

Review

A Comparative Analysis of Agricultural Sustainability Approaches: Environmental Performance and Efficiency Implications

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Abstract

The increasing environmental impacts of conventional agriculture have intensified the search for farming approaches capable of balancing food production, resource efficiency, and ecosystem protection. In this context, multiple sustainability-oriented approaches have emerged, including organic agriculture, integrated production, sustainable agriculture, and regenerative agriculture. This study develops a comparative framework based on a structured literature review covering the period January 2000–March 2026 to assess these approaches from both practice-based and governance perspectives. The analysis examines key environmental management dimensions, alongside governance-related aspects. The results reveal substantial convergence across approaches regarding core environmental practices, including cover cropping, crop diversification, reduced tillage, and input optimisation. However, important differences emerge in system integration, governance structures, and sustainability objectives. Efficiency-oriented approaches mainly prioritise productivity and resource optimisation, whereas regenerative and organic approaches place stronger emphasis on ecosystem restoration and soil health. The study highlights the limitations of current sustainability assessment frameworks and emphasises the need for integrated, outcome-based approaches capable of capturing both environmental impacts and regenerative benefits across agricultural systems.

Keywords: environmental sustainability; integrated production systems; organic farming; regenerative agriculture; resource-use efficiency; sustainable agriculture



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1. Introduction

Agriculture is a fundamental cornerstone of human society. The food system is embedded within broader social, economic, cultural, and environmental systems and represents a vital component of the global economy [1]. The world population is projected to grow by approximately 31% by 2050, leading to a substantial increase in food demand. According to the Food and Agriculture Organisation (FAO), global food production may need to increase by 60 to 110% above 2007 levels to meet the global population's nutritional requirements by 2050 [2]. While the Green Revolution, characterised by high-input and technology-dependent production systems, successfully contributed to feeding the growing global

population over the past decades [1], conventional agricultural systems are now facing increasing pressure from multiple challenges that threaten their long-term sustainability [3].

Conventional farming systems frequently rely on the intensive, often inefficient use of natural resources and are increasingly affected by global pressures, including population growth, biodiversity loss, rapid urbanisation, and climate change. In addition, the excessive use of fertilisers and pesticides may lead to harmful residues in food, posing risks to both consumers and farmers [3,4]. These practices also contribute to soil degradation, water contamination, and biodiversity loss, ultimately compromising ecosystem services and the long-term productivity of agricultural land [3,5,6]. In response to these challenges, there is a growing need to transition toward agricultural systems that promote environmental protection, efficient resource use, and long-term resilience [7].

Key approaches investigated since the early 2000s include agroecology, sustainable intensification, organic farming, conservation agriculture, integrated crop–livestock systems, precision agriculture, integrated pest management, and regenerative agriculture. Broader food system transformations such as dietary changes and food waste reduction have also been proposed [8–13]. These approaches seek to reconcile the need for increased food production with the imperative to reduce environmental impacts. Their effectiveness, however, often depends on local environmental conditions, policy frameworks, technological innovation, and stakeholder engagement.

Sustainable agriculture refers to farming systems that meet current needs while promoting environmental quality, preserving natural resources, and ensuring long-term viability [14]. However, the concept remains debated, with two main perspectives: an ecocentric approach focused on ecological processes and resource reduction, and a technocentric approach emphasising technological innovation and efficiency improvements.

Several agricultural approaches have emerged in response to these perspectives. Sustainable intensification aims to increase yields per unit area while minimising adverse environmental impacts through improved input-use efficiency without expanding agricultural land [5,15]. Organic and low-input farming systems avoid synthetic fertilisers and pesticides and prioritise soil health through practices such as crop rotations and organic amendment, though they may require more land per unit of output than conventional systems [16]. Conservation agriculture promotes practices like no-till farming, cover cropping, and crop rotation, which improve soil structure and carbon accrual while reducing erosion and nutrient runoff [17]. Precision and climate-smart agriculture rely on digital technologies and data-driven tools, such as GPS-guided machinery, to optimise resource use efficiency and reduce environmental impacts [18].

In addition to these approaches, regenerative agriculture has recently gained increasing attention as a paradigm for agricultural sustainability [19]. Although many of the practices associated with regenerative agriculture are not new, the approach emphasises the integrated implementation of multiple practices to improve soil health and broader agroecosystem functioning [20]. The term regenerative agriculture was first introduced by Robert Rodale (1983) [21], who argued that industrialised agriculture was progressively degrading its natural resource base. Rodale emphasised that without actively restoring these resources, approaches such as sustainable or conservation agriculture alone would be insufficient to meet the food and resource demands of a growing global population [21]. Thus, regenerative agricultural systems aim not only to reduce environmental impacts but also to restore agroecosystems by enhancing soil health, increasing biodiversity, and maintaining profitable food production [22–24].

Given the conceptual ambiguity and partial overlap among sustainability-oriented approaches, each of the four approaches examined in this study (organic agriculture, integrated production, sustainable agriculture and regenerative agriculture) was delineated

by integrating theoretical perspectives with operational characteristics reported in the literature. This procedure enabled a more rigorous comparison of practices, sustainability dimensions, and potential trade-offs. Although the selected approaches differ in their level of conceptual abstraction and operational definition, this distinction was intentionally retained in the analytical framework. The objective of the comparative framework was not to compare mutually exclusive farming systems, but to analyse how sustainability is conceptualised and operationalised across the principal agricultural sustainability approaches described in the literature. The following definitions are drawn from the conceptual and operational interpretations most commonly reported in the literature.

Organic agriculture is among the most established sustainability-oriented farming systems, although its definition remains contested. According to the International Federation of Organic Agriculture Movements (IFOAM), it is based on ecological processes, biodiversity, and the health of soils, ecosystems, and people [25,26]. In practice, however, it is commonly operationalised through a certified production system characterised by the use of practices such as crop rotations and organic amendments, and the prohibition of synthetic inputs [27–30]. In this study, organic agriculture is defined through a combination of its conceptual foundations and its operational implementation within certified production systems [31].

Integrated production systems encompass a range of practices aimed at optimising input use and reducing environmental impacts. Within this framework, Integrated Pest Management (IPM) represents the dominant crop protection strategy and is mandatory for professional users in the European Union under Directive 2009/128/EC [32]. Despite some definitional variability, IPM is generally conceptualised as a holistic decision-making framework integrating multiple pest control strategies, prioritising preventive, biological, and agronomic measures while restricting chemical pesticide use to situations where it is strictly necessary and applied in a targeted manner [33–36]. In this study, particular attention is given to IPM as a key operational component of integrated production systems.

Sustainable agriculture is widely recognised as a multidimensional and conceptually ambiguous framework, lacking a single, universally agreed definition [37,38]. It is commonly defined as the capacity of agricultural systems to meet current food needs while safeguarding the ability of future generations to do the same, with sustained productivity, reduced pollution, and economic viability as core objectives [39–41]. At the same time, the literature emphasises that sustainable agriculture extends beyond a set of practices, representing a broader systemic transition that integrates environmental stewardship, economic resilience, and social well-being within agricultural systems [42]. In this sense, it functions as an overarching and normative framework, encompassing multiple and sometimes competing sustainability approaches. In this study, sustainable agriculture is interpreted both as a normative framework encompassing multiple sustainability objectives and as a set of strategies aimed at improving resource-use efficiency and reducing environmental impacts.

Regenerative agriculture lacks a single legal, regulatory, or widely accepted scientific definition and is identified in many, often contrasting, ways [19,43–46]. It is generally understood as a principles-based approach aimed at improving soil health, biodiversity, climate resilience, ecosystem functioning, and socio-economic conditions [19,44,47]. Rather than representing a distinct production system, regenerative agriculture is commonly viewed as a goal-oriented approach that promotes the integrated implementation of context-specific management practices to regenerate the natural capital and ecosystem functions [44,46–49]. In this study, regenerative agriculture is interpreted through this combined conceptual and operational perspective, enabling its consistent comparison with the other agricultural approaches.

Despite the proliferation of sustainability-oriented agricultural approaches, none has replaced the dominant model of industrial agriculture. Instead, multiple frameworks have emerged, proposing different pathways to reconcile productivity with environmental sustainability. Recent studies have examined these approaches from a narrative perspective, focusing on their historical evolution, underlying ideologies, and socio-political drivers, including the emergence and positioning of regenerative agriculture within broader sustainability discourses [50].

However, despite advances in understanding the evolution and framing of these approaches, limited attention has been given to their practical implementation. In particular, it remains unclear how they translate into farm-level practices, which sustainability dimensions they address, and how they manage trade-offs between production efficiency and environmental impact. Addressing this gap is essential to better distinguish their practical contributions to sustainable agri-food systems.

Therefore, this study develops a comparative framework that examines both practice-based environmental management strategies and broader framework-level characteristics associated with different agricultural approaches. By structuring these elements into a comparative matrix, the analysis enables an assessment of similarities and differences across approaches in terms of agronomic practices, sustainability dimensions, and system boundaries.

This study contributes to the literature by providing a comparison of agricultural sustainability approaches at both the practice and framework levels, integrating agronomic and governance perspectives. The analysis addresses the following research questions:

- To what extent do different agricultural approaches address the main dimensions of environmental sustainability?
- What trade-offs emerge between production efficiency and environmental impact reduction across these approaches?
- Which approaches can be considered more holistic in scope, and which remain more sectoral or partial in their focus?

In addition, this study aims to assess how sustainability is governed across approaches, with particular attention to differences in standardisation, certification mechanisms, and framework-level characteristics. By doing so, it bridges the gap between practice-based assessments and governance-oriented analyses, which are often treated separately in existing research.

2. Materials and Methods

2.1. Literature Review Strategy

A structured literature review was conducted to identify, analyse, and synthesise the main principles, practices, and sustainability claims associated with the four agricultural approaches: organic agriculture, integrated production, sustainable agriculture, and regenerative agriculture.

The review followed a transparent and replicable protocol, encompassing the stages of identification, screening, eligibility assessment, and final inclusion of relevant studies.

The literature search was performed across major scientific databases, including Web of Science, Scopus, and Google Scholar, to ensure broad coverage of peer-reviewed literature. The search strategy was based on a combination of keywords related to agricultural approaches and terms associated with environmental sustainability and system performance.

Specifically, the following core search strings were applied in the title, abstract, and keyword fields:

- “organic agriculture” OR “organic farming”

- “integrated production” OR “integrated pest management”
- “sustainable agriculture” OR “sustainable farming system”
- “regenerative agriculture” OR “regenerative farming”

These were combined using Boolean operators with sustainability-related terms, including: “environmental impact”, “sustainability assessment”, “life cycle assessment”, “LCA”, “soil health”, “biodiversity”, “carbon sequestration”, “climate change”, “resource efficiency”, and “ecosystem services”.

The temporal scope of the review spanned from January 2000 to March 2026; this time-frame was selected to capture both the consolidation of organic and integrated approaches in the early 2000s and the more recent emergence and rapid expansion of regenerative agriculture. The literature search was completed in March 2026, which was established as the predefined cut-off date for study inclusion.

The initial search yielded many records, which were subsequently refined through a multi-step screening process. Duplicate records were identified and removed using reference management software (e.g., Zotero, version 9), ensuring consistency and avoiding redundancy.

Studies were screened based on title and abstract according to a set of predefined inclusion criteria, consistently applied across all agricultural approaches. Eligible studies were required to explicitly address one of the target agricultural approaches as a primary focus or intervention within agricultural, horticultural, or forestry production systems.

Eligibility criteria were defined to ensure consistency with the research questions and the scope of the comparative analysis: studies were included if they (i) explicitly addressed at least one of the selected agricultural approaches, (ii) examined one or more environmental sustainability dimensions (i.e., soil, biodiversity, climate, or water), and (iii) provided insights into the relationship between environmental performance and resource efficiency. Reflecting this scope, the comparison intentionally included approaches with different levels of conceptual specificity and operational definition, which were analysed using a common comparative framework.

Only documents written in English and falling within the fields of agricultural, environmental, and biological sciences were considered. Eligible records consisted exclusively of peer-reviewed journal articles published in high-impact scientific journals, to ensure robustness and scientific credibility. For the purposes of this review, high-impact journals were defined as those indexed in Web of Science or Scopus with a recognised reputation, providing a standardised proxy for scientific visibility and peer-review quality. Following the eligibility assessment, a final set of studies was selected for in-depth analysis.

In addition to peer-reviewed literature, a limited number of institutional reports, technical documents, and regulatory or standard-setting sources developed by international organisations (e.g., FAO, IFOAM) and regulatory bodies (e.g., EU regulatory acts) were included to broaden the analytical perspective and to characterise the formal governance frameworks of the four approaches. This integration allowed for a more comprehensive understanding of both scientific evidence and evolving sustainability approaches.

2.2. Development of the Comparative Matrix

The comparative framework was structured around a set of practice-based environmental management dimensions, reflecting concrete agronomic practices that are directly observable at the field and farm level and commonly discussed in the literature as key determinants of environmental performance.

These dimensions include soil, biodiversity, input efficiency, and water. For each agricultural approach, relevant practices reported in the literature (e.g., cover cropping, reduced tillage, use of non-synthetic active ingredients, buffer strips, diversified crop

rotations) were identified and systematically mapped to these dimensions to assess overlaps and differences across approaches.

This practice-based matrix enables a structured and comparable analysis of how different agricultural approaches operationalise environmental sustainability through on-field management strategies, highlighting both areas of convergence and divergence among systems.

2.3. Framework-Level Governance Analysis

To complement the practice-based comparison, an additional analysis was conducted to examine how sustainability is governed, standardised, and operationalised across agricultural approaches.

This analysis focused on key governance-related dimensions, including: (i) type of governance (regulatory, certification-based, voluntary), (ii) reference to formal standards (e.g., European Union regulations, international standards, private certification schemes, etc.), (iii) presence of labelling or certification mechanisms, (iv) coverage of sustainability pillars (environmental, economic, social), (v) sectoral scope of application, and (vi) degree of standardisation and measurability.

The identification of relevant information was supported by structured literature exploration and the extraction of comparable descriptors across studies. The resulting evidence was then critically assessed and synthesised by the authors to ensure conceptual consistency and comparability across approaches.

This dual analytical structure enables a comprehensive comparison of agricultural sustainability approaches, distinguishing between similarities in farm-level practices and differences in governance structures, levels of standardisation, and systemic scope.

3. Results and Discussion

3.1. Literature Selection and Dataset Overview

The literature search identified a substantial number of records across the agricultural approaches examined, demonstrating the extensive scope and diversity of sustainability-related research in agricultural systems. Specifically, 3935 records were found for organic agriculture, 2039 for integrated production, 11,632 for sustainable agriculture, and 664 for regenerative agriculture.

After duplicate removal and the application of subject-area and document-type filters, the number of records was significantly reduced. This refinement resulted in 2656 records for organic agriculture, 1374 for integrated production systems, 6046 for sustainable agriculture, and 411 for regenerative agriculture.

Title and abstract screening further narrowed the dataset to studies aligned with the research objectives. This stage resulted in 123 eligible records for organic agriculture, 85 for integrated production systems, 796 for sustainable agriculture, and 96 for regenerative agriculture. A final full-text assessment led to the inclusion of 58 studies for organic agriculture, 25 for integrated production systems, 106 for sustainable agriculture, and 49 for regenerative agriculture.

Across all approaches, the selected studies encompass a wide range of methodological designs, including field experiments, observational studies, comparative analyses, life cycle assessments (LCA), modelling approaches, and systematic reviews or meta-analyses. However, the distribution of study types varies significantly among the four agricultural approaches.

The distribution of records reveals substantial differences in the level of scientific development, conceptual clarity, and empirical consolidation of the four approaches. To further characterise this variation, a supplementary exploratory scan of the recent literature

was conducted for each of the four approaches by classifying records according to the continent of the reported study site, where identifiable. Because a substantial proportion of the included records consisted of reviews, meta-analyses, and conceptual or methodological papers without a single identifiable study location, the geographic distribution is reported only for place-specific empirical studies. This supplementary analysis is intended as an indicative assessment rather than a comprehensive geographical mapping, and the reported percentages should therefore be interpreted as approximate.

Sustainable agriculture clearly dominates the literature in quantitative terms, reflecting its role as a broad and flexible framework encompassing multiple farming approaches. However, this wide representation is also associated with a high degree of heterogeneity in definitions, methodologies, and assessment approaches. It presents the most diverse range of study designs, encompassing LCA, modelling approaches and observational studies. This diversity reflects the broad and integrative nature of the concept, which includes multiple farming systems and evaluation frameworks. Studies are globally distributed, often covering multiple regions within a single analysis, with a strong representation of cross-country comparisons and global assessments. Among place-specific studies, this literature is the most geographically balanced of the four, with Europe (~29%), Asia (~28%), Africa (~15%) and North America (~14%) all carrying meaningful weight. This wide geographical scope contributes to the variability of results, highlighting the importance of local environmental and management conditions in shaping sustainability outcomes.

Organic agriculture is characterised by a relatively high proportion of long-term field experiments, meta-analyses, and LCA studies, reflecting a well-established research domain with strong empirical grounding. The literature encompasses both site-specific experimental studies and large-scale meta-analyses conducted across multiple regions, allowing for robust comparisons with conventional systems. The geographical distribution of studies is broad, covering Europe, North and South America, Asia, Africa, and Oceania, with a predominance of research conducted in temperate regions. Place-specific studies are concentrated in Europe (~40%) and Asia (~31%, driven largely by India), together exceeding 70% of the located evidence, while North America (~8%) and Latin America (~5%) remain narrow.

In contrast, integrated production systems are less represented, suggesting a more specialised and technically oriented research domain. This system shows a more heterogeneous methodological profile, with a prevalence of field-based studies, comparative farm analyses, and system-level assessments focusing on IPM, crop–livestock integration, and nutrient management strategies. These studies are often context-specific and management-oriented, with a strong emphasis on applied research. Geographically, the literature spans multiple continents, including Europe, North and South America, Asia, and particularly emerging economies such as China, India, and Brazil, reflecting the relevance of integrated systems in diverse agroecological and production contexts. Place-specific evidence is fairly balanced across Europe (~24%), Asia (~24%), and North America (~21%), with the strongest Latin American representation of the four approaches (~12%), though roughly 30% of records lack a clear geographic scope.

Regenerative agriculture, although more recent in the scientific literature, shows a growing number of empirical studies, including field experiments, comparative farm assessments, and system-level evaluations. A notable feature of this body of literature is the integration of multiple assessment approaches, combining field measurements with modelling and life cycle analysis. The geographical distribution is similarly broad but still uneven, with a concentration of studies in North America, Europe, and Australia, and fewer contributions from developing regions. Among place-specific studies, this is the most Global-North-skewed of the four approaches, with Europe, North America and Oceania

together accounting for ~73%, against ~11% for Africa and South America combined. This pattern reflects both the emerging nature of the concept and its current diffusion across research and practice contexts.

Overall, the selection process resulted in a balanced and diverse dataset, suitable for a comparative analysis of principles, practices, and sustainability outcomes across different agricultural approaches. The full screening process and the number of records at each stage are illustrated in Figure 1.

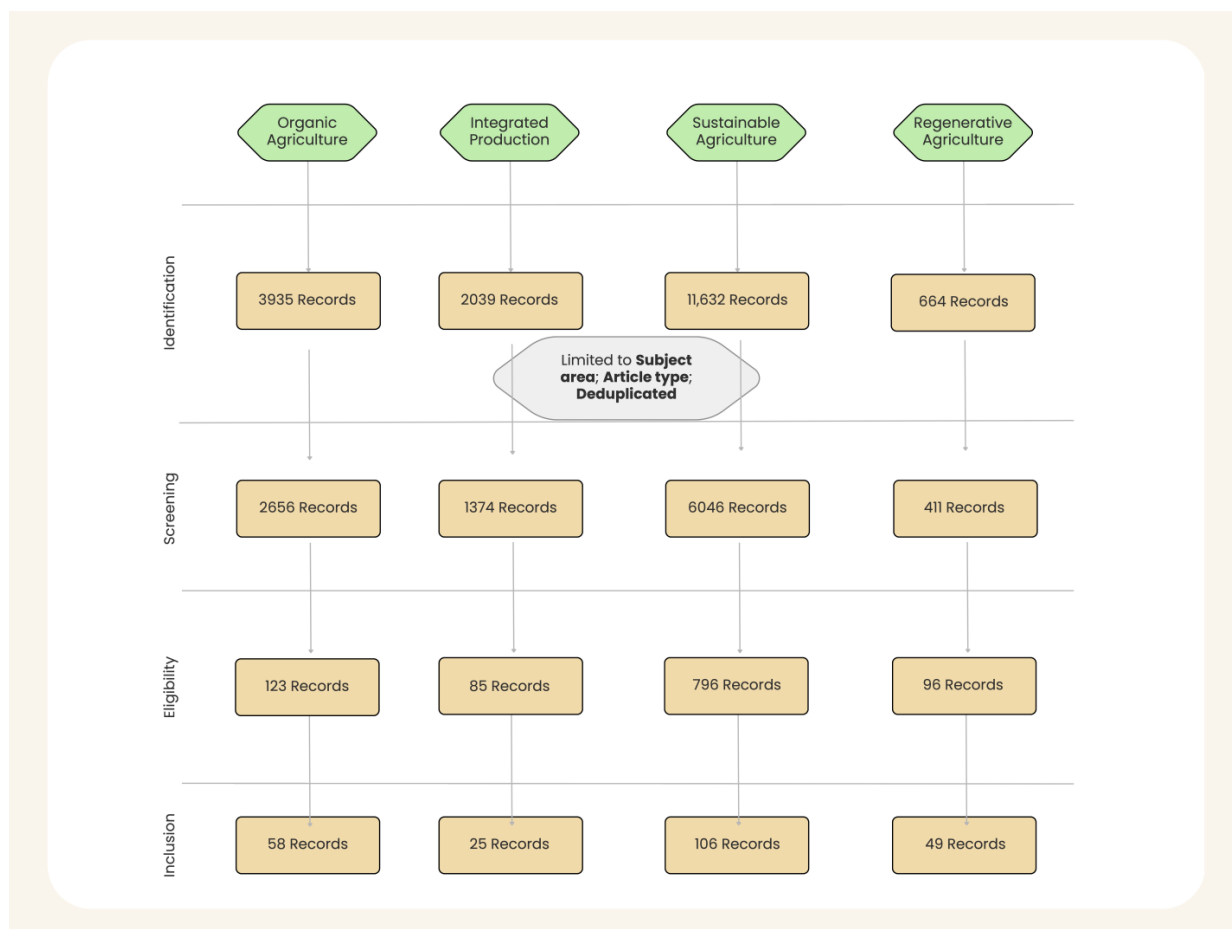


Figure 1. Diagram of the literature identification, screening, eligibility assessment, and inclusion process.

Although additional sustainability-oriented approaches, such as conservation agriculture, agroforestry, and sustainable intensification, are widely discussed in the literature and were retained as analytical references within the overall framework, they were not treated as standalone analytical categories in this first phase of the literature analysis. This decision was motivated by both conceptual and empirical considerations emerging from the literature search and was intended to avoid redundancy, duplication of studies, and artificial fragmentation of the dataset.

From a conceptual perspective, these approaches are not consistently defined as discrete agricultural systems, but rather as sets of practices or management principles that can be implemented across different farming frameworks. In contrast to organic agriculture and integrated production systems, which are generally characterised by clearly defined management protocols and—in some cases—formal regulatory or certification schemes, conservation agriculture, agroforestry, and sustainable intensification primarily function as cross-cutting sustainability approaches.

This conceptual overlap is also reflected in the empirical literature. During the bibliographic search and screening process, these additional approaches rarely appeared as mutually exclusive categories. Instead, they were commonly embedded within studies on organic agriculture, integrated production, sustainable agriculture, or regenerative agriculture, with many of the same management practices associated with multiple approaches.

In the subsequent comparative analysis, a more integrative perspective is adopted. Rather than treating these approaches as separate systems, the analysis focuses on the management practices through which sustainability is operationalised across different agricultural approaches. This practice-based perspective enables the identification of convergence, complementarities, and structural overlaps among the approaches considered.

3.2. Comparative Analysis of Practice-Based Dimensions

The following analysis refers to the practice-based comparison reported in Figure 2, in which agricultural practices are organised into practice clusters, which are in turn grouped under broader macro-categories, such as (i) soil, (ii) biodiversity, (iii) input efficiency and (iv) water. Within this framework, each agricultural approach is assessed in terms of the practices explicitly promoted, those that are conditional or not explicitly stated, and those that are prohibited. This classification is intended to provide analytical clarity and facilitate comparison across different sustainability approaches. However, it is important to note that individual practices often generate multiple and interrelated effects and therefore may contribute simultaneously to different practice clusters and macro-categories rather than belonging exclusively to a single dimension.

3.2.1. Soil

Soil management represents a central dimension in the comparative analysis of environmental strategies, as soil health is widely recognised as a key determinant of agricultural sustainability, productivity, and ecosystem functioning [45,51,52]. Across the approaches examined, a strong convergence emerges around a core set of practices, including reduced soil disturbance, continuous soil cover, diversified crop rotations, incorporation of plant residues, and the use of organic amendments [43,44,53–59]. These practices are consistently associated with improvements in soil organic matter (SOM), aggregate stability, water retention and biological activity, as well as with reduced erosion and nutrient losses [44,53–56,60–63].

Despite this shared foundation, significant differences emerge in how these practices are combined and prioritised within each approach. Conservation agriculture focuses on minimising soil disturbance and maintaining permanent soil cover to reduce erosion and protect soil structure [56,64,65]. Organic farming emphasises biological processes through organic amendments and legume-based rotations to enhance soil fertility and microbial activity [54,66]. Integrated systems adopt a hybrid strategy, combining organic and mineral inputs to enhance soil fertility while ensuring adequate nutrient supply and maintaining productivity goals [67,68]. Similarly, sustainable agriculture incorporates a mix of conservation and efficiency-oriented practices, often supported by technological tools aimed at optimising input use and maintaining yields, particularly within sustainable intensification systems [61,63]. Regenerative agriculture places soil health at the centre of its objectives, promoting the combined application of complementary practices to restore soil functions and ecosystem processes [44,45,58]. Lastly, agroforestry systems represent a structurally distinct approach integrating perennial vegetation, thereby enhancing soil organic carbon, nutrient stocks, and microbial biomass through continuous litter inputs, deep root systems, and improved microclimatic conditions [55,69].

MACRO-CATEGORY	PRACTICE CLUSTER	PRACTICE	SUSTAINABLE APPROACHES						
			CONSERVATIVE	ORGANIC	AGROFORESTRY	SUSTAINABLE	SUSTAINABLE INTENSIVE	INTEGRATED	REGENERATIVE
SOIL	Minimize disturbance	No-till	✓	○	○	✓	✓	○	✓
		Minimum tillage	✓	○	✓	✓	✓	○	✓
		keyline sub-soiling	○	○	✓	✓	✓	○	✓
		Tillage	✗	○	○	○	○	○	○
		Controlled traffic	✓	○	○	○	○	○	✓
	Keep soil covered	Cover-crop	✓	✓	✓	✓	✓	✓	✓
		Living mulch	✓	○	✓	✓	✓	✓	✓
		Crop-residues retained	✓	○	✓	○	○	✓	✓
	Maintain living roots	Off-season cover crops	✓	✓	✓	✓	✓	✓	✓
Agroforestry roots		○	○	✓	○	○	○	✓	
BIODIVERSITY	Increase plant diversity	Crop rotation	✓	✓	✓	✓	✓	✓	✓
		Intercropping	✓	✓	✓	✓	✓	✓	✓
		Multi-species cover	○	○	✓	○	○	✓	✓
	Integrated livestock	Rotational grazing	○	○	✓	○	○	○	✓
		Crop-livestock integration	○	○	✓	○	○	○	✓
	Tree integration	Alley cropping	○	○	✓	○	○	○	○
		Windbreaks / Boundary planting / Shelterbelts	✓	✓	✓	✓	✓	✓	✓
Multi-strata systems		○	○	✓	○	○	○	○	
INPUT EFFICIENCY	Build organic matter	Compost	○	✓	✓	✓	✓	✓	✓
		Manure	○	✓	✓	✓	✓	✓	✓
		Green manure	✓	✓	✓	✓	✓	✓	✓
		Digestate	○	○	○	✓	✓	○	✓
		Biochar	○	○	○	○	○	○	✓
	Synthetic inputs	Strong reduction	✓	✗	✓	✓	✓	✓	✓
		Elimination	○	○	○	○	○	○	○
		Mechanical/thermal weed control	○	✓	✓	✓	✓	✓	✓
		Biological pest control	○	✓	✓	✓	✓	✓	✓
		Integration with chemical inputs	○	✗	○	○	✓	○	○
	Precision Farming	Site-specific nutrient rates	✓	✓	○	✓	✓	○	○
		Site-specific pest and disease control	✓	✓	○	✓	✓	✓	○
Remote sensing		✓	✓	○	✓	✓	✓	○	
Precision water management		✓	✓	○	✓	✓	○	○	
WATER	Protect and manage water	Riparian buffers	✓	✓	✓	✓	✓	○	✓
		Contour planting	✓	✓	✓	✓	✓	✓	✓
		Grassed waterways	✓	✓	✓	✓	✓	○	✓
		Tree rows on slopes	✓	✓	✓	✓	✓	○	✓
		Efficient irrigation	✓	✓	○	✓	✓	✓	○

Figure 2. Comparative assessment of agricultural practices promoted across major agricultural sustainability approaches. Practices identified in the literature were grouped into practice clusters and macro-categories and classified according to their degree of adoption within each approach: ✓ explicitly promoted; ○ conditionally adopted or not explicitly specified; ✗ prohibited. Colors indicate the macro-categories used to classify the agricultural practices.

A key point of differentiation concerns the balance between soil restoration and production efficiency. Approaches such as sustainable intensification and integrated systems tend to prioritise yield stability and input-use efficiency, sometimes maintaining relatively high levels of external inputs. In contrast, organic, regenerative and agroforestry approaches emphasise soil restoration and ecosystem functioning, potentially accepting short- and medium-term yield reductions in exchange for long-term improvements in soil quality and resilience. Overall, these differences reflect the broader distinction between efficiency-oriented and restoration-oriented approaches to agricultural sustainability.

3.2.2. Biodiversity

Another key dimension of environmental performance in agricultural systems is represented by biodiversity. It directly influences ecosystem services such as pollination, pest control and nutrient cycling [70]. As for soil management, biodiversity-enhancing practices are widely shared across agricultural approaches, though they differ in their level of integration. Across approaches, a common set of practices emerges as consistently associated with positive biodiversity outcomes. These include reduced or no use of synthetic pesticides, maintenance of permanent vegetation cover, diversified crop rotations, intercropping or polycultures and the integration of semi-natural habitats (e.g., hedgerows, flower strips). Additional practices, including multi-species cover crops, rotational grazing, and crop-livestock integration, may further contribute to habitat diversification and ecological functioning [71,72]. However, no single practice benefits all taxa and responses vary by group and by the extent to which intensive inputs are reduced. Consequently, combining multiple biodiversity-friendly practices is considered essential to maximise biodiversity outcomes [71].

Despite these shared elements, differences emerge in how biodiversity is managed across systems. Conservation agriculture promotes biodiversity primarily through reduced disturbance and the introduction of ecological infrastructures (e.g., flower strips) [73,74]. Organic farming achieves biodiversity gains mainly through the prohibition of synthetic inputs and the promotion of diversified rotations and vegetation complexity. Organic farming is often associated with higher biodiversity levels compared to conventional systems across multiple taxa [71,75]. Agroforestry systems introduce a higher level of structural complexity by integrating trees, crops and, in some cases, livestock within the same system. Practices such as alley cropping, multistrata systems, and silvopastoral integration increase habitat heterogeneity and connectivity and are associated with higher levels of biodiversity compared to simplified cropping systems [76,77]. Similarly, integrated farming systems combine multiple components, including crops and ecological infrastructures, to increase habitat diversity and support ecological interactions across the farm and landscape levels [78]. Sustainable agriculture incorporates biodiversity-enhancing practices within a broader management strategy aimed at maintaining production while reducing environmental impacts [79]. These include diversified cropping systems, habitat management for beneficial organisms and chemical inputs reduction. Their effectiveness in enhancing biodiversity depends on the extent to which these practices are implemented and on the level of habitat heterogeneity achieved [80]. A similar pattern characterises sustainable intensification, although increasing productivity remains the primary objective [81]. Lastly, regenerative agriculture includes many of the practices identified across other approaches, such as continuous soil cover, high plant diversity, reduced synthetic inputs, livestock integration and, in some cases, agroforestry elements. These practices are associated with efforts to enhance both aboveground and belowground biodiversity through diversified and continuous vegetation cover and reduced disturbance [49,82].

3.2.3. Input Efficiency

Input efficiency was distinguished between: (i) building organic matter, (ii) synthetic inputs, and (iii) precision farming.

Building SOM represents a key component of input efficiency in agricultural systems, as it contributes to nutrient cycling, soil fertility, water retention, and overall system resilience [83–85]. Across systems, SOM enhancement is commonly achieved through the application of organic inputs and the retention of biomass within the system (e.g., prunings, crop residues). Core practices include the use of farmyard manure, compost, green manure, crop residues, and biochar. These practices are often combined with reduced soil disturbance and continuous soil cover, which together support the accumulation and stabilisation of soil organic carbon over time [54,86]. Differences among agricultural approaches mainly relate to how these inputs are used and integrated into farming systems. Conservation agriculture primarily relies on residue retention and reduced tillage to build SOM, with organic amendments playing a complementary role [54,87]. Organic farming places a stronger emphasis on SOM accumulation through the systematic use of compost, manure, and green manure, which are explicitly framed as central inputs for maintaining soil fertility [54,88]. Agroforestry systems contribute to SOM through continuous organic inputs derived from tree litter, root turnover, and pruning residues, often complemented by manure or compost applications [89]. Sustainable agriculture incorporates a combination of organic amendments, cover crops, and residue management practices to restore or maintain SOM, particularly in degraded soils. Sustainable intensification approaches adopt similar practices but often integrate them with nutrient optimisation strategies. Combinations such as biochar and compost, for example, are used to improve nutrient-use efficiency and reduce reliance on synthetic fertilisers [61,63,90]. Integrated farming systems emphasise the recycling of organic matter within the system, particularly through the use of manure from livestock, composted materials, and cover crops. These practices are typically implemented as part of broader nutrient management strategies aimed at improving soil fertility and system efficiency [67]. Regenerative agriculture incorporates a wide range of SOM-building practices, including manure, compost, green manure, crop residues, cover crops, and biochar, often applied in combination with reduced disturbance and continuous soil cover [43,44].

The management of synthetic inputs represents a central component of input efficiency in agricultural systems, as it directly affects both resource-use efficiency and environmental impacts [91]. The comparative analysis indicates that agricultural approaches differ primarily in the extent to which synthetic fertilisers and pesticides are reduced, optimised, or avoided. Reductions in synthetic inputs are associated with the adoption of biological pest control, crop diversification, IPM, and non-chemical weed management strategies. Conservation agriculture generally aims to reduce, but not eliminate, synthetic inputs. This is achieved through practices such as soil cover, crop rotations, and IPM, which decrease input dependency while maintaining productivity. Herbicides are often still used, although typically at lower rates, and are complemented by mechanical weed control methods [92].

Organic farming adopts a different approach, characterised by the prohibition of synthetic fertilisers, herbicides, and most pesticides. Instead, it relies on natural inputs, biological pest control, and mechanical or physical weed management practices such as tillage, mulching, and mowing. Biological control and habitat management are central components of pest regulation in these systems [93].

Agroforestry systems show greater variability in the use of synthetic inputs. Some systems operate with minimal or no synthetic inputs, particularly when aligned with organic principles, while others allow limited use depending on management objectives [94].

Sustainable agriculture generally focuses on reducing synthetic inputs and aims to improve their efficiency rather than eliminate them. This includes the use of precision technologies, optimised nutrient management, IPM and improved rotations to reduce input requirements while maintaining yields [95]. This is similarly approached in sustainable intensification systems. Integrated farming approaches emphasise the reduction and careful management of synthetic inputs through the combination of organic inputs and biological control [96].

Regenerative agriculture is generally characterised by a strong emphasis on reducing or avoiding synthetic inputs, although definitions vary and some systems allow limited or transitional use. These systems rely on practices such as crop diversification, soil cover, and biological pest control to support ecosystem functions and reduce dependency on external inputs [49].

Precision farming represents a technology-based approach to improve input efficiency in agricultural systems through site-specific and data-driven resource management. It relies on tools such as GPS, geographic information systems (GIS), remote and proximal sensing, drones, and variable-rate application technologies. These technologies optimise the use of inputs, including fertilisers, pesticides, and water, while reducing environmental impacts [97]. It can be implemented across all of them, although it is most frequently associated with sustainable agriculture approaches [98]. In conservation and sustainable agriculture systems, precision farming is typically presented as a tool to reduce input losses and improve resource conservation, for example, by optimising fertiliser application and minimising agrochemical runoff [97,99]. Similarly, within sustainable intensification approaches, precision technologies are used to maintain or increase yields while reducing input use, aligning with broader objectives of improving efficiency and lowering environmental impacts. Precision farming is less explicitly associated in the literature with agroforestry or regenerative agriculture. In these approaches, the focus is more commonly placed on ecological processes, system diversification, and biological interactions rather than on technology-driven optimisation.

Lastly, microclimate management may be considered an additional dimension of input efficiency, as it influences resource use (e.g., water, energy, nutrient dynamics) by regulating temperature, radiation, and soil moisture conditions. Across approaches, microclimate regulation is achieved through a combination of soil-based practices, structural elements, and technological solutions such as reduced tillage, residue retention, and permanent soil cover [100]. Agroforestry systems introduce structural complexity through tree–crop and sometimes livestock interactions, which modify radiation and temperature, reduce thermal variability, and improve water-use efficiency [101].

3.2.4. Water

Water management represents a key dimension of environmental performance in agricultural systems, as it directly affects hydrological processes such as runoff, infiltration, water retention, and nutrient transport. The agricultural approaches considered incorporate a range of practices aimed at protecting water resources. Despite differences in implementation, all approaches focus on reducing runoff and erosion, improving soil water retention, and limiting water contamination. Across approaches, improved water regulation is consistently associated with reduced or no tillage, residue retention, permanent soil cover, diversified rotations, and landscape features such as buffer strips, grassed waterways, terraces, and wetlands.

Conservation agriculture emphasises soil-based mechanisms for water protection, particularly through surface cover and reduced disturbance, which enhance water infiltration, reduce evaporation, and mitigate erosion. These practices improve water-holding capacity

and reduce nutrient losses, especially in water-limited environments [102]. Organic farming also focuses on water quality protection, primarily through the avoidance of synthetic fertilisers and pesticides, which reduces nitrate leaching and chemical contamination of water bodies. In addition, practices such as cover cropping, organic amendments, and mulching support soil structure and water retention [103]. Agroforestry provides water protection through structural elements such as trees, riparian buffers, and windbreaks, which intercept runoff, reduce soil loss, and improve infiltration. These systems are associated with substantial reductions in sediment, nutrient, and pesticide transport, as well as improvements in stream water quality and watershed-level regulation [104]. Sustainable agriculture and sustainable intensification approaches integrate multiple practices to enhance water regulation and resilience, such as conservation practices, organic amendments, agroforestry elements, and water-saving irrigation techniques. Together, they contribute to improved infiltration, reduced evaporation, and enhanced drought buffering capacity [105]. Integrated farming combines soil and water conservation practices, often including crop diversification and mulching. Moreover, their reduced use of synthetic inputs and emphasis on resource recycling contribute to lowering the risk of water contamination and improving overall water quality. Regenerative agriculture incorporates reduced disturbance, permanent soil cover, diversified rotations, and organic inputs. These practices contribute to rebuilding soil structure and organic matter, which in turn enhances water infiltration, reduces runoff and erosion, and supports long-term water quality and system resilience [102].

Overall, the approaches show strong convergence in the adoption of core environmental management practices. Their main differences lie not in the practices themselves, but in how they are integrated within farming systems and aligned with broader management objectives. Conservation agriculture and sustainable intensification primarily emphasise efficiency and resource optimisation, often maintaining a degree of reliance on external inputs and technological solutions. In contrast, organic, agroforestry, and regenerative systems place greater emphasis on ecological processes, system diversification, and the restoration of ecosystem functions, often accepting trade-offs in short-term productivity. These findings highlight the importance of moving beyond practice-based assessments towards a more systemic understanding of agricultural sustainability, where environmental performance depends on the coordinated implementation of complementary practices rather than on individual measures in isolation [106].

However, the effectiveness of these practices cannot be fully understood without robust tools to measure their outcomes. Reliable and harmonised indicators are essential to translate management practices into measurable performance, supporting consistent monitoring, evidence-based decision-making, the identification of trade-offs, and the avoidance of unintended burden shifting across sustainability dimensions [107]. They also improve transparency and facilitate communication of sustainability performance to stakeholders. Current indicator frameworks remain largely focused on negative environmental impacts, while the beneficial effects of sustainable practices—such as ecosystem services, biodiversity enhancement, and soil improvement—remain insufficiently captured. Although LCA provides a comprehensive and systematic framework, its conventional application in agriculture does not adequately account for these positive contributions [108]. Furthermore, existing indicators are often fragmented and mono-dimensional, limiting the assessment of trade-offs across environmental, social, and economic dimensions. Advancing agricultural sustainability therefore requires integrated, LCA-based indicator frameworks capable of quantifying both impacts and benefits, enabling a more comprehensive evaluation of sustainability outcomes [108].

3.3. Framework-Level Governance Comparison

The comparative analysis of governance structures (Table 1) reveals substantial differences in how sustainability is defined, operationalised, and verified across agricultural approaches. Overall, the comparison highlights a clear gradient in sustainability governance, ranging from highly standardised and regulated systems (organic agriculture) to loosely defined and principle-based approaches (regenerative agriculture). This gradient reflects a fundamental trade-off between standardisation and adaptability, with important implications for policy design, certification schemes, and market recognition [109]. Furthermore, differences emerge in the coverage of sustainability pillars. While all approaches strongly address environmental dimensions, economic and social aspects are more explicitly integrated within sustainable agriculture frameworks. In contrast, organic and regenerative tend to prioritise environmental objectives, with socio-economic dimensions addressed more implicitly or indirectly.

Table 1. Comparative overview of agricultural sustainability approaches: governance, standards, and certification framework.

Approach	Type of Governance	Reference Standards	Labelling/ Certification	Sustainability Pillars	Scope of Application	Standardisation/ Measurability	Ref.
Organic Agriculture	Predominantly regulatory, based on EU legislation and official control systems with accredited certification bodies	Anchored in EU regulations; complemented by international reference frameworks (e.g., Codex Alimentarius, IFOAM standards)	Yes—mandatory EU organic logo supported by third-party certification and control systems	ENV (with implicit socio-economic elements)	Applies across plant and animal production systems under the EU regulatory framework	High standardisation; compliance-based system with limited emphasis on outcome-based metrics	(Migliorini & Wezel, 2017 [27]; <i>Regulation–834/2007–EN–EUR-Lex</i> , n.d. [110]; <i>Regulation–889/2008–EN–EUR-Lex</i> , n.d. [111])
Integrated Agriculture (IFM/ICM/IPM)	Hybrid governance combining regulatory requirements (e.g., EU IPM Directive) with voluntary and certification-based schemes	Based on EU policy frameworks (Directive 2009/128/EC) and complemented by private standards and farm assurance schemes	Certification and audit schemes are present; consumer-facing labelling is limited or not consistently applied	ENV (with variable inclusion of economic and social aspects)	Primarily applied to crop and livestock production systems, often context-specific	Medium and heterogeneous; standardisation varies across schemes, with limited harmonisation of measurable criteria	(Angon et al., 2023 [96]; Rossi et al., 2023 [112]; Zhou et al., 2024 [113])
Sustainable Agriculture	Predominantly voluntary and certification-based, driven by private and multi-stakeholder sustainability initiatives	Based on diverse private and multi-stakeholder standards, no single harmonised regulatory framework has been identified	Third-party certification is common; labelling varies significantly across initiatives	ENV, EC, SOC	Broad scope across crops and value chains, from local to global initiatives	Variable: monitoring relies on diverse indicator systems, with high heterogeneity across initiatives	(Konefal et al., 2023 [109]; Rugani & Lamastra, 2023 [108]; Schönherr, 2022 [114])
Regenerative Agriculture	Predominantly voluntary and emerging governance, with increasing interest in certification and standardisation initiatives	No harmonised standard; heterogeneous implementation, with emerging standardisation efforts (including ISO-related initiatives)	Certification initiatives are emerging; labelling remains inconsistent across schemes	ENV (with growing attention to socio-economic dimensions)	Broad, system-level application focused on soil health and ecosystem processes	Low and contested; lack of clear definitions and limited measurable and standardised criteria	(Giller et al., 2021 [43]; Kumar et al., 2025 [60]; Newton et al., 2020 [19]; Schreefel et al., 2020 [45]; Shennan-Farpón et al., 2025 [115])

4. Conclusions

This study provides a systematic framework for comparing contemporary agricultural sustainability approaches at both the practice and framework levels. The analysis highlights how the transition toward more sustainable food systems is characterised by a shift from simple impact reduction to more holistic, restoration-oriented objectives, within the geographic and institutional contexts represented in the reviewed literature.

Functional Convergence and Systemic Integration: The results demonstrate significant functional convergence across the approaches considered, with a shared core of management practices, such as reduced tillage, cover cropping, and diversified rotations, promoted across all approaches. This suggests that the primary distinction between these approaches lies not in the individual practices themselves, but in their degree of integration, underlying system design, and overarching objectives.

Governance and Management: This study highlights how agricultural sustainability approaches differ not only in their management practices but also in their governance models. A gradient emerges from highly regulated systems, such as organic agriculture, to more flexible, principle-based approaches, such as regenerative agriculture. These models are associated with different degrees of integration of the environmental, economic, and social dimensions of sustainability, with important implications for the design and implementation of sustainability standards.

Geographical Imbalance and Research Limitations: A limitation of this study is the geographical imbalance of the available literature. While sustainable and organic agriculture are well represented globally, research on regenerative agriculture remains concentrated in North America, Europe, and Australia, limiting the representativeness of the available evidence. Expanding the evidence base and undertaking systematic geographical mapping across agricultural sustainability approaches are important priorities for future research to support more context-sensitive sustainability pathways. As a result, the scientific consensus on the efficacy of regenerative practices may not be directly transferable to the Global South or to tropical agroecosystems, where pedoclimatic conditions, farming systems, and socio-economic constraints differ substantially.

Methodological Implications for Future Research: This study highlights the urgent need to move beyond practice-based assessments toward outcome-based evaluation frameworks. Current indicators remain largely focused on negative environmental impacts, often failing to capture the positive externalities generated by sustainable practices, such as carbon sequestration, biodiversity enhancement, and improved ecosystem services. Future research should focus on developing integrated, multicriteria LCA tools capable of quantifying both impacts and regenerative benefits. Such advancements are essential for ensuring transparency, avoiding unintended burden shifting, and providing a robust evidence base for global agri-food policy transformations.

Ultimately, advancing agricultural sustainability will depend not only on the adoption of individual practices, but on their coherent integration within farming systems and on robust frameworks capable of evaluating both their environmental impacts and their regenerative benefits.

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Abbreviations

The following abbreviations are used in this manuscript:

FAO	Food and Agriculture Organisation
EU	European Union
GIS	Geographic Information Systems
IFOAM	International Federation of Organic Agriculture Movements
IPM	Integrated Pest Management
LCA	Life Cycle Assessment
SDGs	Sustainable Development Goals
SOM	Soil Organic Matter

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