



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; SP-9(7): 479-484
Received: 14-05-2026
Accepted: 19-06-2026

GS Madhu Bindu
Agricultural College, Jagtial,
Professor Jayashankar Telangana
State Agricultural University,
Telangana, India

P Spandana Bhatt
Agricultural College, Jagtial,
Professor Jayashankar Telangana
State Agricultural University,
Telangana, India

I Tirupathi
Agricultural College, Jagtial,
Professor Jayashankar Telangana
State Agricultural University,
Telangana, India

G Venu Gopal
Agricultural College, Jagtial,
Professor Jayashankar Telangana
State Agricultural University,
Telangana, India

V Ravinder
Agricultural College, Jagtial,
Professor Jayashankar Telangana
State Agricultural University,
Telangana, India

B Sowjanya
Agricultural College, Jagtial,
Professor Jayashankar Telangana
State Agricultural University,
Telangana, India

T Archana
Agricultural College, Jagtial,
Professor Jayashankar Telangana
State Agricultural University,
Telangana, India

Corresponding Author:
GS Madhu Bindu
Agricultural College, Jagtial,
Professor Jayashankar Telangana
State Agricultural University,
Telangana, India

Nature-positive agriculture for climate-resilient food systems: Concepts, indicators, practices and future research directions

GS Madhu Bindu, P Spandana Bhatt, I Tirupathi, G Venu Gopal, V Ravinder, B Sowjanya and T Archana

DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i7Sf.6419>

Abstract

Agriculture is simultaneously a major user of land and freshwater, a source of greenhouse-gas emissions and a potential pathway for restoring ecosystem functions. Nature-positive agriculture has therefore emerged as an outcome-oriented framing that seeks not only to reduce environmental damage but also to improve the condition of soils, biodiversity, water resources and ecosystem services while maintaining viable food production and farmer livelihoods. This review synthesizes recent literature on the conceptual basis, indicators, management practices, climate-resilience pathways, enabling conditions and research priorities associated with nature-positive agriculture. The review distinguishes nature-positive agriculture from, while recognizing its strong links with, regenerative agriculture, conservation agriculture, agroecology, climate-smart agriculture and nature-based solutions. Particular attention is given to measurable indicators covering soil health, biodiversity, carbon, water, ecosystem services, productivity and socioeconomic outcomes. Evidence indicates that diversified cropping, agroforestry, conservation agriculture, organic and natural farming approaches, ecological pest management, precision irrigation and digital decision-support tools can generate multiple co-benefits, but their effects are strongly context dependent. A central conclusion is that no single practice can be considered nature positive independently of location, baseline conditions, management intensity and outcomes. Future assessment should therefore move from practice-based claims toward transparent outcome-based monitoring, combining biophysical, economic and social indicators with farmer participation and credible monitoring, reporting and verification. Scaling will require coherent policy, transition finance, extension, market incentives, digital inclusion and integration of scientific and Indigenous knowledge. A practical framework is proposed for linking farm practices to measurable ecosystem outcomes and climate resilience, providing a basis for evidence-led implementation and future comparative research.

Keywords: Biodiversity, climate resilience, ecosystem services, regenerative agriculture, soil health, carbon sequestration, agroecology, sustainable food systems

1. Introduction

Food systems are under simultaneous pressure from climate change, biodiversity decline, land and water degradation, resource scarcity and the need to provide sufficient nutritious food. The challenge is no longer adequately described as increasing production alone. It is increasingly necessary to ask whether agricultural production can be maintained or improved while the ecological systems that support production are restored or strengthened. Recent work explicitly frames nature-positive agriculture as a pathway toward resilient agrifood systems, while the emerging 3N Agriculture framework links net-zero emissions, nature-positive outcomes and nutrient-balanced food production within one systems perspective (Kaushal *et al.*, 2025; Field *et al.*, 2026) [12, 6].

The term nature-positive should nevertheless be used carefully. Sustainability generally emphasizes maintaining acceptable conditions and reducing negative impacts, whereas regeneration and nature-positive approaches emphasize improvement in ecological condition. Regenerative agriculture is particularly relevant because it focuses on rebuilding soil health, biodiversity and ecosystem functioning, although its terminology and practice definitions remain heterogeneous (Sher *et al.*, 2024) [30]. Nature-based solutions similarly emphasize the use of ecosystem processes to address societal challenges, but their application to food systems must

account for production, livelihoods and trade-offs rather than assuming that every ecological intervention produces universal benefits (Keesstra *et al.*, 2023) ^[13].

The purpose of this review is to integrate these related concepts into a coherent framework for climate-resilient food systems. The specific objectives are to: (i) clarify the conceptual relationships among nature-positive agriculture and related approaches; (ii) organize indicators that can be used to assess nature-positive outcomes; (iii) synthesize evidence on major management practices and technologies; (iv) examine adaptation, socioeconomic and governance dimensions; and (v) identify research priorities for scaling credible nature-positive agriculture.

2. Review approach and conceptual scope

This article is a structured narrative review rather than a statistical meta-analysis. The supplied draft was reorganized around concepts, measurable outcomes, practices, climate-resilience pathways and enabling conditions. References were cross-checked against publisher or journal pages, DOI records or accessible full-text records where available. Preference was given to recent peer-reviewed literature, while established conceptual literature was retained where it provides necessary foundations. Because nature-positive agriculture is a rapidly evolving field, the review emphasizes studies published from 2023 to 2026 while retaining selected earlier foundational studies.

The conceptual scope treats nature-positive agriculture as an outcome-oriented umbrella rather than as a single prescribed production system. Thus, a practice is considered potentially nature positive when it contributes, under specified conditions, to measurable improvement in one or more ecological outcomes without unacceptable trade-offs in productivity, livelihoods or other ecosystem functions. This distinction is important because the same intervention can generate different outcomes across soils, climates, crops, scales and management systems.

3. Conceptual foundations

3.1 From sustainable agriculture to regenerative and nature-positive agriculture

Sustainable agriculture commonly seeks to maintain productivity and resource availability while reducing environmental damage. Regenerative agriculture goes further by emphasizing restoration of soil and ecosystem functions. Recent reviews identify soil health, biodiversity, climate mitigation and socioeconomic outcomes as major components of regenerative agriculture, but also highlight the absence of a universally standardized definition (Sher *et al.*, 2024; Caruso *et al.*, 2025) ^[30, 4]. Nature-positive agriculture can be positioned as an outcome-oriented extension of this discussion: the central

question is whether agricultural management produces a measurable improvement in the condition or functioning of nature rather than merely reducing the rate of degradation.

This distinction has practical implications for research. Labels such as regenerative, organic, natural, conservation or climate-smart do not by themselves establish a nature-positive outcome. Evidence should instead demonstrate changes in indicators such as soil organic carbon, aggregate stability, nutrient cycling, habitat quality, species diversity, water-use efficiency, greenhouse-gas balance, farm profitability and resilience. The approach therefore shifts evaluation from practice adoption to verified outcomes.

3.2 Nature-based solutions and the food-system perspective

Nature-based solutions provide a complementary conceptual basis because they seek to use ecosystem processes to address environmental and societal challenges. Keesstra *et al.* (2023) ^[13] emphasize that nature-based solutions can function as building blocks for climate-resilient food systems, but their effectiveness depends on ecological and socioeconomic context. Agroforestry illustrates this multifunctionality: trees can contribute to carbon storage, erosion control, microclimate regulation and livelihood diversification, while competition for light, water or nutrients can reduce crop performance in some designs. Consequently, nature-positive management should be assessed using explicit objectives and trade-off analysis rather than generalized claims of benefit.

3.3 The 3N perspective

The recently proposed 3N Agriculture framework integrates Net-Zero, Nature-Positive and Nutrient-Balanced objectives (Field *et al.*, 2026) ^[6]. This framework is useful because climate mitigation, biodiversity and nutrition are often treated separately even though they interact through land management, energy use, dietary patterns and resource allocation. A nature-positive food system should therefore be assessed across environmental and human outcomes rather than through a single carbon or biodiversity metric.

4. Indicators and monitoring framework

A credible nature-positive transition requires measurable baselines, defined direction of change and monitoring over an appropriate time period. The indicator system should be multidimensional because improvements in one domain may be accompanied by deterioration in another. Recent work has demonstrated the feasibility of combining farmer-selected and technical soil indicators, while ecosystem-service research has assembled large collections of field-based indicators suitable for direct empirical measurement (Soto *et al.*, 2020; Leveau *et al.*, 2025) ^[32, 16].

Table 1: A multidimensional indicator framework for assessing nature-positive agriculture. Indicator selection should be adapted to the production system and baseline conditions rather than applied as a universal checklist

Dimension	Representative indicators	Expected nature-positive direction	Suggested scale
Soil health	SOC, aggregate stability, bulk density, infiltration, microbial biomass, nutrient cycling	Increasing SOC and biological function; improved structure and infiltration	Plot/farm
Biodiversity	Crop diversity, habitat diversity, pollinators, natural enemies, soil biota	Greater diversity and functional redundancy	Field/landscape
Climate	GHG balance, SOC stocks, energy use, carbon intensity	Lower net emissions; higher stable carbon stocks	Farm/system
Water	Irrigation productivity, soil water retention, runoff, water quality	Higher water productivity; lower losses and pollution	Field/watershed
Ecosystem services	Pest regulation, pollination, erosion control, nutrient retention	Improved service delivery	Farm/landscape
Productivity	Yield, yield stability, quality, nutritional value	Stable or improved output with fewer ecological costs	Farm
Economics	Net returns, input costs, transition costs, risk	Improved profitability and resilience	Farm/household
Social	Labour, gendered access, knowledge, food security, participation	More inclusive access and adaptive capacity	Household/community

4.1 Soil health

Soil health is a core outcome because soil physical, chemical and biological functions underpin productivity and resilience. Relevant measurements include soil organic carbon, aggregate stability, bulk density, infiltration, available nutrients, microbial biomass and biological activity. Participatory assessment is particularly useful because farmers often identify practical indicators related to water regulation, erosion, fertility and crop performance that complement laboratory measurements (Soto *et al.*, 2020) ^[32]. Conservation agriculture can improve several physical, chemical and biological soil attributes, although magnitude and direction vary with climate, soil and management (Maqbool *et al.*, 2025) ^[17].

4.2 Carbon and greenhouse gases

Soil carbon is important for both soil function and climate mitigation, but carbon claims should distinguish changes in concentration from changes in stocks and should consider sampling depth, bulk density and temporal variability. A worldwide systematic review reported strong potential for conservation agriculture to increase soil carbon sequestration, with responses influenced by climate and soil texture (Ibnnmrhar *et al.*, 2023) ^[7]. Carbon should therefore be monitored with standardized sampling and mass-balance methods wherever possible. Claims about long-term sequestration should also account for permanence and possible reversibility.

4.3 Biodiversity and ecosystem services

Biodiversity indicators should cover both compositional and functional dimensions. Crop and habitat diversity, pollinator abundance, natural-enemy activity, soil biological indicators and semi-natural habitat can be integrated with ecosystem-service indicators. Martínez-Jauregui *et al.* (2019) ^[18] showed that social perceptions of biodiversity and ecosystem services influence the relevance of indicators, while Leveau *et al.* (2025) ^[16] demonstrated the availability of 128 field-based indicators for provisioning and regulating ecosystem services. Such approaches support more transparent selection of indicators according to the service being evaluated.

4.4 Water and resource efficiency

Water is a critical resilience variable. Deficit irrigation and precision water management can reduce irrigation demand while maintaining acceptable yields when stress is carefully scheduled, and sensor-based systems can improve the spatial and temporal resolution of irrigation decisions (Jadhav *et al.*, 2026) ^[9]. However, technology should be evaluated against total system costs, reliability, energy requirements and accessibility to smallholders rather than on technical performance alone.

4.5 Socioeconomic and resilience indicators

Nature-positive agriculture must remain economically and socially viable. Relevant indicators include net returns, input expenditure, yield variability, transition-period costs, access to finance, extension contact, climate information, gender-equitable access to resources and household food security. Evidence from Ethiopia and Kenya indicates that access to credit, information, extension and other institutional factors can materially influence adaptation and climate-smart practice adoption (Cherinet *et al.*, 2025; Mwanzia *et al.*, 2025; Abaynew *et al.*, 2026) ^[5, 20, 1].

5. Practices and technologies supporting nature-positive agriculture

5.1 Agroforestry

Agroforestry integrates woody perennials with crops and/or livestock and can simultaneously influence carbon storage, soil protection, microclimate and livelihood diversification. Recent Indian evidence indicates substantial variability in carbon-sequestration potential among agroforestry systems, while policy support remains important for scaling (Sharma *et al.*, 2025; Ram *et al.*, 2024) ^[29, 25]. Diversity within agroforestry systems is also important. In coffee systems, simplification of shade-tree diversity reduced the resilience of nutrient cycling, illustrating that the ecological quality of tree cover can matter as much as tree presence itself (Nesper *et al.*, 2019) ^[22].

5.2 Conservation agriculture and zero tillage

Conservation agriculture is commonly characterized by reduced soil disturbance, soil cover and crop diversification. Its potential contributions include improved soil structure, water retention, nutrient cycling and carbon storage. However, outcomes are not uniform, and pest dynamics can shift under residue retention and altered soil microclimate (Jasrotia *et al.*, 2023) ^[10]. Zero tillage can support moisture conservation and erosion reduction, but performance depends on weed management, residue availability, machinery, soil conditions and cropping sequence (Kumari *et al.*, 2023) ^[14].

5.3 Organic, natural and agroecological systems

Organic farming, natural farming and agroecological systems emphasize ecological processes, biological regulation and reduced dependence on synthetic inputs. A recent review of organic farming identifies potential benefits for soil health, biodiversity and drought resilience but also recognizes yield gaps, weed pressure and transition costs (Panotra *et al.*, 2026) ^[24]. Natural farming has similarly been proposed as a climate-adaptation pathway through reduced external-input dependence and emphasis on soil and water conservation (Lakhani *et al.*, 2024) ^[15]. These approaches should nevertheless be compared using measured outcomes rather than assumptions about input type alone.

5.4 Crop diversification and intercropping

Diversification can enhance ecological stability by increasing functional diversity and disrupting pest dynamics. Experimental evidence from Dutch organic cabbage systems showed that spatial and genetic diversity reduced herbivore feeding injury and maintained total yield in most tested designs (Juventia *et al.*, 2021) ^[11]. A broader synthesis of agroecological practices identifies crop diversification, agroforestry, intercropping, cover crops, crop rotation and mixed farming as recurring resilience-oriented strategies, while emphasizing that responses depend strongly on local context (von Cossel *et al.*, 2025) ^[35].

5.5 Ecological pest management

Nature-positive plant protection seeks to increase biological regulation while reducing unnecessary chemical pressure. Diversified habitats, biological control, soil-mediated resistance and integrated pest management can contribute to this objective. Recent synthesis emphasizes the need to examine biodiversity-based pest suppression, biocontrol networks and soil-mediated defense together rather than as isolated interventions (Tetarwal *et al.*, 2026) ^[34].

5.6 Precision agriculture, AI and smart irrigation

Digital agriculture can improve the spatial targeting and timing of inputs. Smart irrigation increasingly combines soil sensors, remote sensing, wireless networks and machine learning. Recent reviews identify machine-learning approaches and sensor integration as promising tools for adaptive irrigation, but also identify high initial costs, infrastructure limitations and digital-literacy constraints (Irum & Hameed, 2025) ^[8]. AI-enabled climate-smart systems have also been proposed for crop forecasting, pest surveillance and resource optimization, although reported performance figures should be treated cautiously because they are often system- and dataset-specific (Roy *et al.*, 2025) ^[27].

6. Climate resilience and adaptation pathways

6.1 Farm-level adaptation

Climate resilience depends on the capacity of farms to absorb shocks, adapt management and maintain essential functions. Smallholder farmers use combinations of altered planting dates, crop diversification, improved varieties, soil and water conservation, irrigation, livestock diversification and livelihood diversification. Studies in Ethiopia demonstrate that adaptation choices are shaped by agroecology, education, extension, credit, climate information and household characteristics (Cherinet *et al.*, 2025; Abaynew *et al.*, 2026) ^[5, 1]. These findings reinforce the need to treat resilience as both a biophysical and institutional outcome.

6.2 Traditional and Indigenous knowledge

Local knowledge can strengthen adaptation when it is combined with scientific assessment rather than treated as either infallible or irrelevant. Research in Ghana and Mexico illustrates the importance of locally adapted soil and water management, participatory knowledge and community institutions (Naazie *et al.*, 2023; Reyes-Hernández *et al.*, 2025) ^[21, 26]. A systematic assessment of Indigenous Knowledge and ecosystem services in Ethiopia further indicates that institutional recognition, community ownership and participatory monitoring are important for successful integration (Yihune & Sangha, 2026) ^[36].

6.3 Climate information and extension

Access to timely, understandable climate information can determine whether farmers are able to translate knowledge into action. Evidence from Northern Ghana shows that radio, extension, farmer networks and mobile communication can all contribute to information access, while limited localization, infrastructure and gender-related differences can restrict effectiveness (Mumuni *et al.*, 2026) ^[19]. The implication is that digital systems should complement rather than automatically replace local extension and peer-learning networks.

6.4 Water management

Agricultural water management is a major climate-resilience pathway. Deficit irrigation, precision scheduling, soil-water conservation, mulching and improved infiltration can increase water productivity. Jadhav *et al.* (2026) ^[9] summarize evidence that appropriately designed deficit irrigation can reduce irrigation demand substantially while limiting yield penalties, but emphasize the need for long-term field validation, economic analysis and integration with real-time sensing.

7. Policy, finance and scaling

Adoption is not determined by technical performance alone. Policy coherence, finance, extension, markets, infrastructure and institutional capacity influence whether practices can move from experimental plots to farms and landscapes. Nepal's food-system transformation experience highlights policy incoherence, insufficient local capacity, limited research and weak empirical evidence as barriers to nature-positive transitions (Suwal *et al.*, 2025) ^[33]. Global food-governance literature similarly emphasizes the influence of institutional legacies, power relations and competing interests on food-system transformation (Slater *et al.*, 2026) ^[31].

Financial mechanisms can support transition where farmers face up-front costs or temporary yield risks. Access to agricultural financial services is associated with climate-smart agriculture adoption, but awareness does not necessarily translate into actual access because collateral, interest rates, distance and service design remain constraints (Mwanzia *et al.*, 2025) ^[20]. Carbon markets and payments for ecosystem services may provide additional incentives, but credible monitoring, reporting and verification and fair benefit distribution are essential to avoid overstating environmental outcomes.

Gender-responsive governance is also necessary. Women contribute substantially to soil management, water conservation, seed selection, livestock care and biodiversity stewardship, yet access to land, information, finance and decision-making can be unequal. Gender-responsive environmental policies can therefore improve both equity and the effectiveness of climate adaptation (Assan *et al.*, 2026) ^[2].

8. Integrated framework for nature-positive agriculture

The evidence reviewed here supports a five-step framework: baseline, intervention, outcome, trade-off and scaling. First, establish a baseline for soil, biodiversity, water, carbon, productivity and socioeconomic conditions. Second, select context-appropriate practices or combinations. Third, quantify changes in agreed indicators. Fourth, identify trade-offs and distributional effects. Fifth, scale only those interventions for which benefits are sufficiently robust and economically feasible. This approach avoids the common error of equating adoption of a named practice with achievement of a nature-positive outcome.

Table 2: Outcome-oriented framework for implementing and evaluating nature-positive agriculture

Stage	Core question	Examples of evidence
Baseline	What is the starting ecological and socioeconomic condition?	SOC, biodiversity, water use, yield, income, vulnerability
Intervention	What management change is being implemented?	Diversification, agroforestry, CA, irrigation, ecological IPM
Outcome	What changed, and in what direction?	SOC stock, habitat quality, water productivity, yield stability
Trade-off	What negative or uneven effects occurred?	Yield reduction, labour burden, water competition, transition cost
Scaling	Can the outcome be reproduced economically and institutionally?	Farmer demand, extension capacity, finance, markets, MRV

9. Research gaps and future priorities

Develop standardized but flexible nature-positive indicator sets that allow comparison across crops, soils, climates and farming

systems.

Move from short-term measurements to multi-year monitoring of soil carbon, biodiversity, water and yield stability.

Quantify trade-offs among productivity, biodiversity, carbon, water and farmer income rather than reporting only positive outcomes.

Develop low-cost monitoring, reporting and verification systems suitable for smallholders and mixed farming systems.

Integrate soil microbiome, plant health, biodiversity and climate observations to clarify mechanisms of resilience (Sedhupathi *et al.*, 2026) ^[28].

Combine remote sensing, IoT and AI with field measurements, while reporting uncertainty and external validation rather than only model accuracy.

Evaluate transition economics, labour requirements, risk and market incentives under real farm conditions.

Strengthen participatory monitoring so farmer knowledge contributes to indicator selection and interpretation.

Investigate landscape-scale biodiversity, pest regulation and water outcomes because many ecosystem services extend beyond farm boundaries.

Develop policy and finance mechanisms that reward verified outcomes rather than merely subsidizing individual practices.

10. Conclusion

Nature-positive agriculture offers a useful framework for reconciling food production with restoration of ecological functions, but its credibility depends on measurable outcomes. The literature supports the potential of agroforestry, conservation agriculture, diversification, organic and natural farming, ecological pest management, precision water management and digital tools to contribute to climate resilience and ecosystem services. At the same time, the evidence shows substantial context dependence and important trade-offs. Nature-positive agriculture should therefore not be defined by a fixed package of practices. It should be defined by a transparent process in which baseline conditions are established, appropriate interventions are selected, ecological and socioeconomic outcomes are monitored, trade-offs are disclosed and successful approaches are scaled through supportive institutions and markets. The most important research opportunity is consequently to develop robust, affordable and participatory monitoring frameworks capable of linking farm management with measurable changes in nature and resilience. Such an outcome-based approach can help move nature-positive agriculture from an aspirational concept toward an evidence-led pathway for climate-resilient food systems.

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