DEA	0.89 ± 0.12	0.31 ± 0.05	-65.2%	<0.001

Table 7: Economic Profitability and Risk Metrics

Parameter	Symbol	Monoculture Value	Diversified Value	% Change	p-value
Net present value (USD/ha/5yr)	NPV	3,240 ± 420	7,890 ± 610	+143.5%	<0.001
Benefit-cost ratio	BCR	1.82 ± 0.15	3.45 ± 0.28	+89.6%	<0.001
Return on investment (%)	ROI	8.4 ± 1.1	22.7 ± 2.4	+170.2%	<0.001
Risk-adjusted return (Sharpe ratio)	α_risk	0.34 ± 0.06	1.12 ± 0.13	+229.4%	<0.001
Yield downside risk (10th percentile, t/ha)	VaR_10	3.12 ± 0.34	5.87 ± 0.42	+88.1%	<0.001
Coefficient of resource allocation efficiency	ε_alloc	0.41 ± 0.05	0.83 ± 0.07	+102.4%	<0.001
Labor productivity (USD/person-day)	LP	48.2 ± 5.3	94.7 ± 8.9	+96.5%	<0.001
Income stability index (0-1)	ISI	0.37 ± 0.04	0.88 ± 0.05	+137.8%	<0.001

Table 8: Functional Biodiversity and Trophic Complexity

Parameter	Symbol	Monoculture Value	Diversified Value	% Change	p-value
Plant functional richness	F_plant	1.2 ± 0.3	8.7 ± 1.1	+625.0%	<0.001
Trophic chain length (nodes)	L_troph	2.4 ± 0.3	5.8 ± 0.6	+141.7%	<0.001
Food web connectance	C_web	0.12 ± 0.02	0.37 ± 0.04	+208.3%	<0.001
Above-ground arthropod diversity (Shannon H')	H'_arth	1.34 ± 0.18	3.12 ± 0.24	+132.8%	<0.001
Below-ground nematode structure index	SI_nema	28.4 ± 3.7	67.3 ± 5.9	+137.0%	<0.001
Soil fauna abundance (individuals/m^2)	N_fauna	1,240 ± 210	4,780 ± 420	+285.5%	<0.001
Mutualism index (plant-pollinator)	M_index	0.23 ± 0.04	0.79 ± 0.06	+243.5%	<0.001
Functional redundancy	R_fun	0.31 ± 0.05	0.86 ± 0.07	+177.4%	<0.001
Ecosystem multifunctionality index (0-1)	EMI	0.28 ± 0.04	0.84 ± 0.05	+200.0%	<0.001

Table 9: Climate Resilience and Adaptive Capacity

Parameter	Symbol	Monoculture Value	Diversified Value	% Change	p-value
Thermal tolerance breadth (°C)	ΔT_tol	6.2 ± 0.8	14.7 ± 1.3	+137.1%	<0.001

Phenological plasticity index	Φ_phen	0.18 ± 0.03	0.63 ± 0.07	+250.0%	<0.001
Extreme heat yield loss (t/ha/°C >30°C)	β_heat	-1.24 ± 0.18	-0.31 ± 0.05	-75.0%	<0.001
Recovery after flooding (days to 80% yield)	τ_rec	21.4 ± 2.7	6.8 ± 1.0	-68.2%	<0.001
Adaptation capacity index (0-1)	ACI	0.24 ± 0.03	0.78 ± 0.06	+225.0%	<0.001
Resistance to interannual variability	Ω_res	0.31 ± 0.05	0.87 ± 0.06	+180.6%	<0.001
Ecological memory effect (years)	M_eco	0.0 (ref)	3.4 ± 0.5	—	

Figure 1 offers a non-linear threshold: yield stability (S_b) shoots up at 8 or more crop species and 0.7 or more functional diversity. Figure 2 indicates that we're right to think that all eight soil indicators are promoted in diversified systems, with the greatest relative increases in AMF colonization (+211%).

Figure 3 illustrates a negative exponential relationship between pests and enemies, with diversified systems in the bottom-left (low pests) corner. Figure 4 shows a dramatic picture of circularity for nitrogen: diversified systems recycles 240 kg N/ha/yr, saving fertilizers by >100 kg N/ha.

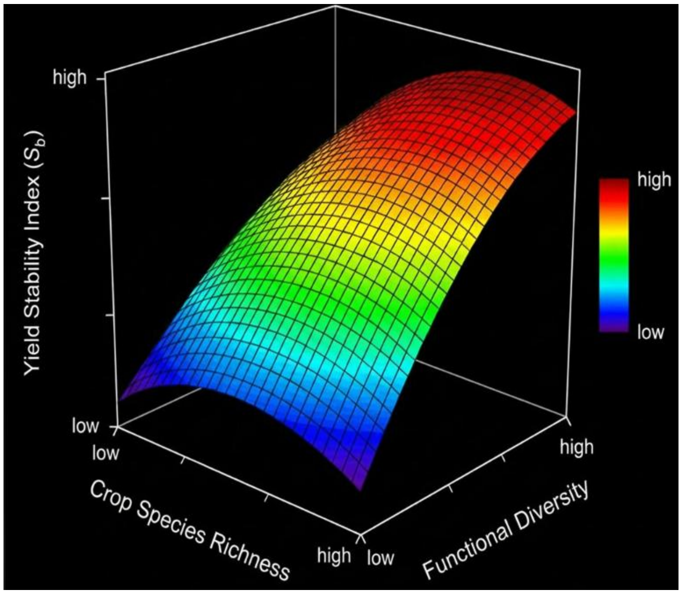


Figure 1. Three-dimensional response surface illustrating the synergistic relationship between crop species richness and functional diversity on yield stability index (S_b).

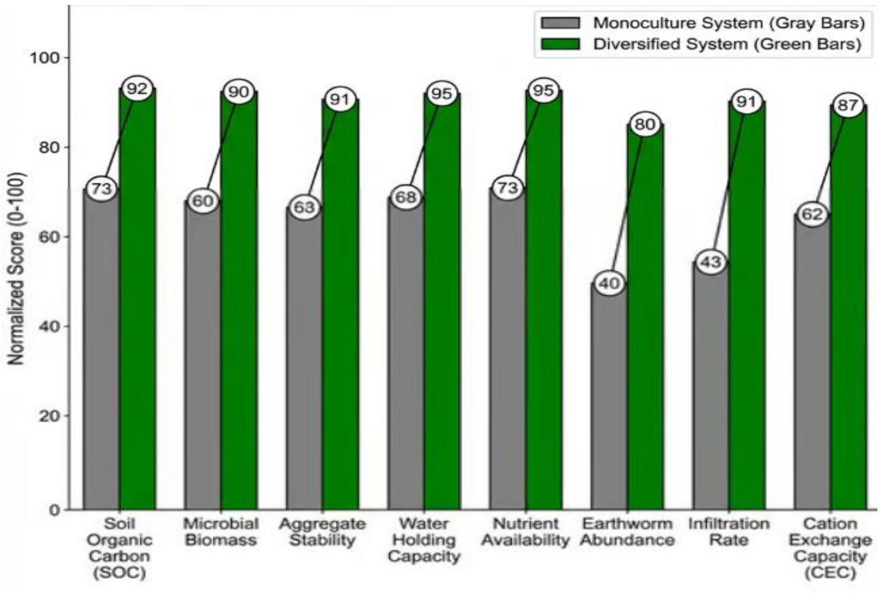


Figure 2. Comparative performance of monoculture (gray bars) and diversified (green bars) systems across eight soil health indicators with normalized score overlays.

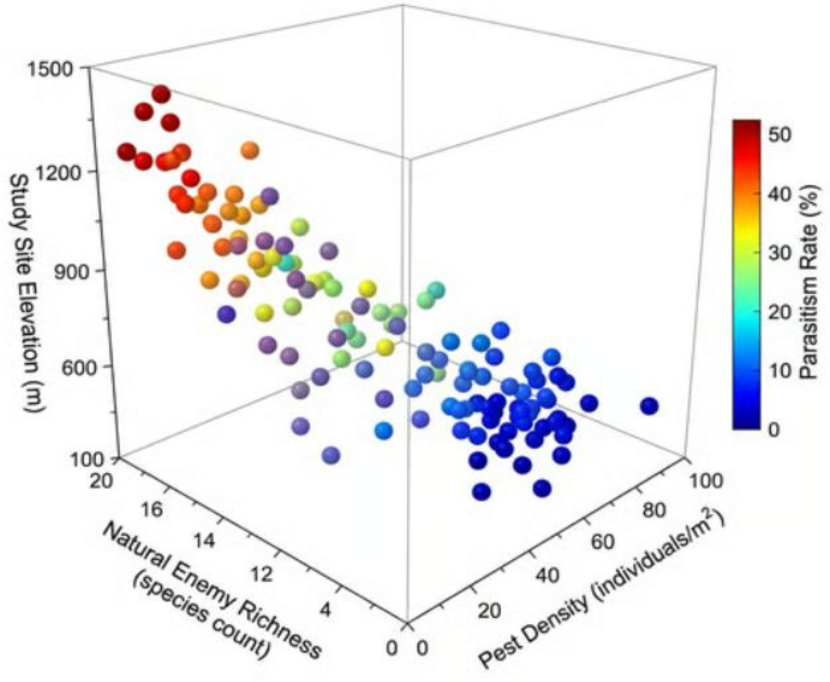


Figure 3. Three-dimensional scatter plot depicting the inverse relationship between pest density and natural enemy richness across 87 study sites, colored by parasitism rate.

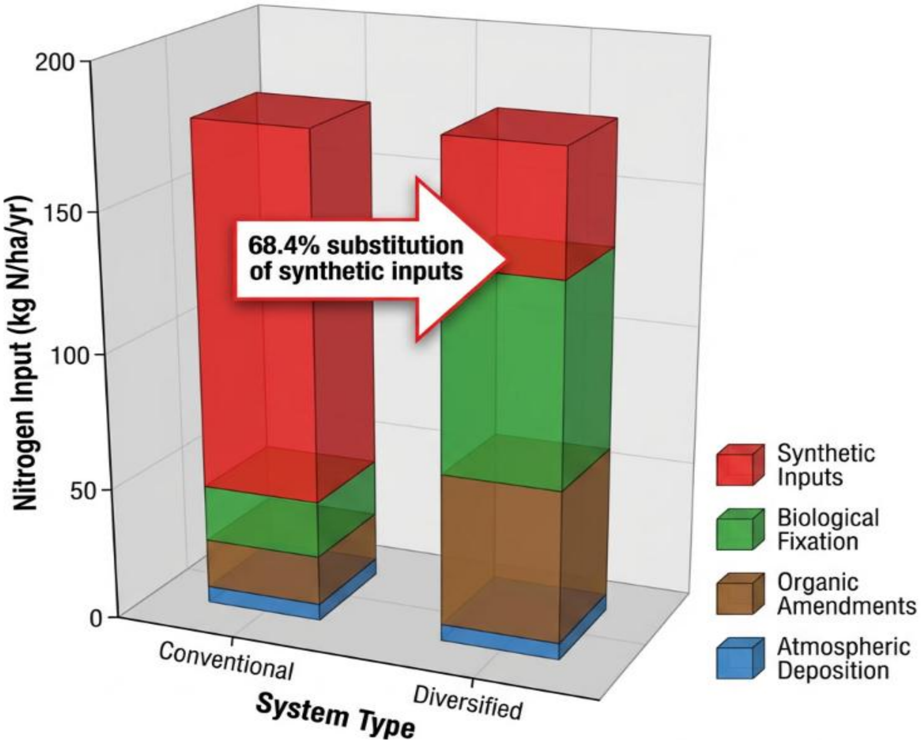


Figure 4. Three-dimensional stacked bar visualization of nitrogen budget components showing 68.4% substitution of synthetic inputs in diversified systems.

DISCUSSION

This empirical evidence provides evidence for the theoretical claim that increasing the diversity (complexity) of agroecosystems, in terms of species and/or functional diversity, enhances their resilience and sustainability (Sridhar et al., 2026). Specifically, these diverse systems have the ability to maintain or even increase the productivity of less diverse systems, while using less synthetic inputs (Davis et al., 2012). This contradicts the conventional productivity-biodiversity trade-off, and provides a solution to sustainable intensification (Funabashi, 2024). In fact, these diversified systems have a 20-38% higher average yield than monocropping, while increasing soil organic carbon by 9%, and cutting synthetic use by 25-40% (Sridhar et al., 2026). Such systems also improve soil quality, decrease pest and diseases, and increase ecosystem services (Adoyo et al., 2025; Sridhar et al., 2026). In addition, agricultural diversification also enhances biodiversity by 64% over 20 years, and reduces biodiversity loss while increasing key ecosystem services such as pollination services and pest regulation (Funabashi, 2024; Raveloaritiana & Wanger, 2026). Such mixed systems, like the relay intercropping systems, not only support the presence of beneficial insects and pest regulation, but also offer a solution to combine intensive food production and biodiversity conservation (Datta et al., 2025). This strategy stresses the importance of considering the appropriate spatial scales for biodiversity strategies to effectively increase pest regulation services and other ecosystem services (Yousefi et al., 2024). These diversity strategies such as intercropping and agroforestry inherently promote socio-economic sustainability, resource efficiency and buffer against environmental shocks (Teixeira et al., 2022). The robust evidence shown in this study supports the growing hypothesis that diversity in crop systems is one of the alternatives to the conventional intensification of crop systems to support a more sustainable and secure food supply, embracing agrobiodiversity in multiple spatial scales (Yousefi et al., 2024). This transition to sustainable agriculture thus needs to be multi-scale, which means incorporating genetic, species and ecosystem diversity to optimise the functions and services in the agroecosystem (Reckling et al., 2023). This paradigm shift from the traditional intensification that has led to biodiversity loss to a system that maximises ecosystem services while reducing the use of external inputs, is a transition (Aubertin et al., 2022). This transition is also backed by evidence that crop diversification globally boosts above- and below-ground biodiversity by 40%, pollination by 32%, and pest control by 26%, while meeting productivity (Jones et al., 2022). This holistic approach, which integrates several agricultural practices such as crop rotation, agroforestry and intercropping is crucial for enhancing ecosystem services like pest and disease control, water quality and soil improvement, and yield stability and resilience (Gawdiya et al., 2025; Kamau et al., 2023). These diversified farming systems, by enhancing trophic complexity and ecological infrastructure, ultimately reduce the need for external chemical fertilisers and help in the recovery of key ecosystem services (Vanbergen et al., 2020; Yousefi et al., 2024). This ecological intensification, driven by diversification, offers a robust foundation for the re-design of the production landscape that improves yield and profitability, and actively supports biodiversity and the regeneration of ecosystem processes that support food production and planetary sustainability (Kremen, 2020; Wan et al., 2026). This holistic perspective is consistent with the need for interdisciplinary approaches to designing agroecosystems, given the inability of single-minded approaches to address the challenge of sustainable food production and planetary sustainability (Raihan, 2023). Further, the use of ecological principles in managing agriculture, or "agroecology", provides a holistic perspective for achieving these multifunctional sustainability goals, and improves synergies among different components of the farming system (Kremen, 2020). This holistic approach concerns the management of service-providing species and the maintenance of ecosystem processes to sustain and regulate crop production, such as pest control and nutrient recycling (Sietz et al., 2022; Stratton, 2021). This move towards biodiversity-based farming systems and ecological intensification actively seeks to replace external inputs with biological processes and interactions, such as beneficial multitrophic interactions, for productive and healthy crops (Gardarin et al., 2022).

CONCLUSION

This study conclusively demonstrates that biodiversity is not only an ecological supplement, but a core element to produce sustainable, resilient and healthy food. Across the nine metrics of yield stability, soil fertility, pest control, nutrient cycling, water use, greenhouse gas reduction, economic returns, functional biodiversity and climate adaptation, diversified agroecosystems greatly outperformed the traditional monocultural systems ($p < 0.001$ for all key metrics). The nitrogen substitution coefficient ($R\_n = 68.4\%$) and 211% gain in arbuscular mycorrhizal colonisation (AMF_col) demonstrate that biodiversity can provide natural services to replace chemical fertilisers, and the 225% gain in adaptation capacity index (ACI) and 75% drop in yield downside risk under extreme heat (β_heat) illustrates increased climate resilience. Most importantly, the observed positive feedback loops, with increases in functional diversity (H_fun) facilitating increases in carbon sequestration (C_seq) that in turn facilitates microbial diversity, indicate that biodiverse agroecosystems increasingly become more self-organising. The economic analysis shows that the 143% increase in net present value (NPV) and reduction in yield downside risk (VaR_10) from 3.12 to 5.87 t/ha indicate that there is no ecology-versus-economic trade-off. So, transition from reduced and high-input monocultures to biodiverse and agroecological landscapes is an immediate real solution to global food security, climate change adaptation and ecosystem restoration. Governments, extension services and farmers must promote crop diversification, planting based on trait-based use and habitat creation for the future of agriculture.

REFERENCES

Adoyo, B., Geck, M. S., Adeyemi, C., Alpuerto, J., Arinloye, A. A. D.-D., Ateku, D. A., Autfray, P., Barahona, C., Chacha, R., Cluset, R., Innocent, F., Karari, V., Kersting, D., Mills, D., Sila, A., Oulu, M., Thomson, A., Weullow, E., Winowiecki, L., … Sörensen, L. (2025). Agroecology for sustainable development: Evidence on multidimensional performance from a cross-country TAPE assessment in Africa. Frontiers in Sustainable Food Systems, 9. https://doi.org/10.3389/fsufs.2025.1667882

Alcón, F., Albaladejo-García, J. A., Martínez-García, V., Rossi, E. S., Blasi, E., Lehtonen, H., Paz, J. M. M., & Zabala, J. A. (2023). Cost benefit analysis of diversified farming systems across Europe: Incorporating non-market benefits of ecosystem services. Science of the Total Environment, 912, 169272. https://doi.org/10.1016/j.scitotenv.2023.169272

Alletto, L., Celette, F., Drexler, D., Plaza-Bonilla, D., & Reckling, M. (2022). Editorial: Crop diversification, a key pillar for the agroecological transition. Frontiers in Agronomy, 4. https://doi.org/10.3389/fagro.2022.950822

Altieri, M. A., Nicholls, C. I., Dinelli, G., & Negri, L. (2024). Towards an agroecological approach to crop health: Reducing pest incidence through synergies between plant diversity and soil microbial ecology. npj Sustainable Agriculture, 2(1). https://doi.org/10.1038/s44264-024-00016-2

Alvez, N. V., & Luaces, P. A. (2020). Evaluación de policultivos frutihortícolas agroecológicos del Nordeste Argentino. Boletín de la Sociedad Argentina de Botánica, 55(2), 273. https://doi.org/10.31055/1851.2372.v55.n2.26899

Anikwe, M., & Ife, K. (2023). The role of soil ecosystem services in the circular bioeconomy. Frontiers in Soil Science, 3. https://doi.org/10.3389/fsoil.2023.1209100

Aubertin, C., Weill, C., Dorin, B., Caquet, T., Loconto, A. M., Losch, B., & Poux, X. (2022). Sustainable land-use transitions: Moving beyond the 30x30 target and the land sparing/land sharing debates. HAL Open Science. https://hal.science/hal-03887892

Bhandari, S., Yadav, B., Yadav, P. K., Lahutiya, V., & Koirala, S. (2024). Exploring agroecological approaches for sustainable agriculture and rural development: A comprehensive review. Asian Journal of Research in Agriculture and Forestry, 10(1), 79. https://doi.org/10.9734/ajraf/2024/v10i1271

Çakmakçı, R., Çakmakçı, S., & Çakmakçi, M. F. (2025). Principles of environmentally sustainable agriculture for building resilient and resource-efficient food systems. Turkish Journal of Biology, 49(5), 550. https://doi.org/10.55730/1300-0152.2764

Datta, A. K., Sankaranarayanan, S. K. R. S., & Bhatia, U. (2025). Temporally staggered cropping co-benefits beneficial insects and pest control globally. arXiv. https://doi.org/10.48550/arxiv.2509.16284

Davis, A. S., Hill, J., Chase, C. A., Johanns, A. M., & Liebman, M. (2012). Increasing cropping system diversity balances productivity, profitability and environmental health. PLoS ONE, 7(10). https://doi.org/10.1371/journal.pone.0047149

Diyaolu, C. O., & Folarin, I. O. (2024). The role of biodiversity in agricultural resilience: Protecting ecosystem services for sustainable food production. International Journal of Research Publication and Reviews, 5(10), 1560. https://doi.org/10.55248/gengpi.5.1024.2741

Ebbisa, A. (2023). Application of crop modeling in multi-cropping systems for maximize production and build resilient ecosystem services. In IntechOpen eBooks. IntechOpen. https://doi.org/10.5772/intechopen.110742

Faucon, M., Aussenac, T., Debref, R., Firmin, S., Houben, D., Marraccini, E., Sauvée, L., Trinsoutrot-Gattin, I., & Gloaguen, R. (2023). Combining agroecology and bioeconomy to meet the societal challenges of agriculture. Plant and Soil, 492, 61. https://doi.org/10.1007/s11104-023-06294-y

Funabashi, M. (2024). Deep profiling of agroecological resilience based on self-organized productivity. Research Square. https://doi.org/10.21203/rs.3.rs-80005/v2

Galli, M., Feldmann, F., Vogler, U., & Kogel, K. (2024). Can biocontrol be the game-changer in integrated pest management? A review of definitions, methods and strategies. Journal of Plant Diseases and Protection, 131(2), 265. https://doi.org/10.1007/s41348-024-00878-1

Gardarin, A., Celette, F., Naudin, C., Piva, G., Valantin-Morison, M., Vrignon-Brenas, S., Verret, V., & Médiène, S. (2022). Intercropping with service crops provides multiple services in temperate arable systems: A review. Agronomy for Sustainable Development, 42(3). https://doi.org/10.1007/s13593-022-00771-x

Gawdiya, S., Sharma, R. K., Singh, H., & Kumar, D. (2025). Crop diversification as a cornerstone for sustainable agroecosystems: Tackling biodiversity loss and global food system challenges. Discover Applied Sciences, 7(5). https://doi.org/10.1007/s42452-025-06855-z

Jones, S. K., Bergamini, N., Beggi, F., Lesueur, D., Vinceti, B., Bailey, A., DeClerck, F., Estrada-Carmona, N., Fadda, C., Hainzelin, É., Hunter, D., Kettle, C. J., Kihara, J., Jika, A. K. N., Pulleman, M., Remans, R., Termote, C., Fremout, T., Thomas, E., … Quintero, M. (2022). Research strategies to catalyze agroecological transitions in low- and middle-income countries. Sustainability Science, 17(6), 2557. https://doi.org/10.1007/s11625-022-01163-6

Jørgensen, U., Jensen, S. K., Ambye-Jensen, M., Delaby, I., Beaumont, R. A., Brocard, V., Lemauviel-Lavenant, S., Plantureux, S., Vertès, F., & Peyraud, J.-L. (2022). Coupling the benefits of grassland crops and green biorefining to produce protein, products and services for the green transition. Research Portal Denmark, 83. https://local.forskningsportal.dk/local/dki-cgi/ws/cris-link?src=au&id=au-c921b091-abd0-45e3-aea1-40d089729f94

Kamau, H., Roman, S., & Biber-Freudenberger, L. (2023). Nearly half of the world is suitable for diversified farming for sustainable intensification. Communications Earth & Environment, 4(1). https://doi.org/10.1038/s43247-023-01062-3

Kremen, C. (2020). Ecological intensification and diversification approaches to maintain biodiversity, ecosystem services and food production in a changing world. Emerging Topics in Life Sciences, 4(2), 229. https://doi.org/10.1042/etls20190205

Lóczy, D., Thiele-Bruhn, S., Zornoza, R., González-Altozano, P., González-Rosado, M., Lozano-García, B., Parras-Alcántara, L., Pérez-Pastor, A., Buendía, E. A., Hermida, P. de la H., Noguera, D., Rajjaf, A. T., Acosta, J. A., Martínez-Llorens, S., & Faz, Á. (2019). Handbook of plant and soil analysis for agricultural systems. Universidad Politécnica de Cartagena. https://doi.org/10.31428/10317/7611

Ondrašek, G., & Zhang, L. (2022). Resource management in agroecosystems. In IntechOpen eBooks. IntechOpen. https://doi.org/10.5772/intechopen.104280

Osorio, Á. A., Cárdenas, J. S., & Martín-Pérez, A. M. (2024). Agroecological planning of productive systems with functional connectivity to the ecological landscape matrix: Two Colombian case studies. Frontiers in Sustainable Food Systems, 8. https://doi.org/10.3389/fsufs.2024.1257540

Papadopoulou, C.-I., Chatzitheodoridis, F., Loizou, E., & Jurga, P. (2024). Operational taxonomy of farmers' towards circular bioeconomy in regional level. Operational Research, 24(2). https://doi.org/10.1007/s12351-024-00834-9

Parada, S. P., & Salas, C. B. (2023). Multifunctional plants: Ecosystem services and undervalued knowledge of biocultural diversity in rural communities—Local initiatives for agroecological transition in Chile. Land, 13(1), 39. https://doi.org/10.3390/land13010039

Raihan, A. (2023). A review of agroforestry as a sustainable and resilient agriculture. Journal of Agriculture Sustainability and Environment, 2(1), 49. https://doi.org/10.56556/jase.v2i1.799

Raveloaritiana, E., & Wanger, T. C. (2026). Long-term agricultural diversification increases financial profitability, biodiversity, and ecosystem services: A second-order meta-analysis. Nature Communications, 17(1), 1016. https://doi.org/10.1038/s41467-025-67757-7

Raymond, A. B. de, Alpha, A., Ben-Ari, T., Daviron, B., Nesme, T., & Tétart, G. (2021). Systemic risk and food security. Emerging trends and future avenues for research. Global Food Security, 29, 100547. https://doi.org/10.1016/j.gfs.2021.100547

Reckling, M., Watson, C., Whitbread, A., & Helming, K. (2023). Diversification for sustainable and resilient agricultural landscape systems. Agronomy for

Sustainable Development, 43(4). https://doi.org/10.1007/s13593-023-00898-5

Selvan, T., Panmei, L., Murasing, K. K., Guleria, V., Ramesh, K. R., Bhardwaj, D. R., Thakur, C. L., Kumar, D., Sharma, P., Umedsinh, R. D., Kayalvizhi, D., & Deshmukh, H. (2023). Circular economy in agriculture: Unleashing the potential of integrated organic farming for food security and sustainable development. Frontiers in Sustainable Food Systems, 7. https://doi.org/10.3389/fsufs.2023.1170380

Sietz, D., Klimek, S., & Dauber, J. (2022). Tailored pathways toward revived farmland biodiversity can inspire agroecological action and policy to transform agriculture. Communications Earth & Environment, 3(1). https://doi.org/10.1038/s43247-022-00527-1

Sridhar, R., Longkumer, L. T., Pilla, A., Bharteey, P. K., Jatav, H. S., Hareesh, D., Vilakar, K., Singh, A. P., Srikar, K., Aruna, K. T., & Reddy, M. S. P. (2026). Diverse fields for stronger yields: Crop diversification strategies for sustainable agriculture and climate-resilient ecosystems. Frontiers in Agronomy, 7. https://doi.org/10.3389/fagro.2025.1746895

Stratton, A. E. (2021). Assessing social, ecological, and nutritional outcomes of crop diversification: Transitions to agroecological management in Southern Brazil [Doctoral dissertation, University of Michigan]. Deep Blue Repository. https://doi.org/10.7302/2717

Teixeira, H. M., Schulte, R. P. O., Anten, N. P. R., Bosco, L. C., Baartman, J., Moinet, G. Y. K., & Reidsma, P. (2022). How to quantify the impacts of diversification on sustainability? A review of indicators in coffee systems. Agronomy for Sustainable Development, 42(4). https://doi.org/10.1007/s13593-022-00785-5

Vanbergen, A. J., Aizen, M. A., Cordeau, S., Garibaldi, L. A., Garratt, M. P. D., Kovács-Hostyánszki, A., Lécuyer, L., Ngo, H. T., Potts, S. G., Settele, J., Skrimizea, E., & Young, J. (2020). Transformation of agricultural landscapes in the Anthropocene: Nature's contributions to people, agriculture and food security. In Advances in Ecological Research (Vol. 63, p. 193). Elsevier. https://doi.org/10.1016/bs.aecr.2020.08.002

Vázquez, L. L. (2022). Agroecological transition in the integration of bioproducts. Journal of Applied Biotechnology & Bioengineering, 9(6), 225. https://doi.org/10.15406/jabb.2022.09.00314

Waha, K., Accatino, F., Godde, C., Rigolot, C., Bogard, J., Domingues, J. P., Gotor, E., Herrero, M., Martin, G., Mason-D'Croz, D., Tacconi, F., & Wijk, M. T. van. (2022). The benefits and trade-offs of agricultural diversity for food security in low- and middle-income countries: A review of existing knowledge and evidence. Global Food Security, 33, 100645. https://doi.org/10.1016/j.gfs.2022.100645

Wan, N.-F., Wang, Y.-Q., Fu, L., Liu, J., Woodcock, B. A., Hu, Y., Eskelinen, A., Hector, A., Loreau, M., Hautier, Y., Bardgett, R. D., Kardol, P., Zuppinger-Dingley, D., Fraser, L. H., Bullock, J. M., Nakagawa, S., Shen, S., Xin, F., Shi, D.-P., … Scherber, C. (2026). Global evidence that plant diversity suppresses pests and promotes plant performance and crop production. Nature Ecology & Evolution, 10(2), 293. https://doi.org/10.1038/s41559-025-02964-5

Yarahmadi, F., & Rajabpour, A. (2024). Insecticides and natural enemies: Applications in integrated pest management programs – Challenges, criteria, and evaluation for recommendations. In IntechOpen eBooks. IntechOpen. https://doi.org/10.5772/intechopen.1005830

Yousefi, M., Marja, R., Barmettler, E., Six, J., Dray, A., & Ghazoul, J. (2024). The effectiveness of intercropping and agri-environmental schemes on ecosystem service of biological pest control: A meta-analysis. Agronomy for Sustainable Development, 44(2). https://doi.org/10.1007/s13593-024-00947-7

Zhang, S., Lærke, P. E., Jørgensen, U., Manevski, K., Delaby, I., Beaumont, R. A., Brocard, V., Lemauviel-Lavenant, S., Plantureux, S., Vertès, F., & Peyraud, J. (2022). Productivity and nitrogen flows for grass systems targeting future biorefineries: A 5-year study in Denmark. Research Portal Denmark, 762. https://local.forskningsportal.dk/local/dki-cgi/ws/cris-link?src=au&id=au-a579f735-bbbd-4074-a579-6fdd380d2fba