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Agricultural sustainability in the European Union: a review of concepts, policies and economic perspectives

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Introduction: Sustainability in European Union (EU) agriculture has become a priority in both academic research and public policy, reflecting its central role in shaping resilient and balanced development models. The European agricultural landscape is characterized by significant agronomic diversity, including cereals, oilseeds, protein crops, industrial crops, vegetables, fruits, and fodder crops that support the livestock sector. These are integrated into multiple production systems: conservation agriculture, organic farming, integrated crop management, permanent pastures, and agroforestry, each contributing differently to environmental protection, economic efficiency, and social equity. Land use structures reveal a mosaic of arable land, permanent pastures, permanent crops, and mixed systems, reflecting the climatic and socio-economic diversity of Europe. In this context, the study examines how the economic, social, and environmental dimensions of sustainability are conceptualized and integrated into EU agricultural strategies.

Methods: The study uses a multi-level methodological approach, integrating conceptual, legislative, empirical, and bibliometric analyses. First, key concepts of agricultural sustainability were examined through a systematic review of academic literature and EU policy documents. Second, a legislative analysis assessed the regulatory framework shaping sustainability, with a focus on the common agricultural policy and related instruments. Third, empirical evidence from recent studies on the economic and financial performance of EU farms was synthesized to identify the structural determinants of viability. Finally, a bibliometric assessment mapped publication dynamics and emerging research themes, allowing for the triangulation of results across methodological dimensions.

Results: The findings indicate a significant intensification of academic and political interest in sustainable agriculture after 2016, driven mainly by climate change pressures, digital transformation, and structural changes in rural areas. Research trends highlight an increasing focus on eco-efficiency, digitalization, and performance-based sustainability indicators. Although the CAP remains the central policy instrument supporting the transition to sustainable agriculture, its effects are mixed: it provides income stability and supports environmental commitments, but also contributes to persistent disparities between countries and farm types. Empirical studies show that the economic viability of EU agriculture is strongly influenced by the financial management of farms, their

capacity for innovation, and the degree to which policies are tailored to national and regional specificities.

Discussion: The literature and policy evidence converge on the conclusion that the sustainability of EU agriculture cannot be based on one-size-fits-all solutions. Instead, it requires flexible, integrated, and context-sensitive approaches that are aligned with the heterogeneity of European agricultural systems. The social dimension, in particular the involvement of farmers, generational renewal, and the resilience of rural communities, is emerging as an essential pillar of the green transition, alongside technological innovation and digitalization. The study emphasizes that achieving long-term sustainability in EU agriculture depends on balancing productivity with environmental restoration and ensuring equitable socio-economic opportunities across all Member States.

KEYWORDS

agricultural sustainability, agricultural policies, economic perspectives, sustainability indicators, conservation agriculture, organic farming, arable land, European Union

1 Introduction

The concept of "sustainable agriculture" became prominent following the publication of the Brundtland Report in 1987, which introduced and popularized the idea of "sustainable development" (Mensah, 2019). Thus, sustainability in agriculture is a hotly debated topic and is internationally recognized as essential for the transition to sustainable global development, although there is general consensus on its importance, and definitions of agricultural sustainability and how to implement it in public policy vary considerably. This variation is partly due to the fact that agricultural sustainability is a concept derived from various types of "alternative" agriculture, such as organic (Fess and Benedito, 2018), regenerative, and ecological agriculture (O'Donoghue et al., 2022), with essentially three dimensions and different levels being used to assess sustainability in agriculture (Alaoui et al., 2022).

A highlevel political agreement by the heads of the European Union member states supported the adoption of the principle of sustainable development in 1988 in the Declaration on the Environment as "an overarching objective of all Community policies" (Eckert and Kovalevska, 2021). In pursuit of this objective, the Declaration called for new solutions to existing environmental problems "in the interests of sustainable growth and a better quality of life." In the 1992 Maastricht Treaty on European Union, the term was given importance in defining the Community's objective of achieving "sustainable development" in the context of economic and environmental policies (Špelić and Mihelić-Bogdanić, 2024).

Sustainability was enshrined in Article 11 of the Treaty on European Union: "Environmental protection requirements must be integrated into the definition and implementation of the Union's policies and activities, in particular with a view to promoting sustainable development" (Calliess and Tuncel, 2023). It is clear that sustainability is a normative concept, representing a highlevel desire or aspiration. Although there is general consensus that it is a beneficial concept, there are profound differences in its intellectual approach. These differences may explain the real difficulties in applying sustainability concepts, and they may also constitute an obstacle to the implementation of derivatives of sustainability, such as sustainable intensification. It is commonly suggested that sustainability should be considered in the context of the three classic pillars: economic, environmental, and social (Schoor et al., 2023). It is generally argued that these three aspects must be fulfilled individually and, sometimes, given equal weight. However, there are difficulties in determining what it means to give equal weight to these very different aspects of human activity. For example, commercial interests often emphasize the primacy of the economic pillar (Prigoreanu et al., 2025), arguing that without economic viability, farmers cannot care for the environment. In contrast, environmentalists argue that if natural capital is undermined, the longterm survival of farms cannot be guaranteed (Meraj et al., 2021). These positions seem difficult to reconcile and reflect fundamentally different paradigms or worldviews, essentially the economic versus the ecological. Although much attention is paid to the need to consider all three pillars, discussions on sustainability often focus on the environmental dimension (Hariram et al., 2023). Economic interests are strongly represented in most debates, while the social dimension usually receives the least attention, has a less developed conceptual basis, and covers a wide range of factors, including employment, income, demographics, gender roles and balance, as well as access to rural services, affordable housing, transportation, education, and health (Lomazzi et al., 2019). Ethical issues, such as animal welfare, are often included under this heading, with the result that the meaning of social unsustainability is less clear and stakeholder pressure to address social sustainability is weaker.

The multidimensional approach developed by the FAO (Lütteken and Hagedorn, 1999), which summarises these principles as "the management and conservation of natural resources, as well as the orientation of technological and institutional change so as to ensure that the needs of present and future generations are met". Such development (in agriculture, forestry, and fisheries, etc.) protects the genetic resources of soil, water, and wildlife, while being environmentally sustainable, economically viable, and socially acceptable.

The "sustainability" paradigm applies to agriculture as well as other economic sectors or human activities. Similar to the broader concept of "sustainable development," discussions about "sustainable agriculture" include various definitions and interpretations, Thus, the multiple attempts to define "sustainable agriculture" reflect different perspectives. In the social sphere, the main premise, emphasizing the ethical aspect, is "meeting the needs of the present generation without compromising the prosperity of future generations," according to the Brundtland Report (Janker et al., 2018). The social and natural aspects of "agricultural sustainability", as well as its longterm importance, are highlighted by Francis and Youngberg (1990), who consider it "a philosophy based on human goals and an understanding of the longterm impact of our activities on the environment."

The OECD has been active for many years in developing and promoting environmental sustainability indicators. Conceptually, the framework for the set of environmental indicators is defined by the PSR (pressure, state, response) model and the identification of 15 key environmental issues facing OECD member states (OECD, 2001).

A different set of indicators, focused on environmental issues, is described by Faber in the ELISA project, which attempted to "apply the OECD model in the selection of indicators for the assessment of agriculture across the EU, member states, and regions." The main objective of the project was to establish a set of standardized indicators to be used to measure and evaluate agricultural performance in accordance with OECD criteria. These indicators were intended to provide comparable and consistent data at European level, thus facilitating the analysis and formulation of agricultural policies. The project was essential for harmonizing agricultural assessment methodologies and ensuring an integrated perspective on agricultural development across the EU. The project succeeded in creating a uniform framework of indicators to be applied in all EU Member States, facilitating data comparability between regions, and the indicators developed provided a solid basis for the formulation and adjustment of agricultural policies at European, national, and regional levels, contributing to better management of agricultural resources and the promotion of sustainability. The project placed particular emphasis on including environmental and social aspects in the assessment of agricultural performance, thereby promoting fairer and more sustainable agriculture, and the indicators enabled the collection and analysis of homogeneous and comparable data across the EU, facilitating the monitoring of progress and the identification of issues specific to each region. By applying these indicators, the project contributed to promoting sustainable development in agriculture, balancing economic, environmental, and social needs.

The project proposed by Majewski (2013) is remarkable for two main reasons. In their model of sustainability indicators, they combined two schemes: FESLM, with its five pillars of sustainability, and SRL, which analyzes the relationships between livelihoods and the use of natural resources. The first model, FESLM (Framework for Evaluating Sustainable Land Management), focuses on the five pillars of sustainability: productivity, stability, environmental protection, economic viability, and social acceptability. This framework provides a holistic approach to assessing the sustainability of land and agricultural practices, taking into account economic, environmental, and social aspects. The second model, SRL (Sustainable Rural Livelihoods), provides insight into how the livelihoods of rural communities are interconnected with the use and management of natural resources. It analyzes the dynamics between available resources, the economic activities of rural populations, and their impact on environmental sustainability. By combining FESLM and SRL, the project manages to capture not only the ecological and economic dimensions of sustainability, but also to highlight the complex interactions between human activities and natural resources.

The aim of this study is to conduct a comprehensive analysis of the literature on agricultural sustainability at the European Union level by identifying the main concepts, indicators, policies, and perspectives on agricultural holdings. The study aims to highlight how academic research and institutional reports define and assess sustainability, as well as to provide an integrated picture of the economic, social, environmental, and economic dimensions.

The objectives of the study are:

- O1: To analyze the concepts and indicators used in the literature to define and measure the sustainability of agriculture in the European Union.
- O2: To evaluate studies addressing the implementation and impact of European agricultural policies on the sustainability of the agricultural sector.
- O3: To investigate the literature on the sustainability of agricultural holdings, with a focus on the economic and financial dimension.

In this context, the paper provides an integrated review of European agricultural sustainability, articulating the conceptual, public policy, and financial managerial dimensions in an analytical framework capable of linking the objectives of the European Green Deal and the CAP to farm practices through a coherent system of indicators and evidence. it motivates the need to align measurement methods (from FADN/FSDN and composite indicators to participatory assessments) with the diverse structural and territorial realities of the EU, places climate risk at the center of the analysis, market volatility and social equity, and puts forward the hypothesis that digitalization, technological innovation, and green financial instruments can accelerate the transition if they are calibrated to farm types and clear conditions. The study therefore

justifies both a review of the literature and a critical examination of the regulatory framework and economic performance at micro and macro level as a prerequisite for operational recommendations and for prioritizing public investment and farmer training for widespread adoption and financial innovation.

The originality of this study lies in its integrated approach to agricultural sustainability in the European Union, which brings together conceptual, political, economic, and bibliometric analysis in a unified framework. Unlike previous studies that treat the economic, social, and environmental dimensions separately, this research highlights the interdependencies between them and how they manifest themselves differently across Member States. The major contribution of the study is to correlate the theoretical foundations of sustainability with the financial and structural realities of agricultural farms, offering a new perspective on the relationship between economic viability, environmental performance, and the coherence of European policies.

The conclusions of the paper complement the existing literature with a critical synthesis that integrates public policy developments, methodological diversity, and recent empirical results, differing from previous research in its emphasis on the role of digitalization, innovation, and green financial instruments in accelerating the transition to sustainable agriculture, dimensions that have often been neglected in studies to date. Thus, the research makes a significant theoretical and practical contribution, providing a flexible and comparable framework for assessing agricultural sustainability in the European Union, in line with the objectives of the Green Deal, the Farm to Fork Strategy, and the new Common Agricultural Policy (2023–2027).

2 Methodology

The study uses a four stage methodology, each corresponding to a major line of investigation: (i) conceptual and theoretical delimitation of agricultural sustainability, (ii) analysis of the political and regulatory framework, (iii) economic and financial evaluation at the farm level, and (iv) bibliographic and bibliometric analysis of the relevant scientific literature. This methodological structure allows for the articulation of a comprehensive framework that provides both a descriptive interpretative perspective on the specialized literature and a critical assessment of the measurement tools and public policies applied in the European Union.

2.1 Conceptual and theoretical delimitation

The first stage of the methodology consisted of clarifying the conceptual and theoretical dimensions of sustainability in agriculture. Since the concept of "sustainable agriculture" is polysemantic, being defined and used differently by various authors, organizations, and institutions, it was necessary to apply a systematic analysis of the specialized literature to identify the main schools of thought and conceptual trends.

The literature selection process was guided by several essential methodological criteria:

1. Thematic relevance, i.e., the inclusion of studies that explicitly address sustainability in agriculture, with a focus on economic, ecological, and social dimensions.

2. The period of analysis, covering works published between 2010 and 2025, in order to capture both the consolidation of the traditional conceptual framework and the emergence of new interdisciplinary approaches.

The period analyzed, 2010–2025, was selected to capture the consolidation of the traditional conceptual framework of agricultural sustainability and, at the same time, the emergence of new interdisciplinary approaches generated by structural and political transformations in agriculture at the European Union level. The interval coincides with the implementation period of the major reforms of the Common Agricultural Policy (CAP 2014–2020 and CAP 2023–2027), as well as with the launch of the Catarinella and Kram (2019) and the related Farm to Fork and Biodiversity 2030 strategies, which have redefined research and public policy priorities in the field of sustainability. The choice of this time frame thus allows for the correlation of the conceptual and empirical evolution of agricultural sustainability with recent institutional and technological changes, providing a comprehensive perspective on the green transition in European agriculture.

3. Academic sources, selected from recognized databases (Web of Science and Scopus) to ensure the quality and validity of the studies.

Figure 1 shows the PRISMA 2020 diagram, which illustrates the process of identifying, selecting, and including relevant studies on agricultural sustainability in the European Union.

The PRISMA diagram illustrates the systematic process of selecting studies included in the analysis. In the first stage, 843 records were identified in scientific databases (Web of Science and Scopus), to which results from additional sources, such as websites, organizations, and citations, were added. After removing 315 duplicates and ineligible records, 513 articles remained to be screened based on title and abstract (at this stage, 100 articles were excluded for lack of thematic relevance). Of the total 413 articles for which full text access was requested, 45 could not be retrieved, resulting in a complete analysis of 368 papers. Following verification of the eligibility criteria, 195 articles were excluded (175 considered outside the scope and 20 review articles), and 55 papers were obtained from complementary sources, but after further verification, 27 were eliminated. Finally, 153 studies were considered eligible and included in the synthesis analysis.

The geographical distribution of the 153 studies selected for final analysis and review reflects a clear dominance of research from Western Europe, where Germany (14 studies, 9.15%), the Netherlands (12 studies, 7.84%), and France (11 studies, 7.19%) hold the highest shares, due to consistent investment in research and active implementation of green transition policies. Italy, Spain, and Switzerland also contribute a significant number of papers (between 4 and 7 studies each), reflecting academic interest in

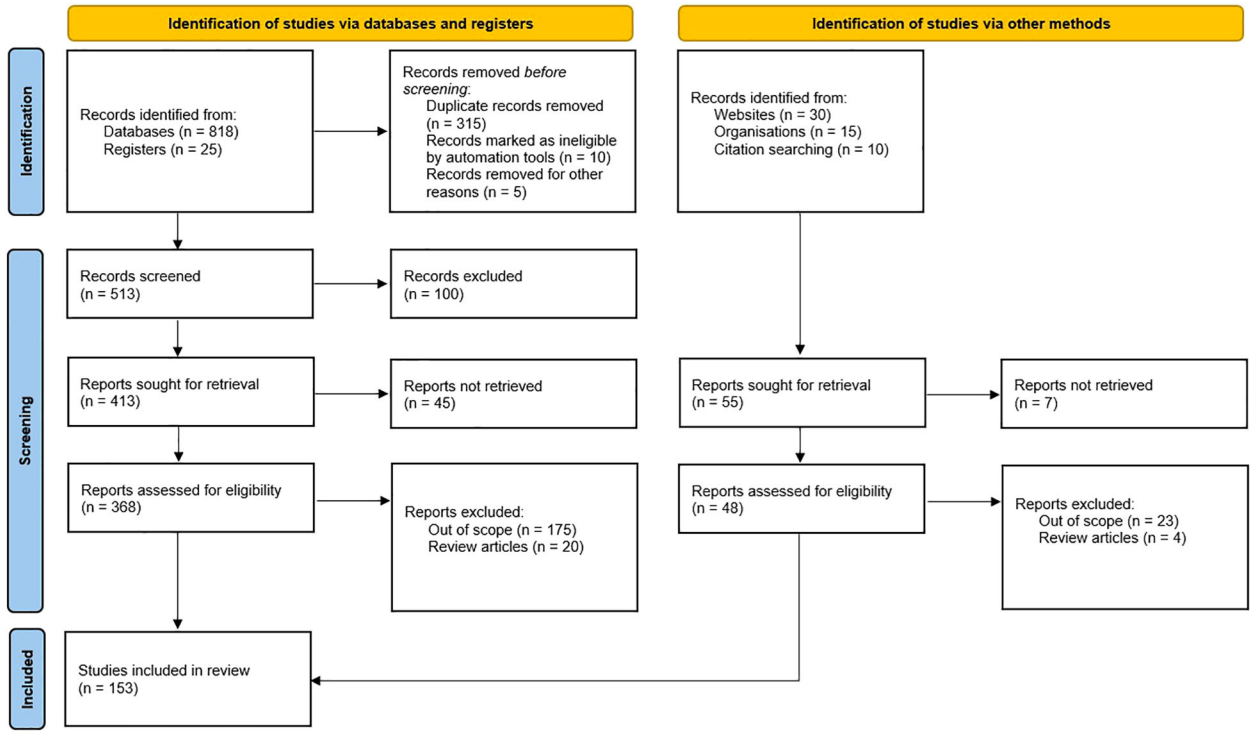

FIGURE 1
PRISMA diagram of the selection process for studies on agricultural sustainability in the European Union. Source: Own processing.

agricultural sustainability and environmental policies. In contrast, Central and Eastern European countries such as Poland, Hungary, Romania, Lithuania, and Slovakia are underrepresented (together accounting for approximately 10–12% of the total), indicating a regional disparity in participation in applied research on agricultural sustainability. A significant proportion of the studies (around 15%) are pan-European or institutional in nature, carried out under the auspices of the European Commission, FAO, OECD, European Parliament, or European Court of Auditors, contributing to the theoretical and legislative basis of the European Union's agricultural and environmental policies. This distribution highlights a partial balance between Western European approaches, with an emphasis on economic performance and innovation, and Eastern European contributions, focused on structural transition and policy convergence, confirming the need for methodological and institutional harmonization in the assessment of agricultural sustainability at the European Union level.

The bibliometric analysis was performed using VOSviewer software (version 1.6.19), which was used to identify collaborative relationships between authors and institutions, as well as to analyze the co-occurrence of terms and keywords in the selected articles. Based on bibliographic data imported from the Scopus and Web of Science databases, VOSviewer generated density maps and thematic networks, which allowed the main research clusters on agricultural sustainability, performance indicators, and European agricultural policies to be highlighted. The methodology used included the steps of metadata processing, term standardisation and duplicate removal, followed by the construction of keyword co-occurrence networks and the analysis of the degree of centrality of terms within the thematic map. The results obtained through VOSviewer allowed for the visualization of the geographical and conceptual distribution of studies and the identification of emerging trends in the literature on agricultural sustainability in the European Union.

2.2 Analysis of the political and regulatory framework

The second methodological dimension focused on assessing the European Union's policy and regulatory framework for sustainable agriculture. At this stage, a document analysis was carried out, a method specific to qualitative research, used to examine the programs, regulations, strategies, and official reports of European institutions.

The documents were selected based on criteria of relevance and timeliness:

2.2.1 Strategic and legislative documents

Common Agricultural Policy (European Commission, 2025; Linares Quero et al., 2022; Fusco, 2021; Pawłowska and Grochowska, 2021; Cristea et al., 2021), European Green Deal (European Commission, 2025; Prigoreanu et al., 2024; Ciot, 2022; Gobin and Uljee, 2025; Muska et al., 2025), Farm to Fork Strategy (European Commission, 2025; Matías et al., 2024; Byrne and

Zabetakis, 2023; Elshaer et al., 2023; European Parliament and Council of the European Union, 2021) and other related regulations.

2.2.2 Reports and assessments

studies published by the European Commission (Dupoux and Martens, 2025; European Commission, 2021; European Commission, 2025d; European University Institute et al., 2025), the European Parliament (Bluszcz et al., 2024; Ciot, 2021; European Parliament, 2025), the European Court of Auditors (European Court of Auditors, 2025a, European Court of Auditors, 2025b) and international bodies such as the FAO (FAO, 2023, FAO, 2025a; FAO, 2025b) or the OECD (OECD, 2019; Frezal and Deuss, 2025; OECD, 2025).

2.2.3 Reference period

2010–2025, with a focus on the CAP reforms 2014–2020 (Žičkienė et al., 2022; Doukas et al., 2023; Herman, 2025; Szálteleki et al., 2024) and 2021–2027 (Cagliero et al., 2021; Radlińska, 2025; Zieliński et al., 2025; Manta et al., 2024).

The thematic analytical framework method was used to analyze these documents, whereby policies were classified into three main areas: (i) policies for environmental sustainability, (ii) policies for social and rural sustainability, and (iii) policies for economic and financial sustainability.

A complementary tool was the application of comparative analysis between the stated policy objectives and the actual performance indicators used at European level. Thus, the methodology made it possible to identify both the progress achieved and the limitations and contradictions existing in European policies on agricultural sustainability.

2.3 Bibliographic and bibliometric analysis

The third methodological dimension focused on analyzing literature dealing with the economic and financial sustainability of agricultural holdings. For this stage, empirical and applied studies were selected that use economic and financial indicators to measure the performance and viability of farms.

The methodological process included:

1. *Study selection criteria*: papers using financial indicators (ROA, ROE, liquidity, profitability, gross value added), econometric models, multivariate statistical techniques, and risk assessment tools.
2. *Data sources*: agricultural accounting networks (FADN), financial reports, official statistical data (Eurostat, FAO), as well as case studies on farms or agrifood companies.
3. *Methods used*: multiple regression analysis, cluster analysis, principal component analysis (PCA), fuzzy logic, and participatory methods (Delphi, interviews with farmers and experts).

This stage allowed us to build an overview of how the literature addresses the issue of economic viability and financial sustainability at the microeconomic level. The methodology sought not only to identify the indicators used, but also to assess their validity and comparability across studies and European regions.

The three methodological dimensions were not applied independently, but in an integrated manner to ensure the coherence and consistency of the study. This integration was achieved through:

1. *Methodological triangulation*, which aimed to combine conceptual, documentary, empirical, and bibliometric analysis to obtain a more complete picture of agricultural sustainability.
2. *Crossvalidation* by comparing the results of policy analysis with those of empirical and financial literature to identify convergences and discrepancies.
3. *Building a unified analytical framework* through which theoretical concepts, European policies, financial indicators, and scientific literature are analyzed within a common logic.

This integrated methodological approach allows not only for a review of the literature, but also for a critical assessment of how sustainability is conceptualized, implemented, and measured at the European Union level.

3 Results and discussion

3.1 Concepts and indicators of sustainability in agriculture at European Union level

The analysis is based on a bibliographic and bibliometric review of the literature on agricultural sustainability at the European Union level. The results of the analysis highlighted a steady increase in interest in sustainable agriculture in the EU, particularly after 2016, with a peak in publications in 2022; the identification of dominant keywords such as "sustainable agriculture," "sustainability indicators," "energy efficiency," "digitalization in agriculture," "sustainable practices," "CAP," and "sustainable intensification"; the emergence of five major research directions: economic sustainability (40%), environmental sustainability (30%), digitalization in agriculture (10%), energy efficiency (12%), and organic farming (8%).

The geographical distribution of studies shows a strong concentration in Western European countries: Germany (14 studies), the Netherlands (12 studies), and France (11 studies), reflecting substantial investment in academic research and active policies on the green transition. Central and Eastern European countries (Poland, Hungary, Slovakia) are less well represented, suggesting a need for greater involvement in specialized studies on agricultural sustainability (Figure 2).

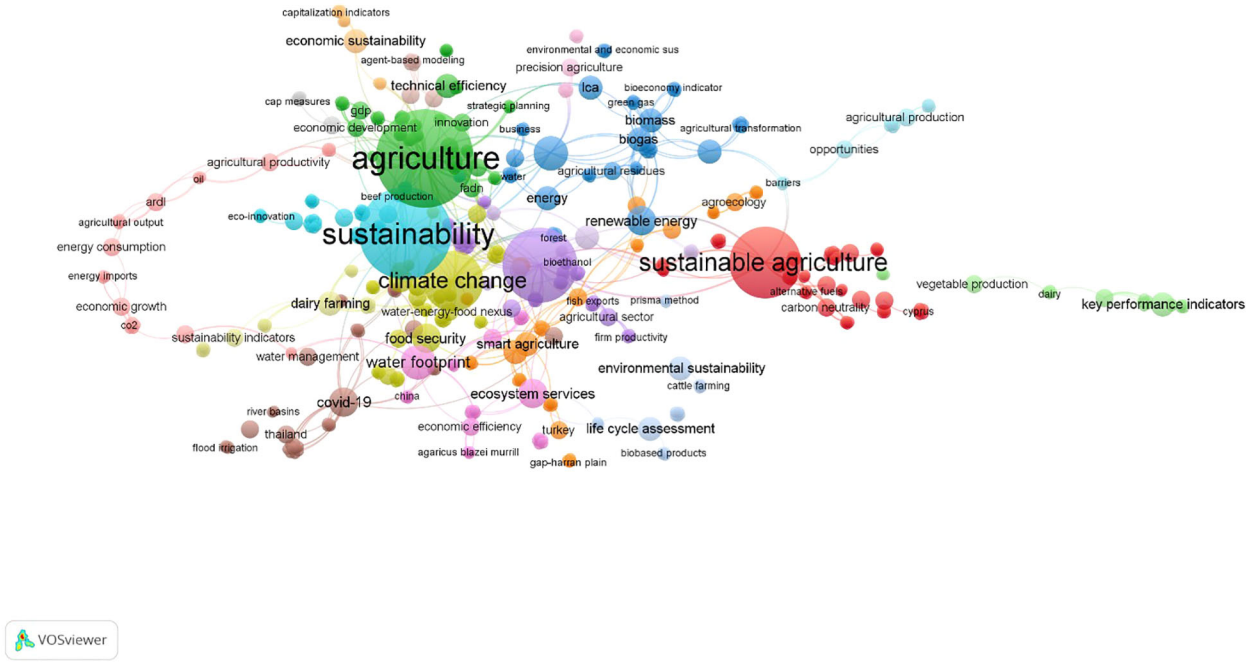

FIGURE 2
Cooccurrence matrix of keywords related to the main themes and concepts associated with sustainable agriculture in the European Union. Source: Own processing in VOSviewer.

The authors' analysis reveals that agricultural sustainability in the European Union is a complex concept that integrates financial, structural, environmental, and technological dimensions. Brad et al. (2018) emphasize that farmers' financial balance is strongly influenced by decoupled subsidies, which reduce debt pressure, while external costs increase indebtedness, calling for the development of financial instruments tailored to the specific characteristics of farms. At the structural level, Martinho (2019)

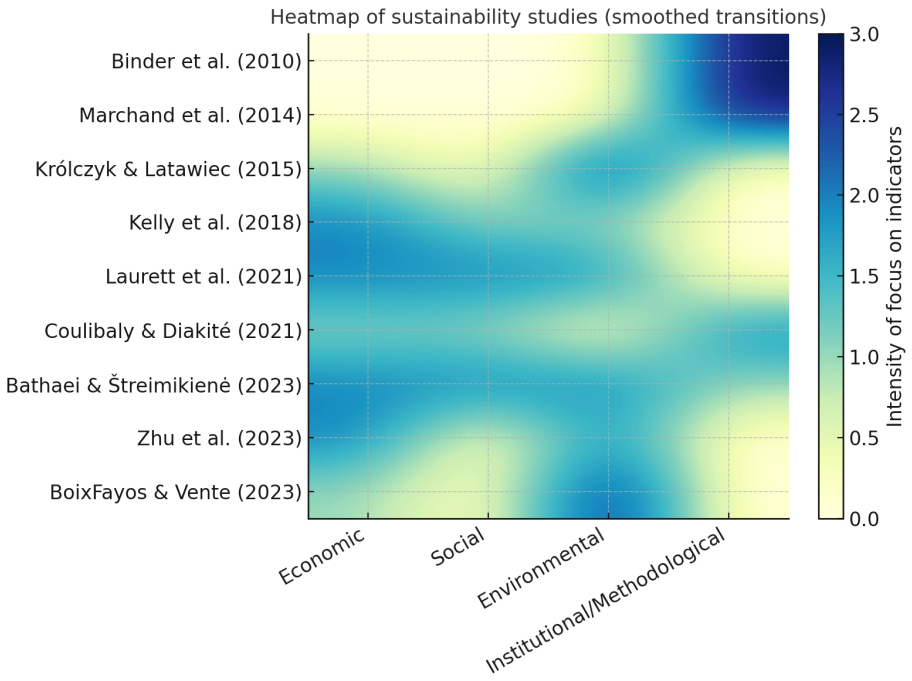

FIGURE 3
Assessments of methodological approaches in sustainability research.

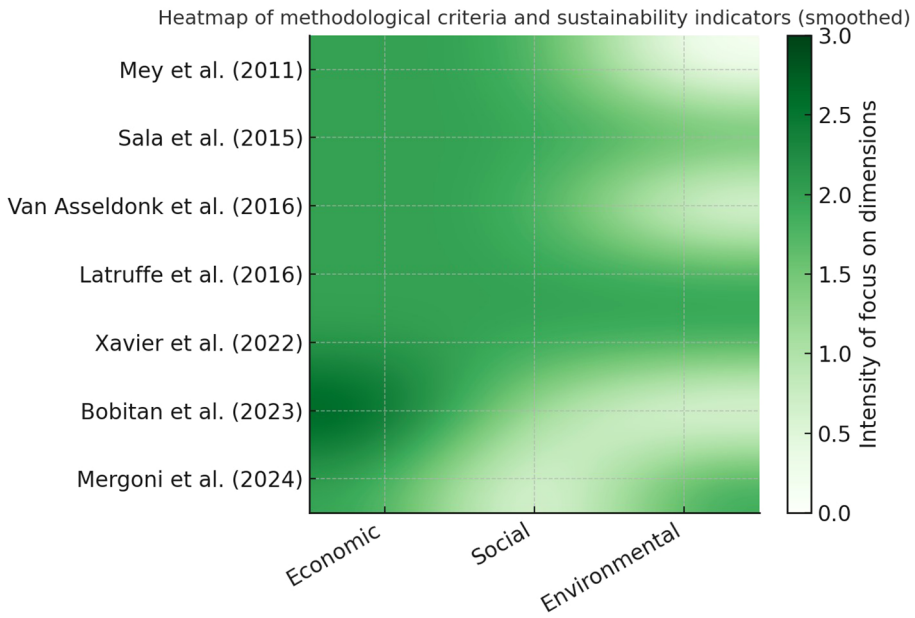

FIGURE 4
Methodological criteria and proposed indicators for agricultural sustainability.

highlight that macroeconomic events, such as the global financial crisis, have had a deeper impact on sustainability than CAP reforms, showing that European agriculture is vulnerable to external factors. Complementarily, Domagała (2021) uses the DEA method to analyze economic, energy, and environmental performance, identifying a core group of countries capable of simultaneously achieving ecoefficiency and emissions reduction, alongside other countries lagging behind, which indicates significant gaps in the implementation of sustainability.

On the other hand, Magrini (2022) demonstrates through clustering techniques the existence of divergent sustainability trajectories, grouping European countries from high performance to major difficulties, while Staniszewski et al. (2023) identify four structural typologies of farms and regions, highlighting the polarization and internal diversity of European agriculture. In the same vein, MacPherson et al. (2022) draw attention to the emerging role of digitalization in increasing productivity and food security, but warn that unequal access to advanced technologies such as IoT, artificial intelligence, or robotics may accentuate polarization and concentration of economic power.

Figure 3 highlights the major contributions of methodological studies on sustainability in agriculture, capturing the extent to which each paper addressed key dimensions, from economic and social performance indicators to epistemological foundations and analytical tools.

Sustainable agriculture is a concept that varies over time and location, which means that any assessment of sustainability must be contextualized according to the specifics of an agricultural system. A significant challenge in assessing these systems is identifying and applying appropriate spatial and temporal indicators to determine whether an agricultural practice is sustainable or not. This difficulty arises because sustainability involves at least three interdependent dimensions: ecological, economic, and social, which can be difficult to reconcile, given that each has a different time scale and perspective in each context (Sala et al., 2015).

The literature on agricultural sustainability in the European Union highlights a variety of theoretical and methodological approaches, reflecting the complexity of this multidimensional concept. Thus, Kelly et al. (2018) emphasize the role of the FADN network as a central monitoring tool, demonstrating its usefulness in assessing economic performance, but also its major limitations in terms of social and environmental dimensions, which suggests the need for additional indicators. In terms of perceptions, Laurett et al. (2021) show that farmers define sustainability in terms of the interaction of economic, social, and environmental factors, motivated by access to financial resources, cooperation, and consumer pressure, but faced with barriers such as lack of capital, insufficient technical support, and certification bureaucracy. Complementarily, Coulibaly et al. (2021) highlight the role of sustainable agricultural practices as a response to the negative effects of conventional agriculture, emphasizing the importance of education, access to resources, and government support in facilitating the transition.

On the methodological dimension, Bathaei and Štreimikienė (2023) provide a systematic analysis of indicators, demonstrating the difficulty of standardizing them at the European level and highlighting the relevance of criteria such as farmers' rights, farm structure, and access to markets. In terms of productivity and energy efficiency, Zhu et al. (2023) use the DEA method to show that, despite modest productivity gains, structural inefficiencies and energy-related emissions negatively affect sustainability, calling for CAP policies that are better geared towards resource optimization and the promotion of green technologies. In the same context, BoixFayos and de Vente (2023) place the issue in the context of the

European Green Deal, highlighting the tensions between the Farm to Fork, Biodiversity, and Soil Strategies and the associated challenges, such as maintaining agricultural yields, nutrient management, land pressure, and the risk of externalizing environmental costs. Thus, the contributions of these authors converge on the idea that agricultural sustainability requires an integrated approach, in which the analysis of economic, social, and ecological indicators is harmonized with European policies, and the transition to sustainable practices is supported by education, financial resources, and coherent institutional frameworks.

Figure 4 summarizes the methodological criteria and indicators proposed by authors for analyzing sustainability in agriculture.

Sustainable agriculture cannot be reduced to a simple set of principles and abstract theories. In order to support decisionmaking, it is essential to assess the current state of the environment, which is complex and dynamic, and to define the processes of change (Marchand et al., 2014). Sustainable agriculture can be measured and described using various methods, such as costbenefit analysis, risk analysis, ecosystem diagrams, and indicator systems (Ciot, 2022). Recent research shows that agricultural sustainability in the European Union is understood and assessed from a variety of perspectives, each of which makes specific contributions to the development of an integrated analytical framework, as Van Asseldonk et al. (2016) emphasize risk management as a central element of financial sustainability, highlighting the role of instruments such as insurance, price contracts, and external investments, all collected and integrated through the FLINT project alongside the FADN database. In a complementary direction, Latruffe et al. (2016) provide a synthetic perspective, reviewing the indicators organized around the three pillars: economic, social, and environmental, and noting the proliferation of environmental indicators, such as soil quality or GHG emissions, in contrast to the methodological difficulties of quantifying the social dimension. In this context, Xavier et al. (2022) propose a composite solution to capture the tradeoffs between dimensions, applying multivariate methods (HJBiplot, cluster analysis) to agricultural census data from Portugal, obtaining a synthetic picture of sustainability.

At the national level, Bobitan et al. (2023) investigate Romania through the lens of farm financial performance, using DEA and the Malmquist index to highlight variations in agricultural efficiency, accentuated by the COVID19 pandemic, and to emphasize the role of managerial and technological strategies in maintaining economic viability. In the same vein, Mergoni et al. (2024) analyze the interaction between efficiency, sustainability, and environmental risk, developing composite indicators that show that, although efficiency and sustainability can be complementary, environmental risks reduce economic performance but at the same time stimulate the adoption of sustainable practices.

Research shows that, although there is a core group of Western European countries that dominate the literature and performance in this field, Central and Eastern European regions are less represented, highlighting the need for involvement and the development of policies tailored to the local context. Studies show the diversity of indicators and methodologies used, but also the difficulty of standardising them. While economic and environmental sustainability are relatively well covered, the social dimension remains insufficiently quantified. In addition, digitization and innovation are emerging as factors of sustainability, with the potential to reduce structural gaps but also with the risk of accentuating inequalities. Thus, the sustainability of European agriculture requires the balanced integration of economic performance, environmental protection, and social cohesion through flexible policies, harmonized indicators, and the active involvement of farmers and local actors.

3.2 Agricultural policies and sustainability of the sector in the European Union

The Common Agricultural Policy is essential for ensuring the longterm sustainability of agriculture, including through support for small farmers and redistributive payments that have a positive impact on rural communities. These measures not only support farmers, but also have a socially inclusive effect, contributing to equity in the distribution of resources.

The environmental measures under the CAP are designed to be socially sustainable, and by supporting farmers in implementing practices that protect natural resources and biodiversity, the CAP contributes to the provision of essential services to society that would otherwise not be rewarded by the market, thus making farmers guardians of the environment and ensuring essential resources for future generations. To support this vision, the CAP promotes: reducing the use of pesticides and fertilizers and implementing natural, technological, and digital solutions to optimize agricultural production. strengthening agricultural incomes through support measures that improve farmers' incomes, increase competitiveness, and promote sustainability. funding information measures to educate the public about the safety and sustainability of EU food products.

In the literature, numerous studies have analyzed the impact, sustainability, and effectiveness of the CAP, offering diverse perspectives on how the policy can be improved to better respond to current challenges. The selected studies were published between 2010 and 2025, resulting in a total of 86 studies after applying these criteria. The data were analyzed using VOSviewer software to visualize collaboration networks and determine keyword frequency (Figure 5).

The map highlights key aspects of relevant studies in the literature on the main keywords covering a wide range of topics, including agricultural policies, sustainability, agriculture, innovation, and efficiency, in order to understand the impact and effectiveness of the CAP in promoting sustainable agricultural practices and combating climate change. It also emphasizes the importance of integrating public policies with technological innovations and the active involvement of stakeholders to achieve sustainability and performance objectives.

Most studies focus on shortterm assessments or crosssectional analyses of the effects of agricultural policies. Although many studies focus on the economic and environmental impact of the

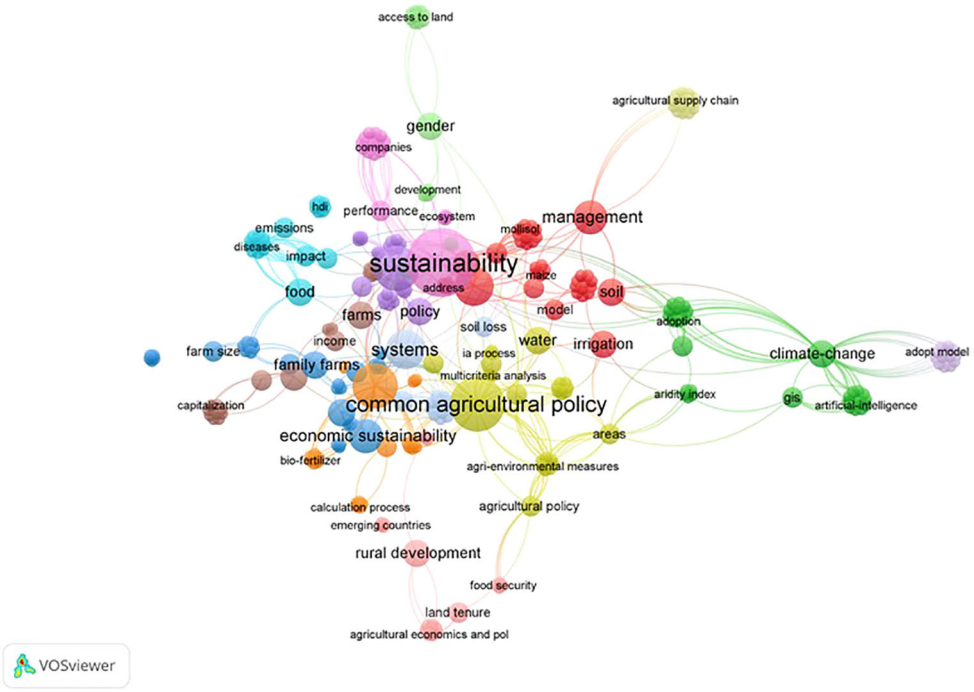

FIGURE 5
Cooccurrence matrix of keywords related to the implementation of sustainable agricultural policies in the European Union. Source: Own processing in VOSviewer.

Common Agricultural Policy, there is a significant gap in understanding the social dimension of sustainability, and most studies focus on national or regional specificities without making detailed comparisons between different EU Member States or with other regions of the world.

Figure 6 reflects critical assessments and perspectives on the reform of the Common Agricultural Policy.

Recent academic analyses highlight that the Common Agricultural Policy is at the intersection of economic and environmental objectives, but continues to show significant limitations in integrating sustainability, biodiversity, and climate change adaptation, as Pe'er et al. (2020) point out that the CAP, in its current form, has failed to respond effectively to major challenges such as biodiversity loss and soil degradation, highlighting the risk that post2020 reforms will be implemented with reduced ambitions at Member State level. In a similar vein, Morkunas and Labukas (2020) highlight the adverse effects of direct payments to farmers under Pillar I of the Common Agricultural Policy, pointing out that these non-repayable agricultural subsidies, intended to ensure the income and economic stability of farms, have in some cases led to increased land prices, reduced crop diversification, and increased the financial vulnerability of farmers, with significant implications for the sustainability of rural areas and the structure of the European agricultural landscape. Peeters et al. (2020) go further, arguing for a structural reform of the CAP geared towards agroecological systems by supporting family farming, biodiversity, and adaptation to climate change. At the same time, Doukas et al. (2023) analyze the historical evolution of the CAP, identifying the 1992 reform and the introduction of agrienvironmental measures as a turning point, but also highlighting the tension between the costs borne by farmers and the environmental benefits.

In a recent comparative analysis, Zhang and Drury (2024) position European and Chinese agricultural policies on a heuristic sustainability scale, placing them between "weak sustainability" and "strong sustainability." The authors show that both policy frameworks mainly reproduce the techno-economic/productionist discourse, focused on innovation, productivity, and competitiveness, which reflects a predominant orientation towards weak sustainability, while agroecological and ruralist perspectives, specific to strong sustainability, remain marginal in agricultural policy-making processes. They emphasize the need for participatory approaches and policies that go beyond the productivist logic to address the complexity of sustainability in agriculture.

Studies on the sustainability of agricultural policies focus on assessing the effectiveness and sustainability of various instruments used in agricultural policymaking, such as ecoconditionality and farm typologies. This research examines the mechanisms through which agricultural policies can be optimized to deliver public goods, such as environmental protection, and to ensure sound institutional performance.

Figure 7 illustrates the results of research on the impact of CAP subsidies and measures on European agriculture.

Studies on the effectiveness of agricultural policies examine how economic and financial policies influence agricultural performance, with a particular focus on assessing the effectiveness of subsidies and

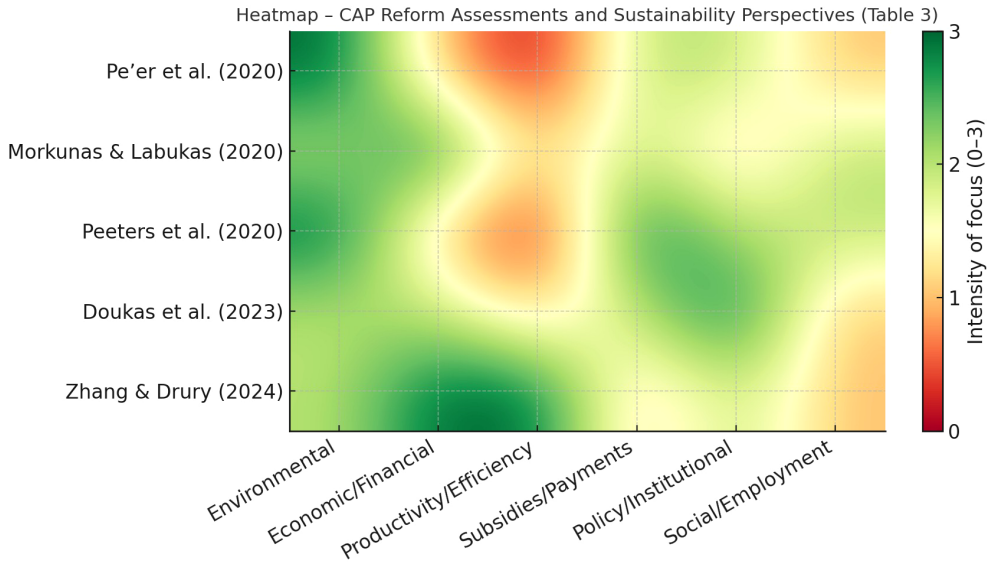

FIGURE 6
Assessments and perspectives on CAP reform in the context of agricultural sustainability.

policy measures implemented under the European Union's Common Agricultural Policy (Tsiouni et al., 2021). This research explores various approaches to improving policy efficiency, including the use of economic experiments to evaluate evidencebased measures and identifying ways to optimize the costs of agrienvironmental policy measures. Thus, ecoconditionality is analyzed as an important payment mechanism for public goods, investigating its impact on property rights and on the sustainability of environmental policy implementation. studies explore how the use of farm typologies can improve the formulation and implementation of agricultural policies, thereby facilitating the creation of policies that are better tailored to the needs of different types of farms. In addition, research examines the effects of rural development measures on the sustainability of agriculture, using advanced evaluation models to better understand their impact on farms.

Recent analyses show that the Common Agricultural Policy is an essential pillar in steering European agriculture towards sustainability, but it remains marked by contradictions and

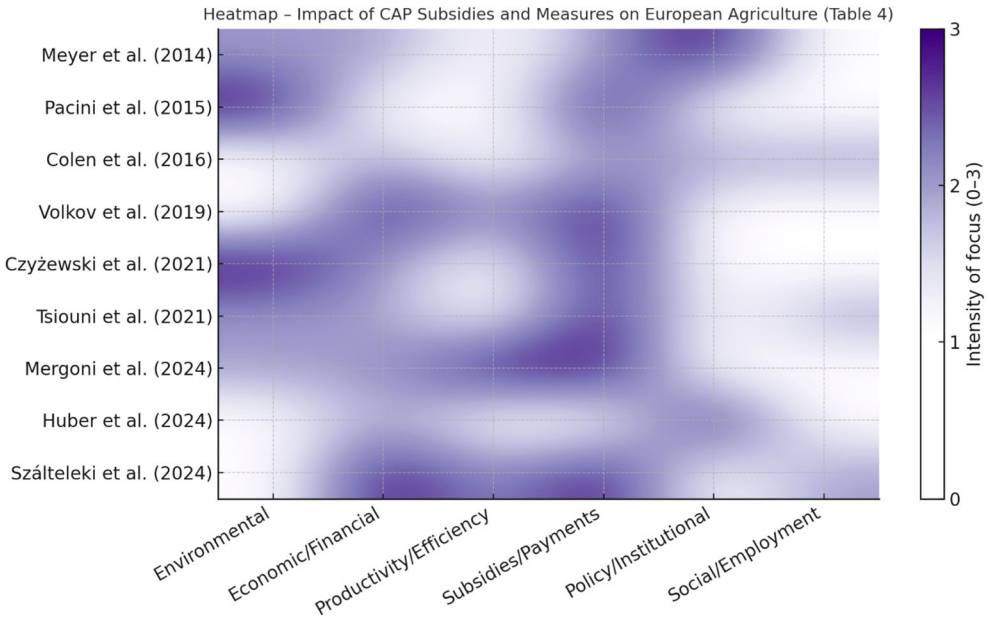

FIGURE 7
Impact of CAP subsidies and measures on European agriculture.

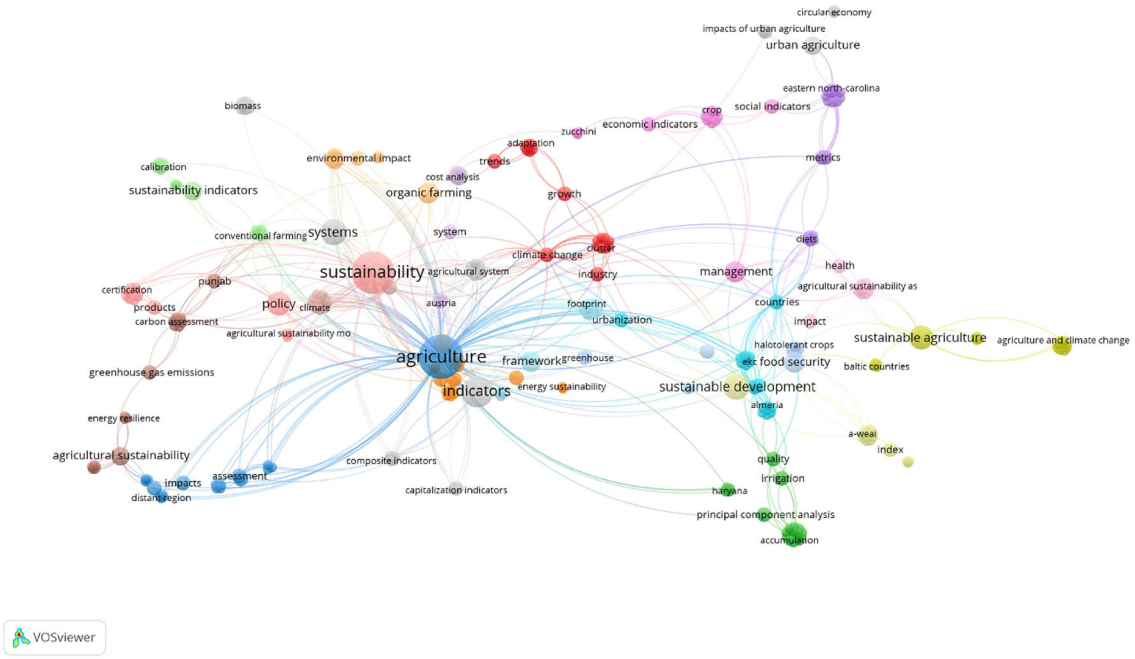

FIGURE 8
Cooccurrence matrix of keywords related to the sustainability of agricultural holdings in the European Union. Source: Own processing in VOSviewer.

compromises, as Meyer et al. (2014) compare ecoconditionality in the EU and the US, pointing out that, although in Europe it contributes to stricter enforcement of environmental legislation, it can generate misperceptions and institutional dysfunctions, while in the US it ensures the protection of land and sensitive areas, but dependence on public support raises questions about its longterm viability. In the same critical vein, Czyżewski et al. (2021) introduce the environmental sustainability value (ESV) indicator, demonstrating that certain types of payments, such as those for investment and environmental protection, have positive effects on ecoefficiency, while others, such as decoupled payments or support for disadvantaged areas, reduce environmental performance.

From a constructive perspective, Huber et al. (2024) propose the use of farm typologies to adapt CAP measures to the specific structural characteristics of farms, thereby increasing the relevance and effectiveness of policies.

The studies analyzed highlight that the Common Agricultural Policy is an essential tool for guiding European agriculture towards sustainability, but its effects remain heterogeneous and often contradictory. On the one hand, research such as that by Pacini et al. (2015) shows that agrienvironmental measures, integrated through innovative approaches such as the "Sustainable Value Approach," can generate clear benefits for biodiversity, reduce nitrogen pollution, and limit soil erosion, confirming the superiority of ecological systems over conventional ones. On the other hand, analyses such as those by Colen et al. (2016) suggest that traditional assessment methods are insufficient, arguing for the use of economic experiments to better calibrate policy effectiveness.

In terms of convergence and equity, Volkov et al. (2019) show that the current direct payment mechanism favors farmers in developed countries, accentuating disparities, while Mergoni et al. (2024) highlight the mixed effects of subsidies on productivity, signaling risks for lowperforming farms. Szálteleki et al. (2024) point to a paradox: financial support strengthens the financial stability of small farms but reduces employment.

3.3 Sustainability of farms and the financial dimension

The sustainability of farms depends on various financial management strategies, economic and environmental factors, as well as the economic size of farms. Therefore, assessment models that include opportunity costs and profitability analyses provide a more comprehensive view of economic viability and are more suitable for assessing longterm sustainability. The integration of digital technologies and accounting systems can improve sustainability reporting, reducing administrative burdens and supporting more efficient resource management.

Figure 8 illustrates the co-occurrence matrix of keywords associated with the sustainability of agricultural farms in the European Union, highlighting the main thematic clusters and interconnections between concepts such as economic performance, innovation, digitalization, and environmental efficiency.

The studies analysed highlight the importance of economic and environmental indicators in determining the sustainability of agricultural holdings. Within these studies, the authors propose different models for assessing economic viability, including opportunity costs, cash flow analysis and return on assets, and some authors investigate the role of financial indicators in assessing

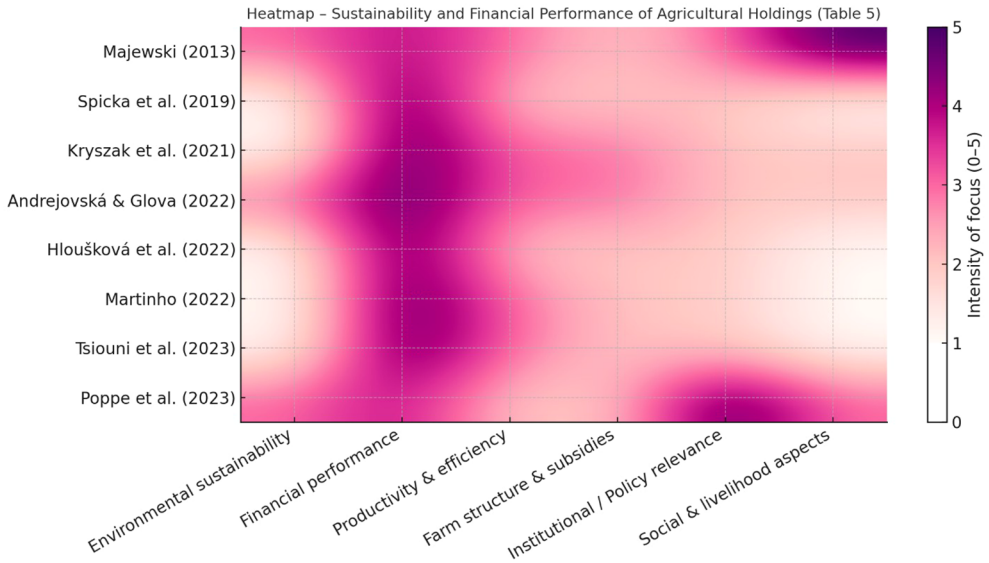

FIGURE 9
Sustainability and financial performance of agricultural holdings.

the economic sustainability of farms (Mey et al., 2011). Many studies treat economic and environmental sustainability separately, without exploring the interactions between them in depth, and future research should adopt a more integrated approach, investigating how economic and environmental objectives can be balanced to support more sustainable and resilient agriculture. Comparative research is needed to assess differences in performance and sustainability between different regions and countries of the European Union in order to help identify good practices and understand regional variations in the implementation and impact of agricultural policies.

The annual distribution of publications shows a steady increase in the number of publications from 2015 to 2023, suggesting growing interest and research activity in the field of agricultural sustainability as new challenges and solutions develop in this sector. while the frequency of keywords used shows the most frequently used keywords in research, such as "sustainability," "finance," "agriculture," "efficiency," and "performance."

The trend in the use of sustainability indicators shows an increase in the use of all three types of indicators (economic, environmental, and social) between 2013 and 2021, with social indicators being the most used, reflecting a greater concern for the social aspects of sustainability, followed by environmental and economic indicators (Kroólczyk and Latawiec, 2015).

In terms of the distribution of research topics by region, Eastern Europe has a high share of risk management studies, while Western Europe has a greater focus on economic studies, and the distribution of the types of farms used in the studies indicates that most studies focus on conventional farms (53%), followed by mixed farms (33%) and organic farms (14%). Thus, current research does not sufficiently investigate the impact of emerging technologies, such as precision agriculture, artificial intelligence, and digitization, on the economic sustainability and viability of farms, and the existing literature provides little information on the impact of economic crises and macroeconomic changes, such as recessions, global market fluctuations, and pandemics, on the economic sustainability of farms.

Analysis of collaboration networks indicates an increase in international partnerships in sustainable agriculture research, and interdisciplinary studies involve agricultural economists, ecologists, public policy experts, and agricultural technology specialists. Current trends therefore focus on:

- integrating sustainable agricultural practices with rural development, explored through studies on the impact of small farms on the sustainability of rural areas, and analyzing the performance of farms from an ecological and economic perspective;
- investigating the adoption of sustainable agricultural technologies, including the impact of climate smart agriculture and the use of green production technologies;
- longitudinal studies on the effects of the common agricultural policy on the economic and ecological sustainability of farms, including analysis of risk management and income stability tools.

Figure 9 captures the relationship between financial performance and farm sustainability, highlighting the differences between studies focusing on traditional financial indicators and those integrating social, environmental, and institutional dimensions.

Recent academic studies confirm that the economic sustainability of farms is inextricably linked to financial management strategies, income structure, and the impact of economic and environmental factors, which calls for an integrated approach to the definition and implementation of agricultural policies. The authors' contributions reveal a variety of models and tools designed to capture the complexity of economic

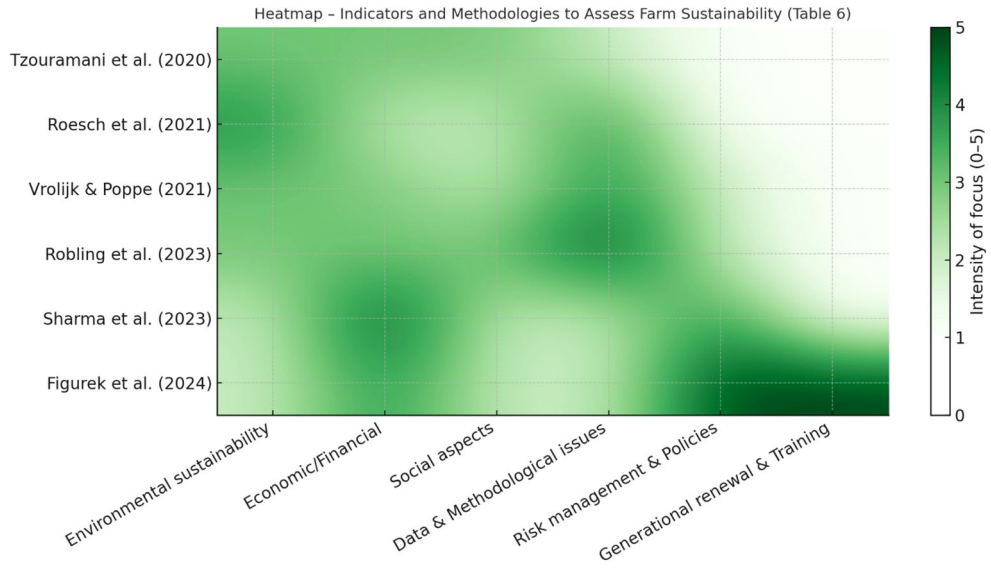

FIGURE 10
Indicators and methodologies for assessing farm sustainability.

viability. Spicka et al. (2019) draw attention to the limitations of the FADN basis for assessing sustainability, proposing an adjusted net value added indicator that includes the opportunity costs of land and capital. In a complementary direction, Andrejovská and Glova (2022) show that agricultural incomes depend on environmental factors and fiscal policies, highlighting the role of farm size, while Hloušková et al. (2022) reinforce this perspective with an economic viability index based on opportunity costs, which is useful for informing support policies.

In terms of financial performance analysis, Martinho (2022) demonstrates the importance of a balanced financial structure for profitability, while Tsiouni et al. (2023) confirm the complexity of the relationships between liquidity, solvency, and efficiency in pig farms. In practical terms, Poppe et al. (2023) propose integrating financial accounting with digital agricultural management to reduce the administrative burden and generate relevant sustainability indicators.

Figure 10 shows the indicators and methodologies used to assess farm sustainability.

Recent research clearly illustrates that agricultural sustainability cannot be assessed using a single set of indicators or tools, but requires a methodological diversity tailored to the economic, social, and ecological context of each region. Majewski (2013) proposes a synthetic index (SFSI) that integrates economic, social, and ecological dimensions, demonstrating the potential of agricultural practices and investments to increase sustainability without affecting financial viability, as do Prigoreanu et al. (2025), who propose a set of seven indices for assessing the economic sustainability of agricultural sectors in the EU and Romania. In a comparative approach, Tzouramani et al. (2020) show, using the AHP method, that traditional Mediterranean systems offer superior performance compared to intensive ones, confirming the relevance of local models.

Methodologically, Roesch et al. (2021) introduce the useful but complex SALCAsustain tool, suggesting the need for digitization and simplification for largescale application. In the same vein, Vrolijk and Poppe (2021) argue for the extension of the FADN to the FSDN, highlighting the strategic importance of more complete data, even at higher costs. The issue of data quality is detailed by Robling et al. (2023), who recommend coordination and complementary sources for agricultural indicators.

On the financial side, Sharma et al. (2023) emphasize the role of budgeting, access to capital, and public support in facilitating the ecological transition, while Figurek et al. (2024) focus on young farmers, proposing integrated models of financial and educational support. Thus, the literature confirms that agricultural sustainability depends on a multidimensional and flexible framework that combines robust methodologies, efficient financial management, and public policies tailored to different categories of farmers.

The approach in specialized studies of financial sustainability and economic performance in agriculture involves a comprehensive analysis of the factors that contribute to the longterm viability of farms, including economic, environmental, social, and institutional aspects. In the context of rapidly changing global markets, the increasing incidence of extreme weather events, and changes in consumer preferences and public policies, the focus is on developing agricultural strategies and practices that not only maximize shortterm production and profitability but also ensure the ability of agricultural systems to adapt and transform in the face of various risks. These studies investigate how farms can maintain financial stability while ensuring sustainable use of natural resources, contributing to the social and economic balance of rural communities and responding to current and future environmental and economic challenges.

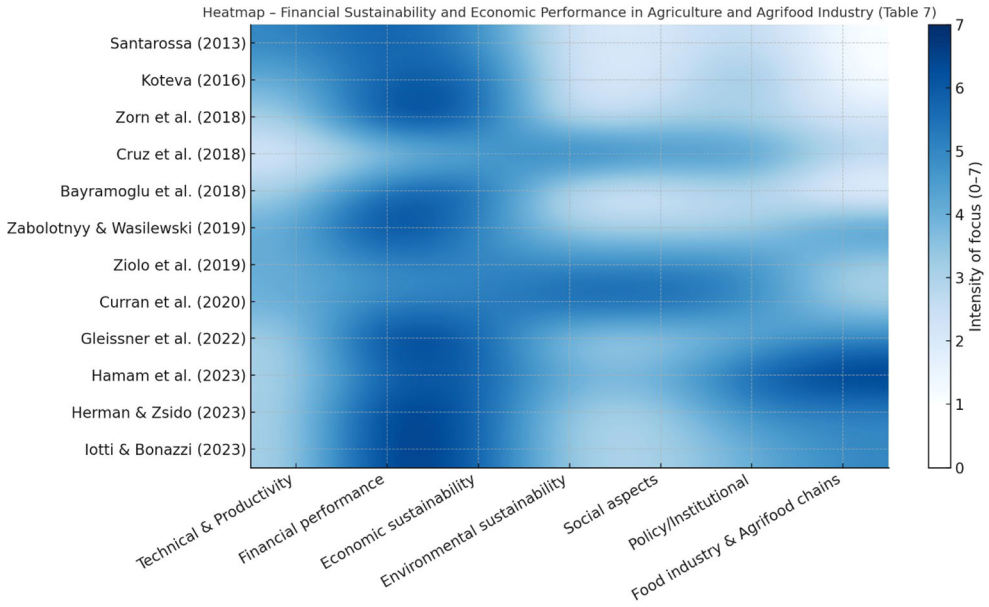

FIGURE 11
Financial sustainability and economic performance in agriculture and the agrifood industry.

Figure 11 shows how the literature analyzes financial sustainability and economic performance in agriculture and the agri-food industry.

Recent studies paint a complex picture of financial sustainability in agriculture and the agrifood industry, highlighting that it depends not only on the internal economic performance of farms and companies (Kryszak et al., 2021), but also on public policies, farm structure, and financial management capacity. Koteva (2016) highlights the vulnerability of Bulgarian farms, where subsidies stabilize incomes but do not stimulate efficiency, and farms with perennial crops are most exposed to financial risk. In a different approach, Zorn et al. (2018) show, based on Swiss dairy farms, that positively correlated financial ratios can simplify sustainability assessment by demonstrating synergies between profitability, stability, and efficiency.

In theory, Zabolotnyy and Wasilewski (2019) propose a framework based on fuzzy logic, highlighting the need to balance value growth and continuity through debt management and maximization of retained profits, and along similar lines, Gleissner et al. (2022) integrate financial sustainability into risk management and governance, showing that firms that comply with criteria such as growth and risk exposure control attract higher returns on capital markets.

At the systemic level, Hamam et al. (2023) emphasize the role of responsible investment and sustainable financing in agrifood chains, especially for developing countries, where water resources and irrigation are crucial factors. In Romania, Herman and Zsido (2023) propose a composite index for SMEs in the food retail sector, confirming the direct link between financial balance and firm performance, while Iotti and Bonazzi (2023) highlight, in the case of companies in Parma Ham PDO, the pressure of long cash conversion cycles and high debt costs, recommending the optimization of working capital. Thus, the literature confirms that financial sustainability is a strategic determinant of economic viability, and that in order to be strengthened, adapted public policies, innovations in assessment tools, and effective financial management of farms and agrifood companies are necessary.

The literature confirms that the sustainability of agricultural holdings cannot be reduced to a single dimension, but results from the interaction between financial, technical, and contextual factors, and is assessed using various methodologies (Binder et al., 2010). Thus, Santarossa (2013) show that in Scotland sustainability is decisively influenced by location, farm size, degree of specialization, and level of indebtedness, with large and specialized farms having an advantage, while those in disadvantaged areas are vulnerable but can remain viable by reducing debt and limiting diversification. Cruz et al. (2018) provide a methodological review, highlighting the role of composite indicators, statistical analyses, and participatory approaches. They emphasize the need for tools to be adapted to the local context and to integrate all three dimensions—economic, social, and environmental.

On the economic front, Bayramoglu et al. (2018) demonstrate that minimum income is a critical condition for sustainability: small farms in Turkey (<10 ha) are unsustainable, while larger farms (>15 ha) have a better chance of viability, requiring technological modernization and access to capital. Complementarily, Ziolo et al. (2019) use a multicriteria taxonomy to highlight the differences between EUOECD countries, showing that developed financial systems favor decoupling economic growth from negative environmental impacts, unlike southern and eastern countries, which perform poorly on all dimensions. In another direction, Curran et al. (2020) assess organic farms in Switzerland using SMARTFarm, obtaining high scores on the social and environmental dimensions, but lower scores on governance,

showing that although the organic sector performs well, vulnerabilities remain in terms of economic resilience and governance quality.

4 Conclusions

An analysis of the literature shows that agricultural sustainability cannot be analyzed in isolation, but must be integrated into a comprehensive framework that includes economic performance, efficient resource management, adaptation to climate change, and compliance with environmental and social standards. In this sense, sustainable agriculture is emerging as a multidimensional process that requires consistency between economic viability, environmental protection, and social equity.

The research analyzed highlights that farmers need to adopt sustainable economic practices aimed at maximizing profitability and resource efficiency while reducing environmental impact. Managing agricultural risks, including market volatility, climate variability, and vulnerability to external factors, is essential to ensuring long-term stability. In this perspective, financial sustainability not only supports the economic development of the agricultural sector, but also contributes to global food security and the well-being of rural communities. Achieving this balance requires a combination of economic efficiency, profitability, responsible resource management, and the ability to adapt to climate and market risks.

A key aspect highlighted in the literature concerns the role of public policies and financial support mechanisms such as subsidies, excise duty refunds, and other fiscal instruments that can have positive effects, but whose effectiveness depends on proper targeting and careful monitoring. At the same time, high production costs, particularly those related to energy and agricultural inputs, pose a major challenge for small and medium-sized farms, requiring stabilization policies and innovative technological solutions. Another important direction is the harmonization of sustainability indicators at the international level to facilitate comparisons between regions and agricultural systems, while maintaining adaptability to local specificities. Strengthening the education and training of farmers in financial management and sustainable practices is also essential for the widespread application of these concepts.

Looking ahead, the directions for developing sustainability in the agricultural sector will depend on technological innovation and the integration of circular economy principles, precision farming, process digitization, and the use of big data to optimize decisions and reduce resource waste. These guidelines can help reduce pressure on the environment and strengthen financial performance, creating the conditions for sustainable, resilient, and competitive agriculture.

The limitations of the study stem mainly from its bibliographic nature and its reliance on secondary sources published between 2010 and 2025, which may lead to a certain degree of selection and omission of recent contributions or those not indexed in international databases. At the same time, the methodological and conceptual heterogeneity of the indicators used to measure economic, social, and environmental sustainability may influence the comparability of results and the consistency of interpretations. Thus, future work should expand balanced regional coverage, standardize indicator sets and reporting protocols, include quantitative meta-analyses of policy effects, and correlate farm-level results with value chain and consumer dynamics.

5 Future directions for research

Research on the sustainability of agriculture in the European Union has highlighted the complexity of issues related to the integration of economic, social, and environmental dimensions, as well as the need for new and harmonized approaches. One of the future directions of research is the development of uniform methodological frameworks for assessing sustainability, which would allow for the comparability of results between Member States and between different agricultural regions. Currently, the indicators used are heterogeneous and difficult to standardize, which makes it necessary to develop a set of common tools but flexible enough to be adapted to local specificities. Thus, integrating economic indicators on profitability and financial resilience with ecological indicators on gas emissions, biodiversity, or soil quality, as well as with the social dimension of sustainability, could provide a more complete and realistic picture of agricultural performance.

Future research needs to clarify how digitalization can contribute to economic and environmental sustainability, as well as to employment, income distribution, and equitable access to resources. In this context, there is a need for indepth analysis of inclusive governance models capable of ensuring the distribution of technological benefits and preventing the concentration of economic power in the hands of dominant actors. In this regard, research should aim to develop economic viability indices that include the opportunity costs of labor, land, and capital, as well as assess the effectiveness of subsidy policies in relation to farm productivity and resilience. At the same time, the development of predictive models based on stochastic simulations or fuzzy logic can contribute to a better understanding of the impact of price fluctuations on financial viability, and the expansion of innovative financial instruments, such as green insurance, performancebased loans, or green bonds, could support the stability of the sector.

Future studies should assess more accurately the redistributive effects of subsidies on economic and social sustainability, investigate tradeoffs between economic and environmental objectives, and propose differentiated support models tailored to the size and type of farms. Comparative analyses between Member States can also highlight good practices and contribute to reforming resource allocation criteria in a more equitable and transparent manner.

Future research should investigate the relationship between farm sustainability and the social dynamics of rural areas, analyze the impact of migration and population aging on agricultural

resilience, and assess the role of education and training in strengthening sustainability. Farmers' and consumers' perceptions of sustainable agricultural practices are also an important area to explore, as they influence both the supply and demand for agricultural products.

Future research directions on the sustainability of European agriculture must integrate all these dimensions into a unified but flexible approach capable of responding to the multiple challenges of the 21st century. Harmonizing indicators, analyzing the impact of digital technologies, strengthening financial sustainability, reevaluating agricultural policies, integrating the social dimension, adapting to climate change, interdisciplinarity, and international comparisons are just some of the central themes that future research must explore in greater depth.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

IP: Visualization, Project administration, Formal Analysis, Writing – original draft, Software, Conceptualization. AG-S: Project administration, Methodology, Visualization, Funding acquisition, Investigation, Writing – review & editing, Resources. SA: Supervision, Conceptualization, Project administration, Validation, Writing – original draft, Visualization, Resources. GR: Methodology, Investigation, Data curation, Writing – review & editing, Resources, Visualization. S-BP: Formal Analysis, Visualization, Writing – review & editing, Methodology, Software. RG: Visualization, Formal Analysis, Investigation, Writing – review & editing. MC: Visualization, Data curation, Writing – review & editing, Software. GI: Methodology, Validation, Project administration, Writing – original draft, Conceptualization, Visualization, Funding acquisition, Resources.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2025.1714297/full#supplementary-material

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