

Article

Environmental Priorities and Methodological Shifts in Agricultural Sustainability Assessment: A Text-Mining Analysis of Scientific Literature

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Abstract

Agricultural sustainability assessment is increasingly required to characterize how food production systems interact with land, soil, water, carbon dynamics, and broader environmental change. However, the extent to which scientific assessment methods capture these environmental-system interactions remains unclear. This study mapped methodological and thematic trends in agricultural sustainability research through text mining of 3302 bibliographic records retrieved from the Web of Science Core Collection, which was selected because of its standardized metadata structure and suitability for reproducible text-mining analysis, covering publications from 2003 to 1 March 2025. After corpus preprocessing and tokenization, term-frequency analysis, dimension-specific lexical classification, co-occurrence networks, and temporal bibliometric trends were used to identify dominant environmental themes and assessment approaches. The results revealed a clear predominance of the environmental dimension in the analyzed literature, particularly through terms associated with land, carbon, soil, and water resources, whereas social and economic dimensions displayed lower lexical representation. Food, production, and systems formed a central semantic cluster linking environmental assessment with food security. Life Cycle Assessment (LCA) was the most frequently identified methodology, reflecting the prominence of impact-oriented environmental evaluation. In contrast, integrative and farm-scale frameworks, including Driver–Pressure–State–Impact–Response (DPSIR), Sustainability Assessment of Food and Agriculture Systems (SAFA), and the Tool for Agroecology Performance Evaluation (TAPE), among others, indicated increasing attention to governance, resilience, and agroecological transitions. These findings show that text mining can support environmental research by identifying methodological biases and emerging priorities in agriculture–environment interactions. Strengthening integrated assessment approaches will be essential for managing natural resources and supporting resilient and environmentally sustainable food systems.

Keywords: agricultural sustainability assessment; text mining; bibliometric analysis; Life Cycle Assessment; environmental indicators; food systems; methodological biases



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1. Introduction

Agricultural production is deeply connected to environmental systems because it depends on land, soil fertility, water availability, biodiversity, and climatic conditions, while simultaneously influencing resource degradation, greenhouse gas emissions, ecosystem functions, and food security. In the context of global environmental change, sustainable agriculture therefore requires assessment approaches capable of identifying how production systems interact with natural resources and how these interactions affect their long-term capacity to provide food without compromising environmental integrity. This need is particularly relevant under increasing climatic uncertainty, resource scarcity, and pressure on agroecosystems, where environmental performance must be interpreted together with productivity, resilience, and human well-being [1].

Sustainability assessment provides a methodological basis for understanding these agriculture–environment interactions. Traditionally, agricultural sustainability has been described through three interconnected dimensions: environmental, economic, and social. The environmental dimension addresses resource use, soil and water quality, biodiversity conservation, emissions, and ecosystem impacts; the economic dimension concerns productivity, profitability, and long-term viability; and the social dimension includes equity, livelihoods, participation, and rural well-being [1,2]. Although these dimensions are conceptually complementary, assessment practice has often concentrated more strongly on environmental indicators, particularly where quantifiable impacts such as emissions, resource consumption, land degradation, and pollution can be measured through standardized procedures.

It is important to clarify that the present study does not constitute a first-order review of agricultural sustainability performance or a technical evaluation of individual assessment tools. Rather, it is a meta-level text-mining and bibliometric analysis of how the scientific literature represents agricultural sustainability assessment. In this sense, methods such as Life Cycle Assessment (LCA), Sustainability Assessment of Food and Agriculture Systems (SAFA), Framework for the Evaluation of Natural Resource Management Systems Incorporating Sustainability Indicators (MESMIS), Tool for Agroecology Performance Evaluation (TAPE), Resilience, Adaptation Pathways and Transformation Approach (RAPTA), and Driver–Pressure–State–Impact–Response (DPSIR) are examined here as methodological and conceptual markers within a bibliographic corpus. By analyzing their frequency, co-occurrence, and temporal evolution, this study evaluates how sustainability dimensions, environmental priorities, and assessment approaches have been emphasized or underrepresented in published research [3].

Life-cycle-based approaches have become central tools for examining the environmental burdens associated with agricultural production, particularly resource use, emissions, and impacts occurring throughout production chains [4]. However, approaches focused predominantly on environmental performance may provide limited information on social conditions, economic resilience, local knowledge, institutional arrangements, or the capacity of farming systems to respond to disturbances. To address these limitations, farm-level frameworks such as Response-Inducing Sustainability Evaluation (RISE) and Indicateurs de Durabilité des Exploitations Agricoles (IDEA) broadened the assessment perspective by incorporating multiple dimensions and management-oriented indicators [5,6]. Similarly, the Sustainability Assessment of Food and Agriculture Systems guidelines developed by the FAO introduced a comprehensive framework structured around environmental integrity, economic resilience, social well-being, and good governance [7]. These developments illustrate a transition from methods focused primarily on environmental impact measurement toward frameworks intended to capture the broader sustainability of agricultural and food systems.

More recent approaches further expand this perspective by integrating attributes that are especially relevant under global environmental change. MESMIS incorporates produc-

tivity, stability, resilience, adaptability, equity, self-reliance, and ecological sustainability in the analysis of natural resource management systems. The SMART-Farm framework operationalizes multidimensional sustainability assessment at farm level, while the Tool for Agroecology Performance Evaluation (TAPE) incorporates agroecological transition, environmental performance, social conditions, culture, health, nutrition, and governance [8]. In parallel, the Resilience, Adaptation Pathways and Transformation Approach (RAPTA) emphasizes adaptive governance and transformation pathways in systems exposed to uncertainty and disturbances [9]. These frameworks indicate that environmental sustainability in agriculture cannot be fully understood without considering resilience, institutional capacity, farmer participation, and food-system outcomes.

This issue is particularly relevant for tropical and Global South agroecosystems, where sustainability assessment often faces environmental and institutional pressures that differ from those of temperate and highly standardized production systems [10,11]. Smallholder and family farming systems in tropical regions frequently operate under high rainfall variability, intense soil weathering and laterisation, rapid biodiversity loss, limited access to infrastructure and technical services, and insecure or informal land tenure [12]. These conditions may affect the suitability of assessment frameworks that rely heavily on standardized datasets, fixed indicator thresholds, or externally defined sustainability criteria. For this reason, approaches that incorporate participatory diagnosis, agroecological transition, adaptive governance, and resilience, such as MESMIS, TAPE, and RAPTA, are especially relevant for evaluating sustainability in non-temperate and smallholder contexts [13]. Incorporating this perspective also helps assess whether the global scientific literature adequately captures the environmental and socioeconomic realities of agricultural systems in the tropics and the Global South.

This broader interpretation is supported by empirical applications and recent reviews. The application of SAFA to organic livestock farms showed its usefulness for identifying strengths and weaknesses across environmental integrity, economic resilience, social well-being, and governance dimensions [14]. Similarly, the application of TAPE to family farming systems in Mali showed that agroecological transitions may be associated with reduced pesticide use, healthier soils, greater biodiversity, improved food self-sufficiency, and more diverse diets [15]. Comparative reviews have also found important differences among assessment tools. Alaoui et al. reported that none of the evaluated frameworks covered all sustainability dimensions equally, with some methods displaying a stronger environmental emphasis and others providing greater representation of social or governance components [16,17]. Likewise, Chopin et al. found that most farming sustainability assessment tools remain structured around the classical three-pillar framework, whereas only a smaller proportion incorporate complex system properties, stakeholder participation, and dynamic indicators [18].

Despite this methodological progress, several limitations remain. First, the environmental, social, and economic dimensions are not represented evenly across assessment methods, and emerging dimensions such as governance, culture, health, and resilience are still inconsistently incorporated [9,10]. Second, the diversity of metrics, indicators, weighting procedures, and operational definitions limits comparability among studies and hinders the development of harmonized assessment approaches for agricultural systems [16,19]. Third, many assessment procedures provide static representations of sustainability and insufficiently address temporal change, climatic disturbances, adaptive capacity, or the transformation of agroecosystems over time [18,19]. Fourth, although agricultural sustainability directly affects rural communities, stakeholder participation remains limited in the design and interpretation of indicators, which may reduce the territorial relevance and practical legitimacy of sustainability assessments [20].

These limitations are particularly relevant from an environmental-system perspective. Frameworks such as DPSIR organize indicators according to driving forces, pressures, state changes, impacts, and responses, thereby linking agricultural activity with environmental management and policy responses [21]. However, determining which environmental themes and assessment approaches actually predominate in the scientific literature requires analysis at a broader scale. Existing reviews have provided valuable comparisons of specific tools and conceptual frameworks, but less attention has been given to mapping, across a large scientific corpus, how agricultural sustainability assessment represents environmental priorities such as land, soil, water, carbon, biodiversity, climate-related risks, and food security. Identifying these patterns is necessary to understand whether assessment research is moving toward approaches capable of representing agriculture as part of interconnected environmental and food systems.

Text mining and bibliometric analysis offer a reproducible strategy for addressing this gap. By examining lexical patterns, co-occurrence structures, and temporal trends in large collections of scientific records, these techniques can reveal the environmental themes that organize agricultural sustainability research and identify which assessment methodologies dominate or are emerging. This approach is especially relevant for environmental research because it enables the systematic identification of conceptual biases, methodological transitions, and underrepresented dimensions that may influence natural resource management and policy formulation.

Accordingly, this bibliometric and text-mining study does not seek to determine which sustainability assessment framework is universally superior, but to map how environmental priorities and methodological trends are represented in the scientific literature on agricultural sustainability assessment. Specifically, it seeks to: (i) identify the relative prominence of environmental, economic, and social dimensions in the analyzed corpus; (ii) determine how environmental-system themes, including land, soil, water, carbon, biodiversity, climate-related pressures, and food security, are represented in the literature; (iii) compare the occurrence and temporal evolution of major assessment approaches, including LCA, SAFA, RISE, MESMIS, SMART-Farm, TAPE, DPSIR, and RAPTA; and (iv) discuss the implications of these patterns for the development of integrated assessment tools capable of supporting natural resource management, climate resilience, and environmentally sustainable food systems.

2. Materials and Methods

The present study adopted a bibliometric and text mining approach to analyze the methodologies employed in agricultural sustainability assessment. The research followed a methodological sequence parallel to the order of the results presented: (i) construction of a word cloud and frequency analysis to identify dimensional emphasis; (ii) lexical classification and a co-occurrence graph to map semantic relationships; and (iii) a comparative analysis of sixteen methodologies and their temporal trends.

2.1. Literature Retrieval and Eligibility Criteria

The bibliographic search was conducted in the Web of Science Core Collection (Clarivate, Philadelphia, PA, USA) on 1 March 2025. This database was selected because of its standardized metadata structure and broad coverage of interdisciplinary research related to agriculture, environmental systems, sustainability assessment, and food production. The search strategy combined terms related to agricultural systems and sustainability assessment using Boolean operators and truncation symbols. The complete search equation was as follows: $TS = ((agricultur OR agroecosystem OR "agro-ecosystem*" OR "farming system*" OR "farm-level" OR "farm level" OR "cropping system*" OR "crop production system*" OR$

“agri-food system*” OR “agrifood system*” OR “food and agriculture system*” OR agroecolog* OR agricol* OR agropecuar* OR agroecosistema*) AND (sustainab* OR sostenib* OR sustentab*) AND (assess* OR evaluat* OR indicator* OR index* OR indice* OR índice* OR metric* OR metodolog* OR “assessment framework*” OR “evaluation framework*” OR “assessment tool*” OR “evaluation tool*” OR evaluac* OR indicador* OR metrica* OR métrica* OR “marco* de evaluac*” OR “herramienta* de evaluac*” OR avalia* OR “ferramenta* de avalia*”). The search was performed in the fields “Topic/Title/Abstract”. Eligible document types were articles, review articles, and proceedings papers that addressed agricultural, farming, agroecosystem, or food-production systems and referred to sustainability assessment, indicators, indices, or evaluation methodologies. No language restriction was applied. Records in English, Spanish, and Portuguese were retained when title, abstract, or author keywords were available, in accordance with the multilingual search strategy. The temporal coverage extended from the earliest retrieved publication to 1 March 2025.

2.2. Corpus Construction and Text Preprocessing

After screening, the corpus comprised 3302 bibliographic records. From the downloaded files, the lines labeled as Title (TI) and Abstract (AB) were explicitly extracted to build a data frame that facilitated subsequent analyses. To clean the corpus, full sentences were segmented and one line was created for each of them, preserving the internal semantic link of every sentence. Next, all sentences that did not contain the word “sustainability” were discarded. With this subset of relevant lines, an additional filter was applied to remove unusable tokens using multilingual stop-word lists for English, Spanish, and Portuguese, including articles, prepositions, conjunctions, and other non-informative terms. Finally, auxiliary columns were generated to identify the main topic of each sentence by searching for keywords associated with the economy, the environment, and the social dimension, which allowed the rapid classification of each statement within the classical sustainability triad. Preprocessing was carried out in R v4.4.3 with the libraries *readr*, *dplyr*, *stringr*, *stringi*, *forcats*, and *tm* [22]. These packages were used to convert text to lowercase, remove diacritics, punctuation, and redundant spaces, normalize lexical variants across English, Spanish, and Portuguese, and eliminate multilingual stop words.

2.3. Text Mining, Lexical Frequency, and Co-Occurrence Analysis

The cleaned corpus was tokenized using the *tidytext* package. Absolute and relative term frequencies were calculated for the complete corpus, the three sustainability dimensions, and the six environmental-system categories. As an exploratory visualization, the 50 most frequent terms were displayed in a word cloud generated with *wordcloud* and *RColorBrewer*. However, interpretations of thematic predominance were based on quantitative frequency distributions and term-by-category matrices rather than on visual inspection of the word cloud alone.

To evaluate the relative representation of environmental, social, and economic themes, as well as the prominence of land, soil, water, carbon/climate, biodiversity/ecosystem, and food-security concepts, term-by-category matrices were constructed and visualized as heat maps using *ggplot2*. In addition, bigrams were generated after removing stop words and non-informative lexical combinations. The most frequent eligible bigrams were transformed into an undirected weighted network using *tidygraph*, *igraph*, and *ggraph*, where nodes represented lexical terms and weighted edges represented co-occurrence frequency. The Fruchterman–Reingold algorithm was used to determine node placement for visualization, whereas interpretation was based on edge weights and thematic clusters.

2.4. Classification of Sustainability Dimensions and Environmental-System Themes

Two complementary lexical classification schemes were developed. First, records were classified according to the three classical sustainability dimensions: environmental, economic, and social. Second, to characterize agriculture–environment interactions in greater detail, an environmental-system dictionary was developed using six categories: (i) land use and land cover; (ii) soil systems and management; (iii) water resources; (iv) carbon emissions and climate-related pressures; (v) biodiversity and ecosystem functions; and (vi) food security and environmental resilience.

Each category was represented by predefined English and Spanish keywords and lexical variants. The complete dictionaries, conceptual definitions, inclusion terms, and exclusion rules are provided in Table S1. Records were assigned to one or more dimensions or environmental-system categories whenever category-specific terms occurred in the title, abstract, or author keywords. Multiple classification was permitted because agricultural environmental challenges may occur simultaneously within individual studies.

2.5. Identification and Temporal Analysis of Assessment Methodologies

A methodology dictionary was constructed to identify the principal assessment approaches represented in the literature, including LCA, LCSA/S-LCA, RISE, IDEA, SAFA, SMART-Farm, MESMIS, RAPTA, TAPE, FESLM, and DPSIR, among others. Methodologies were detected using regular expressions combining acronyms, full names, spelling variants, and context-specific terms. The complete list of methodologies and regular-expression patterns is provided in Table S2. Because several acronyms may occur in unrelated contexts, records identified exclusively through potentially ambiguous terms, including PCA, MCA, SAFE and SMART, were retained only when the surrounding text explicitly referred to sustainability assessment or an associated framework. A manually reviewed sample of classified records was used to estimate false-positive rates and refine the identification rules. This reliability check was included in the main analysis because ambiguous acronyms can occur outside sustainability-assessment contexts; therefore, records containing such acronyms were excluded when the surrounding text referred to unrelated statistical procedures, institutional names, or generic terminology rather than to an assessment methodology [23]. Records were classified as mentioning a methodology when its acronym or full name appeared in the title, abstract, or author keywords. Since mention of a method does not necessarily indicate its empirical implementation, results were interpreted as patterns of methodological occurrence in the scientific literature rather than as direct measures of application. Annual frequencies and annual relative proportions were calculated for each methodology. Relative proportions were obtained by dividing the number of records mentioning each methodology by the total number of eligible records published in the corresponding year. Annual frequencies and annual relative proportions were calculated for each methodology. Relative proportions were obtained by dividing the number of records mentioning each methodology by the total number of eligible records published in the corresponding year [24]. Cumulative frequencies were used only for descriptive visualization and not as evidence of comparative growth rates.

2.6. Reproducibility and Data Availability

Preprocessing and all subsequent analyses were performed in R version 4.4.3 (R Foundation for Statistical Computing, Vienna, Austria). To facilitate reproducibility, the bibliographic dataset, cleaned corpus, sustainability-dimension dictionary, environmental-system dictionary, methodology-identification patterns, source data underlying the figures, and complete analytical scripts were deposited in open repositories. The bibliographic dataset is available in Zenodo [25], and the analytical workflow and R notebook are available under version control

(Figure 2B). In this regard, words such as “environmental”, “soil”, “water”, and “cycle” stand out, exhibiting the most intense shading in this column (Figure 2B). By contrast, the social dimension shows an incipient interest in integrating evaluative frameworks and urban-social aspects into sustainability analysis, as evidenced by terms such as “index”, “dimensions”, “framework”, “urban”, and “impact” (Figure 2B). The economic dimension carried the lowest relative weight, indicating that financial performance is treated only tangentially, with just a few terms such as “land”, “analysis” and “index” (Figure 2B). It is noteworthy that words such as “systems”, “agriculture”, “indicators”, “development”, “assessment”, “food”, and “production” display a balanced distribution; their similar shading across the three columns suggests their potential to serve as integrative axes among the dimensions (Figure 2B). However, the overall pattern confirms the dominance of the environmental focus and shows that both the social and economic perspectives remain under-represented.

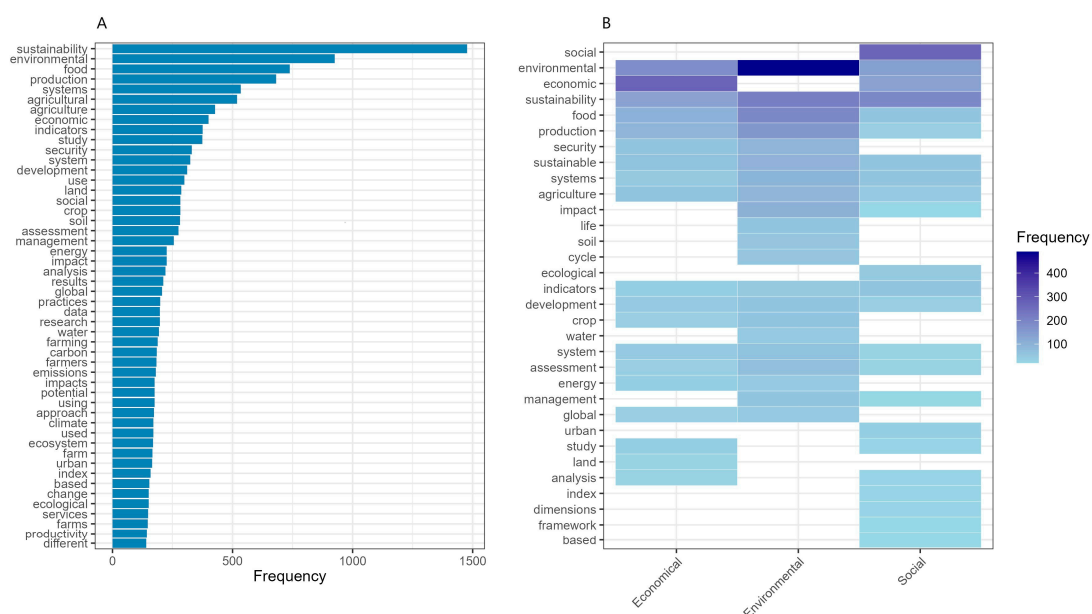


Figure 2. Lexical analysis of key terms in the scientific literature on agricultural sustainability. (A) Absolute frequency of the 50 most common words in titles, abstracts, and keywords of articles on agricultural sustainability. (B) Association of the most frequent words with the three classical dimensions of sustainability (economic, environmental, and social), represented in a heat map where color intensity indicates higher relative frequency.

The co-occurrence graph revealed a hierarchical lexical structure centered on food security, which concentrated the strongest links in the network ($n > 300$) (Figure 3). Food security was directly connected with two main lexical axes: agricultural production systems (“food–production–system”) and sustainable rural development (“rural–development–sustainable”) (Figure 3). A second core grouped the terms “sustainability”, “environmental”, “social”, and “economic”, reflecting the persistence of the classical three-dimensional framing of sustainability within the corpus. This semantic center was connected to methodological vocabulary such as “indicators”, “index”, “assessment”, and “impact/impacts”, suggesting that measurement and evaluation terms functioned as lexical bridges among the environmental, social, and economic dimensions (Figure 3). Around the central core, the co-occurrence map displayed several peripheral subclusters. The cluster formed by “sustainable”, “intensification”, “agriculture”, “crop”, and “farming” may indicate the presence of a lexical association between sustainability assessment and debates on agricultural productivity. Similarly, the cluster including “car-

Likewise, frameworks that break the three-dimensional paradigm and are grounded in functional attributes or systemic processes stood out. MESMIS structures the evaluation around seven critical attributes (productivity, stability, resilience, adaptability, equity, self-reliance, and ecological sustainability), offering a dynamic and participatory characterisation of family agro-ecosystems (Table 1). Similarly, RAPTA (versions 1 and 2) organised the evaluation into modules—system description, evaluation, adaptive governance, and multi-actor participation—to identify transformation pathways and has been piloted in food security programmes in Ethiopia with GEF support. Among emerging approaches, remote sensing combined with spatial indicators stood out for integrating the technological dimension and for its potential to inform territorial environmental policies. Niche tools such as TAPE-FAO focused on agroecological performance and show usefulness in countries of the Global South, although they require technical literacy on the part of farmers (Table 1). Finally, frameworks such as DPSIR facilitate the cause–effect articulation between agricultural activities and the environment, being adopted by international organisations such as the European Environment Agency (EEA) and the Organisation for Economic Co-operation and Development (OECD) to design policies on water and biodiversity, despite the absence of direct quantitative metrics (Table 1).

3.4. Evolution in the Application of Methodologies to Assess Agricultural Sustainability

The bibliometric analysis revealed a clear descriptive hierarchy in the frequency with which sustainability assessment methodologies were mentioned in the scientific literature from 2003 to 2025 (Figure 4A). Life Cycle Assessment (LCA) was the most frequently identified methodology, confirming its central role in studies focused on environmental impacts (Figure 4A,B). It was followed by RISE and IDEA, two farm-scale approaches recognized for integrating multiple dimensions of sustainable development. Methodologies such as PCA, DPSIR, and S-LCA also showed recurrent occurrence in the corpus, indicating their visibility in academic and technical studies. The temporal visualization in Figure 4B should be interpreted descriptively. LCA displayed the highest and most sustained increase in annual mentions across the study period, whereas approaches such as TAPE, SMART-Farm, RAPTA, and FESLM showed lower absolute frequencies but appeared more clearly in recent years. These patterns suggest emerging visibility of frameworks associated with governance, agroecology, and adaptive resilience. However, because no formal statistical trend test was retained in the revised analysis, these temporal patterns are interpreted as descriptive bibliometric tendencies rather than as statistically tested growth rates.

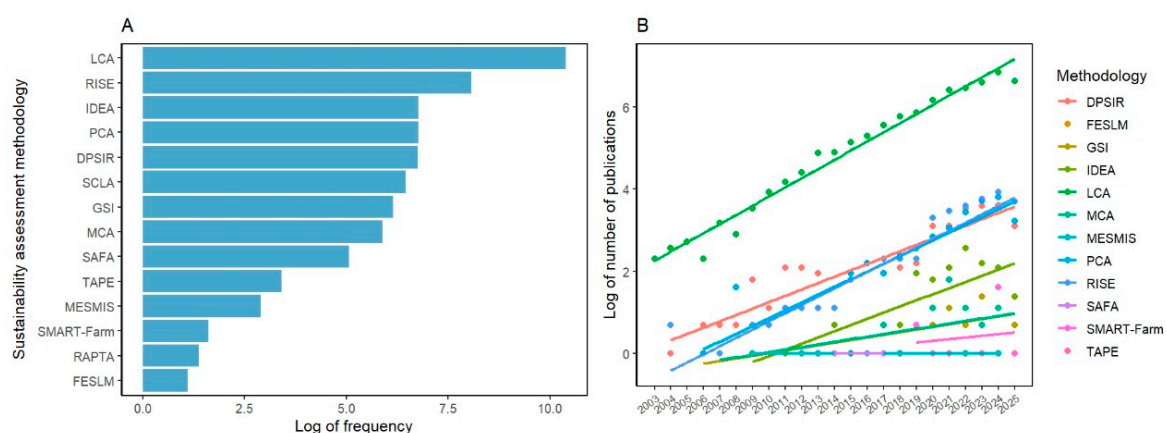


Figure 4. Trends in the application of agricultural sustainability assessment methodologies. (A) Relative frequency of 15 methodologies in the scientific literature from 2003 to 2025, expressed as the logarithm of the total number of publications. (B) Temporal evolution of each methodology. Dots represent the annual publication counts, whereas lines represent the corresponding temporal trends.

Table 1. Corpus-derived occurrence rank and contextual characterization of agricultural sustainability assessment methodologies identified in the bibliographic corpus.

Methodology	Corpus-Derived Occurrence Rank	Dimensions/Assessment Scope	Main Methodological Challenges	Use or Relevance in Policy and Decision-Making	References
LCA (Life Cycle Assessment)	1	Environmental, economic, social	Lack of standards in the evaluation of impacts.	Environmental policies and circular economy strategies. The ISO 14040 and ISO 14044 standards are based on the LCA methodology.	[2,27,28]
RISE (Response-Inducing Sustainability Evaluation)	2	Environmental, economic, social	Limited to individual farm analysis. Limited extrapolation. Requires specialized support in RISE.	Used for public purposes for farm certification and allocation of subsidies.	[29]
IDEA v4.0 (Indicateurs de Durabilité des Exploitations Agricoles)	3	Dual conceptual framework: three sustainability dimensions (environmental, economic, social) and five agro-system properties: autonomy, organisational capacity, adaptability, reproductive capacity, and production of goods and services.	Need for contextual adaptation for non-European countries. Limited direct participation of farmers in the design of sustainability objectives.	Used in the Haute Valeur Environnementale (High Environmental Value) certification.	[6]
PCA (Principal Component Analysis) and MCA (Multiple Correspondence Analysis)	4	Environmental, economic, social	Ordinal scales and subjective interpretation.	Mainly used as analytical tools for dimensionality reduction and sustainability index construction; direct use in public policy is limited.	[30,31]
General Sustainability Index (GSI) based on multivariate analysis (PCA and/or MCA)	7	Environmental, economic, social	Limited consideration of cultural, institutional, and governance dimensions.	Useful for comparative sustainability diagnosis, although direct use in public policy remains limited.	[32–34]
S-LCA (Social Life Cycle Assessment)	6	Social, cultural, governance, and institutional dimensions, with possible linkage to environmental and economic life-cycle information.	Results are often case-study dependent and may have limited extrapolation to regional or national scales, as reported in the S-LCA methodological literature.	Useful for assessing social impacts along product chains, although direct integration into public policy remains less consolidated than environmental LCA.	[35]
SAFA (Sustainability Assessment of Food and Agriculture Systems–FAO)	9	Environmental, economic, social, governance	Complex application due to its global scope. Requires adjustments for local adaptation.	Developed by FAO as a framework for assessing sustainability in food and agriculture systems and supporting multidimensional sustainability reporting.	[7,14]
SMART-Farm Tool (Sustainability Monitoring and Assessment Routine; SAFA-based)	12	Environmental, economic, social, governance	Requires a large amount of data, including numerous indicators, some of which producers may be reluctant to share. Multiple sources and criteria may complicate evaluation and interpretation.	Supports farm-level sustainability assessment and decision-making under SAFA-based standards and development-oriented sustainability programs.	[36]

Table 1. Cont.

Methodology	Corpus-Derived Occurrence Rank	Dimensions/Assessment Scope	Main Methodological Challenges	Use or Relevance in Policy and Decision-Making	References
MESMIS (Marco para la Evaluación de Sistemas de Manejo de Recursos Naturales Incorporando Indicadores de Sustentabilidad)	11	Productivity, stability, resilience, adaptability, equity, self-reliance, and ecological sustainability	The definition of specific indicators depends strongly on the local context, which can lead to ambiguity and limited comparability among studies. Particularly focused on small rural producers.	Relevant for participatory diagnosis and sustainability assessment in rural and family farming systems; may indirectly inform local or regional agricultural policies.	[37,38]
RAPTA (version 1 and 2)	13	Not based on fixed dimensions; structured around system description, system evaluation, adaptive governance and management, and participation of multiple stakeholders.	Lack of robust conceptual models and high subjectivity in application, which may hinder comparison between systems. High demand for time and resources for multi-stakeholder participation.	Used in pilot projects in Ethiopia in food security programs of the Global Environment Facility (GEF).	[9,10]
TAPE (Tool for Agroecology Performance Evaluation)	10	Environmental, social, cultural, health and nutrition, governance	More specific focus on agroecology, which may limit its use as a generic sustainability framework. Requires producer engagement and familiarity with agroecological production approaches.	Used in countries such as Tunisia, Senegal, India, Mexico, Bolivia, and the Dominican Republic as part of national or regional initiatives to promote agroecology and sustainable production.	[8]
FESLM (Framework for Assessing the Sustainability of Natural Resource Management Systems)	14	Productivity, security, protection, economic viability, social acceptability	Complexity in integrating multiple disciplines coherently. Difficulty in defining universal thresholds. Requires specialized knowledge in multiple areas.	Historically relevant for natural resource management assessment and for the development of later multidimensional sustainability frameworks.	[39]
DPSIR (Driver–Pressure–State–Impact–Response)	5	Environmental, institutional	Does not provide specific quantitative indicators, scales, indices, or scores. Focuses mainly on cause–effect relationships between agricultural activities and the environment.	Used in environmental reporting and policy-oriented indicator frameworks, particularly for structuring relationships between human activities and environmental responses.	[21]

Note: The occurrence rank was obtained from the text-mining procedure applied to the bibliographic corpus. The remaining columns synthesize information from the cited methodological literature; therefore, the table combines corpus-derived bibliometric evidence with contextual methodological interpretation.

3.5. Environmental Sub-Themes and Methodological Co-Occurrence Reveal Hidden Structure in Sustainability Assessment Literature

Methodological co-occurrence analysis showed that LCA functioned as the main methodological hub, co-occurring with approaches such as RISE, S-LCA, DPSIR, PCA, IDEA, and MCA, whereas TAPE, MESMIS, SMART-Farm, RAPTA, and FESLM displayed more selective or lower co-occurrence patterns (Figure 5A). This structure indicates that the methodological landscape remains organized around widely standardized and frequently used assessment approaches, while more integrative or transition-oriented frameworks occupy more specialized positions within the corpus. Consistently, the normalized annual composition of methodology-associated dimensions confirmed that the identified methodologies remained largely structured around the classical environmental, economic, and social dimensions, although governance/institutional, cultural, health/nutrition, resilience/adaptation, productivity/security, and system-property dimensions were also represented (Figure 5B). Complementing this methodological pattern, the six-category environmental-system analysis revealed that environmental priorities were also unevenly represented across the corpus. Carbon/climate showed the highest overall share, followed by water resources, biodiversity/ecosystem, and land use/land cover, whereas soil systems/management and food security/resilience appeared less frequently (Supplementary Figure S1A). The normalized annual composition further showed that carbon/climate gained relative prominence over time, while water resources remained moderately stable and land use/land cover, biodiversity/ecosystem, soil systems/management, and food security/resilience showed smaller or more variable contributions (Supplementary Figure S1B). Overall, these patterns suggest that agricultural sustainability assessment is evolving toward broader methodological and environmental-system coverage, but remains strongly shaped by climate-oriented concerns and by the classical three-dimensional sustainability framework.

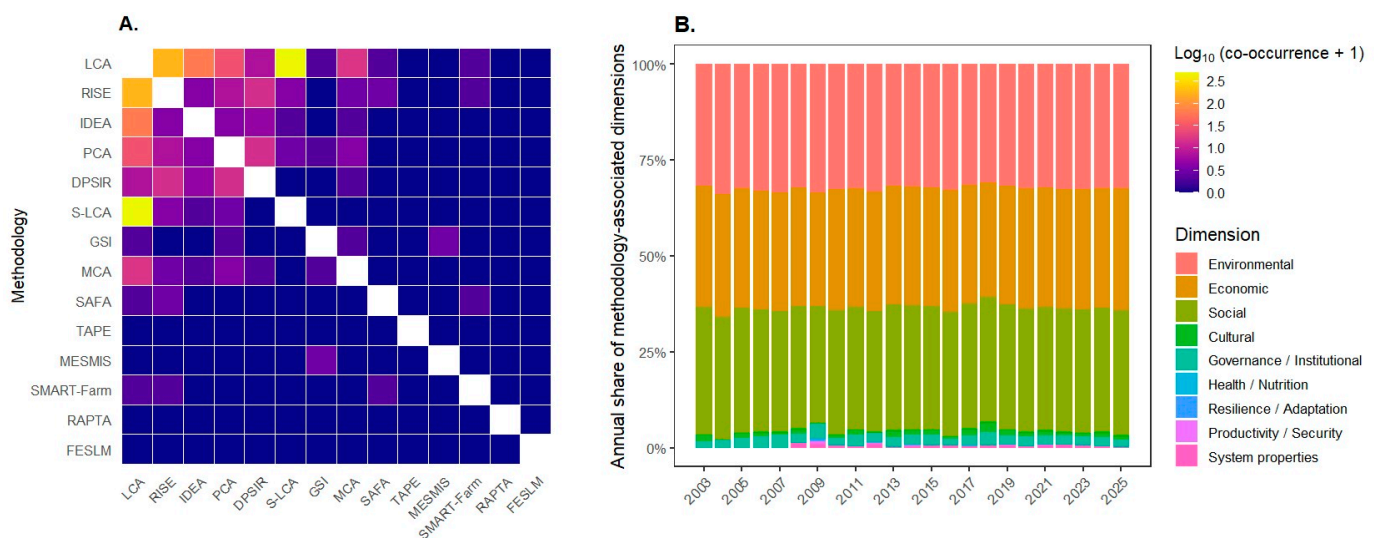


Figure 5. Methodological co-occurrence and dimensional composition of sustainability assessment approaches identified in the bibliographic corpus. **(A)** Pairwise co-occurrence among assessment methodologies mentioned within the same bibliographic records, expressed as $\log_{10}(\text{co-occurrence} + 1)$. Warmer colors indicate more frequent co-occurrence between methodologies. **(B)** Normalized annual composition of methodology-associated dimensions from 2003 to 2025, based on the dimensional scope assigned to each methodology. For each year, percentages sum to 100%, indicating the relative representation of environmental, economic, social, cultural, governance/institutional, health/nutrition, resilience/adaptation, productivity/security, and system-property dimensions among the methodologies detected in the corpus.

4. Discussion

The comparatively lower visibility of integrative frameworks also makes the emergence of governance, culture, resilience, health, and nutrition particularly important. These dimensions represent more than simple additions to the classical environmental–economic–social triad; they respond to weaknesses in assessment approaches that treat sustainability mainly as a set of measurable environmental impacts. Governance introduces questions of participation, transparency, institutional capacity, and responsibility across agri-food systems. Resilience shifts the focus from static performance to the capacity of farming systems to absorb disturbances, adapt to change, and transform under climatic, economic, or social stress. Culture, health, and nutrition broaden the interpretation of sustainability by connecting agricultural practices with local knowledge, food quality, dietary diversity, social cohesion, and rural well-being [16,19,40].

In this regard, TAPE deserves particular attention because it deliberately incorporates “society and culture” and “health and nutrition” into the evaluation of agroecological transitions. This is important because agroecology is not only a set of environmental practices, but also a territorial and social process involving farmer knowledge, food traditions, participation, and the capacity of communities to maintain diversified and healthy food systems [8,15]. The appearance of TAPE, RAPTA, MESMIS, and related approaches in the corpus, although less frequent than LCA, suggests an emerging methodological effort to capture sustainability attributes that are difficult to represent through impact-oriented environmental metrics alone [39,41].

The centrality of food security in the co-occurrence network reinforces this interpretation. The strong lexical links among food, production, systems, and sustainability indicate that the literature does not frame agricultural sustainability only as an environmental efficiency problem, but also as a question of how food systems remain productive, resilient, and socially relevant under global environmental change [15,16,42]. Therefore, the underrepresentation of social and economic dimensions should be understood as a critical gap: the literature recognizes food-system outcomes, but the methodological vocabulary remains more strongly developed for environmental measurement than for social, cultural, nutritional, and institutional assessment.

These issues are especially relevant for tropical and Global South agroecosystems. In equatorial and tropical smallholder systems, sustainability is shaped by pressures that are often insufficiently represented in standardized assessment frameworks, including high rainfall variability, strongly weathered and lateritic soils, steep slopes, rapid biodiversity loss, limited infrastructure, restricted access to technical services, and insecure or informal land tenure [31,33,43–45]. Under these conditions, the dominance of globally standardized environmental metrics may obscure local processes that determine sustainability, such as farmer decision-making, territorial governance, community knowledge, crop diversification, and adaptive capacity. For this reason, frameworks that incorporate participatory diagnosis, agroecological transition, resilience, and governance are particularly relevant for non-temperate agricultural systems. The findings of this study therefore suggest that future agricultural sustainability assessment should not only improve methodological integration across dimensions, but also better represent the environmental and socioeconomic realities of tropical and smallholder farming systems [33,43–45].

The results of this study show that agricultural sustainability assessment is represented in the scientific literature through a marked environmental orientation, a central semantic association with food security, and a methodological hierarchy dominated by LCA. These patterns should not be interpreted simply as a neutral reflection of the importance of environmental issues in agriculture, but also as the outcome of methodological, institutional,

and data-related conditions that shape what is easier to measure, compare, publish, and translate into policy or certification schemes.

The predominance of LCA in the corpus is likely related to its high degree of methodological standardization, its compatibility with ISO-based environmental assessment procedures, and its usefulness for quantifying impacts along product chains. Unlike many multidimensional farm-level frameworks, LCA benefits from established terminology, inventory databases, internationally recognized protocols, and clear links with carbon footprinting, environmental product declarations, circular economy strategies, and agri-food supply-chain assessment [46–49]. These features make LCA highly visible in bibliographic records and explain why impact-oriented environmental evaluation appears as the dominant methodological language in the corpus.

However, this dominance also helps explain the weaker representation of social and economic dimensions. Environmental indicators such as emissions, land use, water use, carbon footprint, eutrophication, or ecotoxicity are usually easier to quantify, standardize, and compare across studies than indicators related to livelihoods, equity, governance, cultural identity, labor conditions, local knowledge, or farmer well-being [32,46,50]. The lower lexical representation of social and economic dimensions therefore does not necessarily imply that these dimensions are considered unimportant in agricultural sustainability. Rather, it suggests a methodological asymmetry in which biophysical variables have achieved greater standardization, while social and territorial indicators remain more context-dependent, data-intensive, and difficult to harmonize across regions and production systems.

This imbalance may also reflect broader research incentives. Funding priorities, data availability, journal expectations, and the demand for measurable environmental indicators often favor approaches that generate comparable quantitative outputs. As a result, assessment methods that rely on farm surveys, participatory diagnosis, local institutional analysis, or long-term monitoring of social outcomes may be less visible in large bibliographic corpora, even when they are highly relevant for evaluating sustainability at the territorial level. The new co-occurrence and dimensional-composition analyses reinforce this interpretation. The methodological co-occurrence matrix showed that LCA operates as the main methodological hub, frequently appearing together with RISE, S-LCA, DPSIR, PCA, IDEA, and MCA, whereas TAPE, MESMIS, SMART-Farm, RAPTA, and FESLM showed more selective or lower co-occurrence patterns (Figure 5A). This suggests that the literature is not only dominated by LCA in terms of frequency, but also structured around methodological combinations in which LCA remains a central reference point.

The environmental-system sub-theme analysis also clarifies which environmental priorities drive this imbalance. The temporal composition further indicated that carbon/climate gained relative prominence over time, while water resources remained moderately stable and the remaining sub-themes showed smaller or more variable contributions. This pattern suggests that the environmental orientation of agricultural sustainability assessment is increasingly shaped by climate-impact and carbon-related concerns. However, the lower representation of soil and food security/resilience also indicates that some environmental-system components that are highly relevant for agroecosystem functioning, smallholder livelihoods, and long-term resilience remain comparatively less visible in the corpus.

Frameworks such as DPSIR help organize the causal relationships between agricultural activities and environmental change, but they also illustrate a broader limitation of the field: many indicators describe drivers, pressures, or current states, whereas fewer indicators capture final sustainability outcomes or long-term transformations. This distinction is important because a corpus dominated by terms related to impacts, indicators, and assessment may

still provide limited evidence on whether agricultural systems are becoming more resilient, equitable, or territorially sustainable over time.

Other emerging dimensions include the cultural sphere and integrate health and nutrition as an inseparable part of rural community well-being. The most recent assessment frameworks recognize that agricultural sustainability depends both on the preservation of local knowledge and on the quality of the diet and the health outcomes of rural populations. A prominent example is the TAPE methodology which, in addition to the economic, environmental, and governance dimensions, adds two specific pillars—“society and culture” and “health and nutrition”—to holistically measure the agroecological transition [8]. This expansion makes it possible to assess indicators such as household diet diversity, the safety and nutritional quality of food, gender equity, social cohesion, and the intergenerational transmission of agricultural and culinary practices [8]. Likewise, community participation in decision-making and the availability of culturally appropriate foods are considered. In this way, next-generation instruments reinforce the need to analyze sustainability from a perspective that connects cultural identity and the right to healthy diets, overcoming evaluations that, until recently, focused almost exclusively on biophysical or economic variables.

Likewise, resilience has been proposed as a key property to be incorporated. Resilience refers to the capacity of the agricultural system to absorb disturbances (climatic, economic, health-related) and continue developing, and to its potential to adapt or transform in the face of long-term changes [41]. Recent studies suggest that including indicators of resilience, viability, and stability of the systems allows their dynamic behavior to be better captured [41]. For example, one can evaluate crop diversity, autonomy from external inputs, support networks among producers, or the existence of management plans for droughts—all of which indicate system resilience to buffer risks. Tools such as RAPTA, FESLM, MESMIS, IDEA precisely address these attributes, promoting evaluations that include long-term perspectives and change scenarios instead of only snapshots of the current state.

In sum, the most advanced methodologies tend toward a holistic, multidimensional approach, where the three traditional pillars are complemented by axes such as governance, culture, resilience, health, or human capital, depending on the evaluation’s purpose. This evolution reflects the understanding that sustainability is not only ecological or economic, but also involves the quality of institutions, adaptive capacity, and the human dimension (values, knowledge, equity) within agroecosystems.

From the perspective of the corpus-level patterns identified here, multilevel indicator methodologies are relevant because they attempt to correct the fragmentation observed between environmental, economic, and social vocabularies. One advantage is that they usually generate easy-to-interpret visual outputs that facilitate decision-making by farmers and advisors. Additionally, frameworks such as the SMART-Farm Tool have been valued for their balance among the three dimensions, avoiding biases and building confidence that no pillar is overlooked [17]. In a comparative analysis, SMART was the only one of six evaluated frameworks that considered environmental, sociocultural, and economic factors in a balanced way, whereas others tended to emphasize some over others. For example, the RISE methodology has a stronger environmental focus, while SAFA places greater emphasis on sociocultural aspects. This shows the importance of selecting the tool according to the objective. When a quick diagnosis of ecological problems on the farm is sought, RISE, PCA, MCA, GSI, or other agri-environmental indices are useful. In contrast, when the aim is to assess the social or cultural impact of agricultural practices, as in traditional smallholder systems, more holistic frameworks such as SAFA or MESMIS may be more appropriate.

Despite their strengths, comprehensive evaluations face practical challenges. A common one is data availability and quality. Clear operational data to calculate certain indicators are often lacking, or obtaining them entails considerable costs and effort. In addition, several reviewed methodologies show a scarcity of robust data for certain indicators and little participation by local actors in defining and collecting information [51]. This limited involvement of producers and communities can lead to indicators that are not very relevant to the local reality or to assessments with lower legitimacy. Recently, it has been identified that including stakeholders (farmers, extension agents, authorities) in the design of the evaluation improves the relevance and adoption of the results [32]. Therefore, an emerging trend is to promote participatory evaluations, where the users themselves help define what to measure and how to interpret the sustainability of their systems.

Another limitation noted is that many tools tend to measure static or short-term conditions and do not adequately capture temporal dynamics (trends, seasonality, resilience to events). Recent literature suggests developing more temporal and dynamic evaluations that monitor sustainability before and after implementing practice changes to understand true impacts over time [18,42]. Likewise, combining *ex ante* approaches (prospective simulations, such as bioeconomic models) with *ex post* approaches (actual monitoring) can offer a more complete picture of sustainability under different management strategies [52].

Regarding applicability in public policies and certifications, several methodologies have moved beyond the academic sphere and are being used in practice. For example, SAFA has served as a conceptual basis for certification and self-assessment schemes of sustainability in agri-food companies, providing a common framework of principles and themes (21 sustainability themes) that can be adapted to different contexts [36]. RISE, for its part, has been applied in numerous countries as a diagnostic tool in rural development projects to improve sustainability at the farm level. Case studies have shown its usefulness for identifying critical points in individual farms and for tracking improvements after interventions [53]. MESMIS, meanwhile, has been widely used in Latin America to evaluate family farming systems and traditional agroecosystems [43] which has facilitated its incorporation into agroecological promotion programs and participatory certification.

A special case is TAPE, whose participatory development with more than 70 experts is explicitly aimed at informing public policies on agroecology [8]. TAPE has been piloted in multiple countries, serving as a guide for governments to steer support and policies for agroecological transition. Preliminary results indicate that TAPE works across diverse regions and systems, generating standardized performance information that goes beyond classical indicators and building a global evidence base to support transformations toward sustainable food systems [8]. This type of collaboration among international organizations, governments, and the private sector has managed to overcome some limitations of previous methodologies, providing clear, validated operational indicators and promoting producer participation in implementation.

Significant gaps have nonetheless been detected in current evaluations. The results showed that most tools devote more indicators to the environmental dimension than to the social or economic ones. This may be because environmental impacts are better studied and quantified, including terms more associated with the environmental component (Figures 2 and 3). Meanwhile, social dimensions such as farmers' well-being, gender equity, social capital, governance, institutionality have received less methodological development (Figures 2 and 3). As a result, certain critical social aspects may remain underrepresented. In addition, social indicators must be adapted to the context, and a generic list might not reflect real social concerns in different places. To address this, it will be necessary to broaden the spectrum of social topics evaluated, including personal and family characteristics of producers (education, generational replacement, cultural identity,

family stability) that influence sustainability but are rarely considered. Likewise, the economic dimension needs to incorporate indicators of market connection, dependence on subsidies, income diversity, and other factors that contextualize viability beyond immediate productivity.

Overall, the corpus suggests that agricultural sustainability assessment is moving from a predominantly environmental and impact-oriented vocabulary toward a broader, but still uneven, methodological landscape. The main challenge is not simply to add more indicators, but to develop assessment approaches capable of connecting environmental performance with governance, culture, resilience, health, nutrition, and the territorial realities of farming systems, particularly in tropical and Global South contexts.

5. Conclusions

This study shows that agricultural sustainability assessment research is predominantly structured around environmental themes, particularly land, soil, water, carbon, emissions, and food-production systems. Among the sixteen methodologies identified, Life Cycle Assessment was the most frequently represented approach, while the occurrence of frameworks integrating governance, resilience, culture, health, and participation suggests a gradual movement toward more comprehensive assessment models. Despite this methodological evolution, important gaps remain, particularly the lower lexical representation of socioeconomic dimensions and the limited inclusion of dynamic indicators capable of capturing resource condition, climate-related risks, and system resilience over time. Future assessment approaches should integrate robust environmental indicators with context-specific socioeconomic information, stakeholder participation, and longitudinal monitoring. Such integration is necessary to support natural resource management, climate adaptation, biodiversity conservation, and resilient food production under global environmental change.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/earth7040117/s1>, Figure S1. Environmental-system category assignments in the agricultural sustainability assessment literature. (A) Overall share of records assigned to each environmental-system category. (B) Normalized annual composition of environmental-system category assignments from 2003 to 2025. Table S1. Lexical dictionary for sustainability dimensions and environmental-system categories; Table S2. Methodology-identification dictionary and regular-expression patterns.

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Data Availability Statement: The plain text downloads used to build the corpus are archived on Zenodo [25]. Additionally, all code and analysis scripts are openly available as a reproducible R 4.4.3. notebook under Git version control on Zenodo [26]; likewise, this code is available on GitHub repository <https://github.com/Angie-Fernanda/sustainability-methods-analysis> (accessed on 2 July 2026).

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Abbreviations

The following abbreviations are used in this manuscript:

LCA	Life Cycle Assessment
PCA	Principal Component Analysis
MCA	Multiple Correspondence Analysis
GSI	General Sustainability Index based on multivariate analysis (PCA and/or MCA)
IDEA	Indicateurs de Durabilité des Exploitations Agricoles
S-LCA	Social Life Cycle Assessment
RISE	Response-Inducing Sustainability Evaluation
SAFA	Sustainability Assessment of Food and Agriculture systems–FAO
SMART-Farm Tool	Sustainability Monitoring and Assessment Routine
MESMIS	Marco para la Evaluación de Sistemas de Manejo de Recursos Naturales Incorporando Indicadores de Sustentabilidad
RAPTA	Resilience, Adaptation Pathways and Transformation Assessment
TAPE	Tool for Agroecology Performance Evaluation
FESLM	Framework for Assessing the Sustainability of Natural Resource Management Systems
DPSIR	Driver–Pressure–State–Impact–Response
EEA	European Environment Agency
OECD	Organisation for Economic Co-operation and Development

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