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Analysis of the mutual influence of sustainability on resilience in a biodistrict

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ABSTRACT

Context: Given the recently exposed vulnerabilities of the global agri-food system, strengthening and reinforcing the development of resilient and sustainable local food systems has emerged as a key strategy. Biodistricts can represent one of the solutions to this end. They integrate organic farming, community management, and environmental protection at a local level. An analysis of their resilience and sustainability could further enhance their potential for contributing to the development of agri-food systems locally. Although sustainability and resilience complement each other, linking economic viability, environmental stewardship, and social responsibility with adaptability to disruptions, their mutual influence remains underexplored, especially in the context of biodistricts.

Objective: This study aims to analyze the mutual influence between sustainability and resilience indicators in biodistricts, with particular attention to identifying and categorizing the key indicators that shape these two domains. In doing so, the study seeks to establish an analytical framework suitable for their integrated assessment.

Methods: A systematic literature review was conducted following the PRISMA protocol. Content analysis using R programming and ATLAS.ti was employed to identify thematic relationships and research gaps across sustainability and resilience domains.

Results and conclusions: Findings reveal strong overlaps between sustainability and resilience themes, particularly in adaptation of climate change, organic agriculture, health, and education. However, notable gaps remain in areas such as fair trade and energy access. The study highlights the multidimensional interdependence of sustainability and resilience indicators and suggests combining Generalized Interval-Valued Trapezoidal Fuzzy Numbers (GIVTFNs) with the Decision-Making Trial and Evaluation Laboratory (DEMATEL) as a potential methodological approach for future analyses.

Significance: By clarifying the reciprocal links between sustainability and resilience, this study contributes to the design of more adaptive, equitable, and sustainable agri-food systems through the strategic implementation of biodistrict models.

1. Introduction

Global disruptions such as population growth, climate change, resource scarcity, the COVID-19 pandemic, and unstable global trade have exposed the fragility of agri-food systems. These shocks have revealed the urgent need for robust, sustainable, and adaptable supply chains (Sharifi et al., 2024; Zivlak and Quilfen, 2024). Sustainability in this context requires a systemic approach that balances environmental, economic, and social pillars. Neglecting their interdependencies leads to poor governance and weakens resilience; scenario-based studies have shown that systems capable of avoiding critical thresholds are more resilient and sustainable (Paas et al., 2021).

The pandemic underscored the importance of adaptive governance, localized food systems, and effective risk management (Balezentis et al., 2023). However, transforming food systems remains challenging due to ecological degradation, inequality, and fragmented governance structures. While strategies like the European Green Deal provide a potential path forward, their success depends on overcoming policy conflicts and embedding inclusive governance (Guerrieri et al., 2025).

Short Food Supply Chains (SFSCs) have gained attention as they

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directly link producers and consumers, reducing intermediaries and environmental impacts while enhancing sustainability and transparency (Jia et al., 2024). Biodistricts, which expand the principles of SFSCs, represent a territorial model of sustainable food systems. By integrating organic farming, local resource management, and community-led governance, they promote eco-tourism, food sovereignty, and rural development (Basile and Cuoco, 2024).

The development of biodistricts is rooted in trust, collaboration, and active participation of local actors. These systems address food security, fair trade, and youth access to land, though they face persistent challenges—particularly environmental and governance-related—that demand coordinated multi-actor approaches and knowledge sharing (Gava et al., 2025).

Different tools were implemented to support the biodistricts development (Assiri et al., 2021; Sciurano, 2021; Chen, 2023).

- **Performance monitoring tool** based on Porter's Diamond model, informed by sustainability and cluster development literature (Zanasi et al., 2020)
- **Integration analysis with organic Public School Food Procurement (PSFP)** to identify drivers and barriers (Kraljevic and Zanasi, 2023)
- **Assessment of the social impact of biodistricts** (Packer and Zanasi, 2023)
- **A resilience analysis model** evaluating adaptability, culture, communication, and collaboration, applied to the Mallorca Biodistrict to inform resilience policies (Kakaei and Zanasi, 2022).

Sustainability remains a central objective in agri-food systems, demanding standards for production, environmental stewardship, animal welfare, and rural development (Carissimi et al., 2023). It is commonly framed through the triple bottom line (TBL) of environmental, social, and economic pillars, while resilience focuses on the system's ability to withstand and recover from disruptions. Both are increasingly evaluated through indicators such as resource efficiency, emission reduction, and adaptive capacity (Carissimi et al., 2023; Longo et al., 2024).

In practice, sustainable transitions often face systemic obstacles like economic dependency and weak governance. Nonetheless, supportive policies, funding mechanisms, and collaboration among stakeholders can enhance both sustainability and resilience especially in biodistricts (Williams et al., 2024). Frameworks such as the Lean-Agile-Resilient-Green (LARG) model demonstrate how supply chains can simultaneously enhance flexibility and environmental performance while supporting Sustainable Development Goals (Sahu et al., 2023).

Resilience in food systems, crucial for sustaining functionality and food security amid disruptions like climate change and market instability, is increasingly vital under global uncertainty (Manikas et al., 2022).

The relevance of resilience is growing in the face of climate change and geopolitical instability. Large-scale projects such as the Belt and Road Initiative may boost infrastructure and agri-food resilience, but also raise sustainability trade-offs (Zivlak and Quilfen, 2024). Scholars have identified three primary relationships between sustainability and resilience: (1) resilience as a component of sustainability, (2) sustainability as a component of resilience, and (3) both as complementary but distinct objectives—each framing has critical implications for food policy (Marchese et al., 2018).

In the European agriculture, effective sustainability and resilience strategies often include diversification, organic practices, and technological innovations. Participatory and context-specific approaches remain essential (Reidsma et al., 2023). This aligns with indicator-based frameworks: sustainability indicators commonly assess resource efficiency, equity, and environmental impacts; resilience indicators evaluate robustness, adaptability, and recovery (Awokuse et al., 2024).

Despite growing convergence, the metrics and definitions linking sustainability and resilience remain fragmented. There is a need for integrated research frameworks that better explain their interdependencies, particularly under increasing climate pressure (Weber, 2023). An interesting contribution to this end is represented by the OASIS Agroecology Europe framework which considers: climate resilience focusing on land and water management practices, and economic resilience emphasizing income diversification, reduced input reliance,

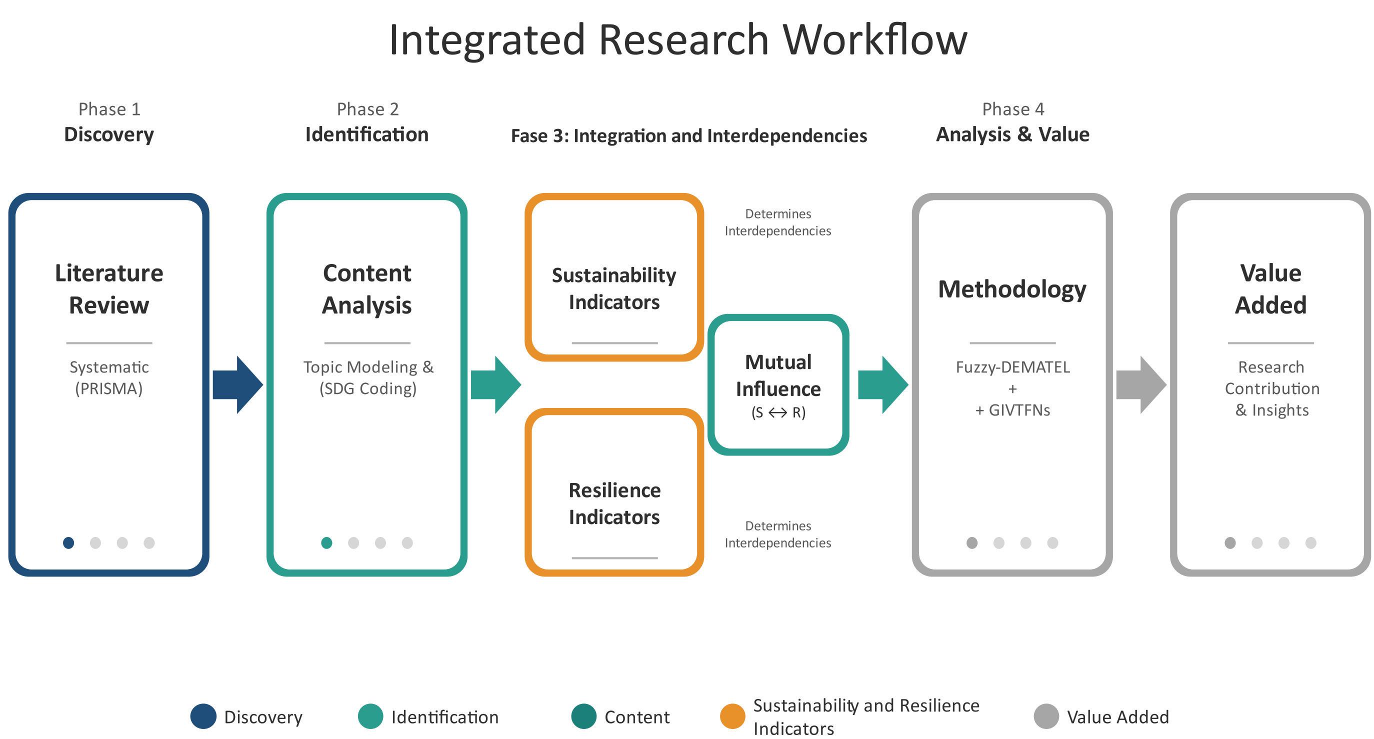

Fig. 1. Research workflow.

and stronger local markets (Peeters et al., 2021).

Ultimately, resilience—defined as the capacity to anticipate, adapt, and respond to disruptions—can enhance sustainability by stabilizing or transforming operations (Ciasullo et al., 2024). However, a comprehensive understanding of their mutual influence in biodistricts is still lacking.

1.1. Research aim and questions

Building on the results of the literature review, the present study aims to contribute to the definition of an analytical framework to assess the impact of sustainability and resilience within biodistricts The following research questions are considered:

1. What are the key categories of indicators used to analyze the impact of sustainability in biodistricts?
2. What are the key categories of indicators used to analyze the impact of resilience in biodistricts?
3. How can existing tools and frameworks be applied to compare the impact of sustainability on resilience, and vice versa, in the context of biodistricts?

Fig. 1 presents a summary of the workflow.

2. Methods

2.1. Systematic literature review

This study adopted the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol (Page et al., 2021), which is a widely accepted method designed to improve the transparency and thoroughness of systematic literature reviews. PRISMA facilitates a structured and replicable research process by clearly outlining the steps for identifying, screening, and selecting relevant studies. The lower temporal boundary of 2016 was established to align the review with the first full calendar year following the adoption of the United Nations 2030 Agenda for Sustainable Development (United Nations General Assembly, 2015) and its 17 Sustainable Development Goals (SDGs). This policy milestone is widely associated with a reorientation of academic research on sustainability and resilience in agri-food systems toward the SDG framework.

The aim of this review was to examine the **mutual impact of sustainability and resilience indicators** within biodistrict contexts. To achieve this, a systematic search was carried out using two academic databases—**Scopus** and **ScienceDirect**—targeting English-language publications from **2016 to the present**.

Table 1
Eligibility criteria for the systematic literature review.

Criteria	Inclusion	Exclusion
Language	English	Non-English publications
Publication Year	2016–present	Publications before 2016
Focus Area	Sustainability and/or resilience in supply chains, with special attention to agri-food systems and biodistricts	Studies unrelated to sustainability, resilience, or supply chains
Geographical Scope	Global, with emphasis on biodistrict or eco-region approaches or Agri-food system	Studies not involving biodistricts, eco-regions, or agri-food systems
Content Type	Peer-reviewed journal articles, reports, and gray literature	Articles lacking methodological or indicator-based analysis
Relevance	Clear exploration of sustainability or resilience indicators, or frameworks comparing them	Irrelevant or superficial mentions without analytical contribution

In Table 1, the eligibility criteria for systematic literature review are shown.

2.2. Content analysis

An R programming language was adopted to evaluate the relevance of selected articles to the topic of sustainability and resilience in biodistricts. The goal was to identify how frequently key concepts appeared across literature and to preliminarily assess the degree of thematic association and co-occurrence between sustainability and resilience themes.

Text from PDF articles was extracted using the *Pdftools* package, while *Stringr* was used for keyword pattern matching and frequency counting. A predefined list of keywords—related to sustainability, resilience, biodistricts, and agri-food supply chains—was analyzed to determine thematic emphasis.

This automated approach provided a structured foundation for understanding how central these themes are within the literature, serving as a precursor to the more detailed qualitative coding process.

To evaluate how the selected literature engages with the Sustainable Development Goals (SDGs), a dual-method approach was employed: qualitative content analysis using ATLAS.ti (Packer and Zanasi, 2023). A predefined codebook was developed, drawing on SDGs most relevant to biodistricts and agri-food systems, particularly those related to sustainability, resilience, social inclusion, and agroecological transitions, as highlighted by Marsden et al. (2019), Cherednichenko et al. (2022) and Ilieva (2017). Each code represented a specific SDG theme—such as organic farming, climate action, social equity, or biodiversity—and was applied to relevant text segments.

The analysis aimed to assess the frequency and distribution of SDG-related content and identify co-occurrence between sustainability and resilience themes, particularly through co-occurrence of relevant codes. Special attention was given to organic farming practices due to their centrality to the biodistrict model. The resulting frequency data provided a proxy for thematic emphasis, offering insights into how the literature conceptualizes and integrates sustainability and resilience in the context of biodistricts.

3. Results

3.1. Systematic literature review

This search yielded a total of 1265 records. After removing duplicates, screening titles and abstracts, based on their relevance to the topic and predefined eligibility criteria (see Table 1), 58 articles were retained. A further 32 relevant studies were identified using the snowballing technique, which involved examining references of selected papers and related studies from platforms like Google Scholar. After a full-text evaluation, a final set of 30 articles was included for in-depth analysis.

3.2. Content analysis

Thematic co-occurrence was operationalized as the simultaneous presence of sustainability and resilience related keywords within the same article (R level) and as the concurrent application of SDG-related codes from both domains to the same text segment (ATLAS.ti level). This procedure identifies patterns of thematic association and does not imply causal or directional relationships between indicators. The most frequently occurring keywords across the 30 articles were:

The plot generated in R, which displays the frequency of the keywords, is presented in Fig. 2.

Additionally, 22 of the 30 articles explicitly referenced both sustainability and resilience, indicating a strong thematic association co-occurrence. From the summarized keyword categories (generated in R with category sums), the counts were as follows Sustainability: 28;

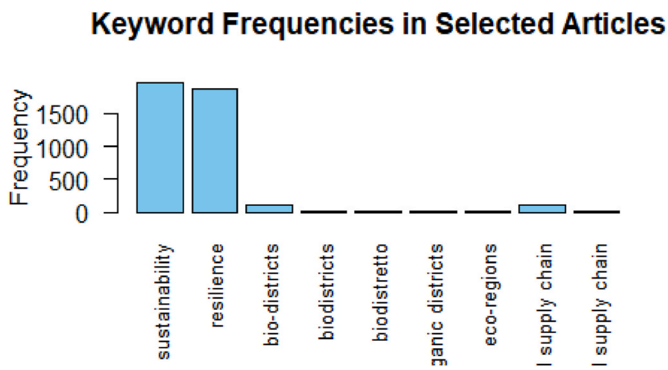

Fig. 2. Keywords frequencies.

Resilience: 23; Agri-food systems: 12.

These findings suggest that most articles place strong emphasis on sustainability and resilience within food systems, while the terms specifically referring to biodistricts or organic territorial models appeared far less frequently.

According to the results generated in **ATLAS.ti** (see Fig. 3), the most frequently applied code across the analyzed articles was Responding to Shocks and Disruptions, which corresponds to SDGs 13, 2, and 3. This code appeared 365 times in the text segments. It was followed by the Organic Agriculture code, linked to SDG 12, which was identified 261 times. In contrast, the Fair Trade and Employment code—associated with SDG 8—was the least frequently applied, with only 10 occurrences throughout the corpus. Fig. 3 illustrates the SDG-related codes identified in the literature.

In the next phase, the co-occurrence between resilience and sustainability codes (as presented in Table 2 and Table 3) was assessed. The highest co-occurrence ofoccurrence of resilience codes was observed with the limited Change Adaptation code, followed by the Health and Well-being then organic agriculture code. Furthermore, the organic agriculture code, showed the greatest co-occurrence with the Education and Awareness also Biodiversity and Nature Conservation in the study.

Table 3 presents the frequency with which sustainability-related SDG codes and resilience-related SDG codes were coded together within the analyzed literature, indicating thematic associations between the two domains.

Table 2
Frequency of SDG-Related codes identified in the literature.

SDG-Related Code	Exact Value
Response to Shocks and Disruptions (SDG 13, 2, 3)	365
Organic Farming Practices (SDG 12)	261
Health and Well-being (SDG 3)	161
Education and Awareness (SDG 4)	140
Governance & Biodiversity (SDG 15)	73
Community Participation (SDG 11)	112
Robustness and Flexibility (SDG 9, 11, 12)	123
Climate Change Adaptation (SDG 13)	118
Access to Markets and Infrastructure (SDG 9)	46
Adaptive Capacity (SDG 2, 11, 13)	47
Waste Reduction (SDG 12)	49
Risk Management (SDG 11, 13)	64
Gender Equality (SDG 5)	44
Local Economic Development (SDG 8)	17
Affordable and Clean Energy (SDG 7)	16
Fair Trade and Employment (SDG 8, 12)	10

As shown in Table 4, 'Organic Farming Practices (SDG 12)' are compared with the other codes.

It is important to emphasize that the co-occurrence of indicators identified in this study reflects patterns of thematic association within the literature and does not imply causal or directional relationships between sustainability and resilience indicators. The co-occurrence analysis provides an exploratory basis for identifying potential connections, which may be further examined through structured methodologies such as fuzzy-DEMATEL. Therefore, the relationships observed in this study should be interpreted as indicative of conceptual proximity rather than evidence of direct influence.

In this study, the term "co-occurrence" refers to the simultaneous appearance of sustainability and resilience themes within the literature, whereas "influence" is used only in the context of the proposed fuzzy-DEMATEL framework.

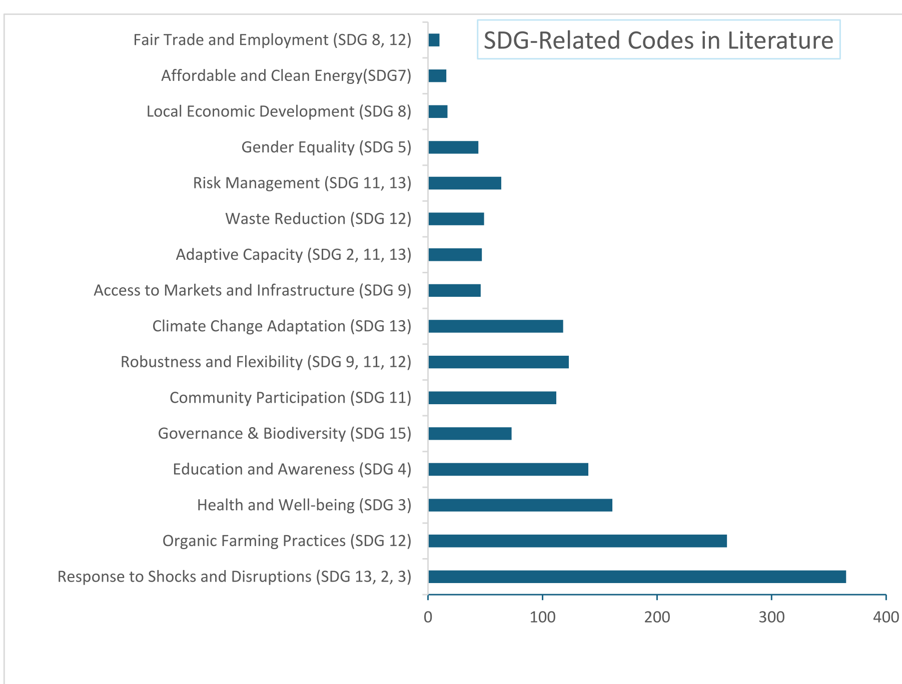

Fig. 3. SDG-related codes in literature.

Table 3
Frequency of co-occurrence between sustainability-related and resilience-related SDG codes identified through content analysis.

Sustainability-related SDG codes	Resilience-related SDG codes				Total Co-occurrence Frequency
	Adaptive Capacity	Risk Management	Robustness & Flexibility	Response to Shocks	Total co-occurrence Count
Climate Change Adaptation (SDG 13)	1	5	0	27	33
Health and Well-being (SDG 3)	1	3	4	16	24
Organic Farming Practices (SDG 12)	0	0	1	14	15
Education and Awareness (SDG 4)	1	1	2	10	14
Biodiversity and Nature Conservation (SDG 15)	1	1	1	9	12
Community Participation (SDG 11)	1	1	2	8	12
Waste Reduction (SDG 12)	0	2	1	7	10
Gender Equality (SDG 5)	0	1	1	7	9
Access to Markets and Infrastructure (SDG 9)	0	0	1	4	5
Local Economic Development (SDG 8)	0	1	0	1	2
Affordable and Clean Energy (SDG 7)	0	0	0	2	2
Fair Trade and Employment (SDG 8, 12)	0	0	0	0	0

Table 4
Comparison of "organic farming practices (SDG 12)" with other codes.

Compared Code	Mentions (Gr)	Co-occurring Count
Fair Trade and Employment (SDG 8, SDG 12)	10	0
Local Economic Development (SDG 8)	17	1
Affordable and Clean Energy (SDG 7)	16	2
Access to Markets and Infrastructure (SDG 9)	46	3
Gender Equality (SDG 5)	44	3
Waste Reduction (SDG 12)	49	5
Climate Change Adaptation (SDG 13)	118	10
Community Participation (SDG 11)	112	10
Health and Well-being (SDG 3)	161	12
Biodiversity and Nature Conservation (SDG 15)	70	17
Education and Awareness (SDG 4)	140	26

3.3. Identifying sustainability and resilience indicators

Based on the PRISMA-guided literature review, key indicators were identified and classified into two main groups: **Sustainability Indicators** and **Resilience Indicators**, reflecting distinct but interconnected aspects of agri-food supply chain (AFSC) performance. Several studies highlight the strong connection between sustainability and resilience in agri-food supply chains.

Arimany-Serrat et al. (2024) demonstrate that companies with higher sustainability performance also exhibit stronger resilience to external shocks, such as the COVID-19 pandemic and geopolitical crises.

Similarly, Paredes-Rodríguez et al. (2024) show that distribution channels prioritizing sustainability indicators, such as low carbon emissions and local employment, also enhance supply chain resilience.

Sharifi et al. (2024); Balezentis et al. (2023) further support this linkage by integrating sustainability, resilience, and agility objectives within supply chain modeling, emphasizing that balancing these aspects is crucial for long-term stability.

Carissimi et al. (2023); Marchese et al. (2018) provide conceptual clarification, indicating that while sustainability and resilience can be viewed as distinct or complementary concepts, they are often complementary in practice: sustainability ensures the long-term availability of resources, whereas resilience enables systems to recover from shocks and stresses.

In this study, sustainability indicators are defined as measurable variables used to assess environmental, social, and economic performance, while resilience indicators capture dynamic system properties such as robustness, adaptability, and recovery capacity. These two categories are treated as complementary in the context of biodistrict-based agri-food systems. The selection of indicators was guided by three criteria: (i) explicit identification in the reviewed literature, (ii) relevance to territorial agri-food systems, and (iii) measurability or suitability for expert-based assessment. Furthermore, the analysis revealed that certain dimensions such as fair trade, energy access, and related SDG 8 themes underrepresented in the literature, highlighting areas that require further empirical investigation in biodistrict contexts.

To improve conceptual clarity, the identified sustainability and resilience indicators were classified according to environmental, social, and economic dimensions, as reflected in Table 4 and Table 5. This classification provides a structured interpretation of how sustainability and resilience are operationalized within agri-food systems and biodistrict contexts. Sustainability indicators primarily assess long-term environmental, social, and economic performance. Environmental sustainability indicators refer to ecological performance (e.g., biodiversity conservation, emissions reduction, and resource efficiency), social indicators relate to community and governance aspects (e.g., equity, participation, and well-being), while economic indicators capture financial and market-related performance (e.g., profitability and local economic development).

Resilience indicators were interpreted as complementary to these dimensions, capturing the dynamic capacity of biodistrict systems to respond to shocks and stresses across environmental, social, and economic domains. These indicators include robustness, adaptability, flexibility, redundancy, and recovery capacity, which enable agri-food systems to maintain functionality under environmental, economic, and social disturbances.

In the context of biodistricts, these indicator groups are directly linked to their core objectives. Environmental indicators support organic farming practices and ecosystem protection; social indicators reflect participatory governance, community engagement, and local identity; and economic indicators relate to the development of local markets, short supply chains, and territorial economic sustainability. This alignment ensures that the selected indicators are not only theoretically relevant but also contextually appropriate for assessing biodistrict-based agri-food systems.

Furthermore, the identified indicators were associated with relevant Sustainable Development Goals (SDGs), providing an additional interpretative framework. Environmental indicators are mainly linked to SDGs 12, 13, and 15; social indicators to SDGs 2, 3, 4, 5, and 11; and economic indicators to SDGs 8 and 9. This linkage strengthens the analytical consistency of the study and situates biodistrict development within the broader global sustainability agenda.

3.3.1. Sustainability indicators

Sustainability in AFSCs is commonly evaluated through the **Triple Bottom Line (TBL)** framework, integrating environmental, economic, and social dimensions. The key sustainability indicators identified include: Table 5 presents the sustainability indicators identified in the

Table 5
Sustainability indicators.

Dimension	Indicator	Reference
Environmental	Biodiversity; greenhouse gas emissions	Reidsma et al. (2023)
Environmental	Resource efficiency; emissions reduction	Carissimi et al. (2023)
Environmental	Resource efficiency	Awokuse et al. (2024)
Environmental	Waste reduction	Sahu et al. (2023)
Environmental	Ecological limits; water-use efficiency; reduction in energy consumption	Gava et al. (2025)
Environmental	Carbon emissions management; biodiversity degradation	Zivlak and Quilfen (2024)
Environmental	Biodiversity conservation; soil protection; prevention of land degradation	Nguyen (2018)
Environmental	Greenhouse gas emissions; resource consumption; pollution control	Fahimnia and Jabbarzadeh (2016)
Environmental	Waste management; emissions reduction; green logistics management	Agyabeng-Mensah et al. (2020)
Environmental	Low-carbon logistics	Barbosa (2021)
Environmental	Climate change adaptation	(Manikas et al., 2022; Weber, 2023)
Environmental and Social	Sustainable land use; youth access to land	Assiri et al. (2021)
Social	Labor safety; community well-being; equity	Marchese et al. (2018)
Social	Stakeholder welfare; fair practices	(Agyabeng-Mensah et al., 2020)
Social	Closer producer–consumer connections; social responsibility	Barbosa (2021)
Social	Eco-tourism promotion	Basile and Cuoco (2024)
Economic	Profitability; cost efficiency; market competitiveness	Marchese et al. (2018)
Economic	Financial performance (profit generation; economic sustainability); market performance (customer satisfaction; competitive positioning)	Agyabeng-Mensah et al. (2020)
Economic	Local economic development	Barbosa (2021)

review.

3.3.2. Resilience indicators

Resilience indicators reflect the ability of AFSCs to adapt and recover from disruptions. As shown in Table 6, the resilience indicators are outlined.

Table 6
Resilience indicators.

Dimension	Indicator	Reference
Environmental	flexibility, redundancy, Robustness, adapt to disruptions	Stone and Rahimifard (2018)
Environmental	Supply chain continuity, food availability, price stability	Davis et al. (2021)
Social	Food availability, Price stability	Davis et al. (2021)
Social	Trust-based networks, local governance, social equity, life quality, Stakeholder involvement, Cooperation, Education, Bio-cultural diversity, Gender diversity	Packer and Zanasi (2023)
Social	Adaptive capacity (ability to reconfigure operations)	Carissimi et al. (2023)
Economic	Flexibility, Redundancy. information flow, traceability	Stone and Rahimifard (2018)
Environmental and Social	Environmental variability, supplier reliability, recovery from external shocks	Fahimnia and Jabbarzadeh (2016)

3.4. Introducing the model and tools

In this study, the articles were initially selected using the PRISMA method, as described in the Methods section. One of the key objectives of this search was to identify a suitable methodology to examine the effects of sustainability indicators on resilience and vice versa. The methods resulting from the literature review were analyzed, with particular attention given to the study designs and analytical techniques employed in each article.

A detailed examination of these methods led to the identification of relevant articles that used approaches suitable for analyzing the mutual influence between sustainability indicators or sustainability and resilience indicators. The following articles utilized methods that align with the goals of this study.

Paredes-Rodríguez et al. (2024) use system dynamics modeling to analyze fresh food distribution channels from a sustainability and resilience perspective. They identify key actors and indicators, build causal-loop and Forrester diagrams, and simulate three distribution models over five years using Vensim DSS, validated through a Colombian citrus supply chain case study.

Sharifi et al. (2024) propose a multi-objective robust fuzzy stochastic programming model to design sustainable, resilient, and responsive agri-food supply chains under uncertainty. Using techniques like BWM and Torabi's fuzzy programming, the model balances cost, environmental/social impacts, resilience, and delivery time, and is tested on a Canadian wheat supply chain.

Balezentis et al. (2023) perform a systematic literature review and use a multi-criteria decision-making (MCDM) approach to assess agri-food supply chain viability, identifying key indicators through bibliometric analysis and prioritizing policy measures to enhance resilience, agility, and sustainability.

Carissimi et al. (2023) apply a two-phase Systematic Literature Network Analysis (SLNA), combining a systematic literature review and bibliometric techniques (CNA, CSA, and Keyword Co-occurrence Analysis) to study the link between sustainability and resilience in supply chains. They find four main perspectives on their relationship and propose a conceptual framework connecting these views to key themes like risk management and sustainable supply chain design. (1) sustainability and resilience as distinct concepts, (2) resilience as a subset of sustainability, (3) sustainability as a subset of resilience, and (4) sustainability and resilience as interchangeable.

Tsai et al. (2023) used an Interval-Valued Hesitant Fuzzy DEMATEL (IVHF-DEMATEL) method to evaluate barriers to blockchain adoption in Vietnam's agricultural supply chain. This approach preserves expert uncertainty during analysis and identifies key cause-effect relationships among barriers, such as lack of government regulation and scalability issues.

Sahu et al. (2023) developed a multistage approach to evaluate challenges in adopting Lean-Agile-Resilient-Green (LARG) practices in sustainable agri-food supply chains.

In Phase 1, they used to quantify expert opinions and create a direct relation matrix of barriers.

In Phase 2, they applied the DEMATEL method to analyze interdependencies and classify challenges into cause and effect groups.

Findings show that lack of stakeholder understanding and transparency are the main barriers, influencing issues like weak competitive advantage and poor monitoring. The integrated fuzzy-DEMATEL framework helps prioritize challenges and guide sustainable AFSC management.

Jalali et al. (2022) applied a hybrid fuzzy decision-making approach to study barriers to Sustainable Supply Chain Management (SSCM) in Iran.

They used the Fuzzy Delphi Method (FDM) to validate 26 barriers collected from literature and experts, then applied fuzzy DEMATEL to analyze causal relationships among them, identifying key driving barriers under uncertainty.

Among these, the approach proposed by (Sahu et al., 2023) was determined to be the most appropriate for the current study. This model integrates Generalized Interval-Valued Trapezoidal Fuzzy Numbers (GIVTFNs) with the DEMATEL (Decision-Making Trial and Evaluation Laboratory) method, allowing for the detailed analysis of cause-effect relationships among interdependent indicators.

The rationale for selecting this approach is threefold:

1. Complexity and Interdependence of Indicators:

Sustainability and resilience indicators in biodistricts are not isolated but interact in complex and often circular ways. A method capable of identifying and quantifying these interdependencies—such as DEMATEL—is essential to understand their mutual influence.

2. Need to Capture Expert Uncertainty:

Expert judgment, especially in socio-ecological systems like biodistricts, is inherently uncertain and often based on subjective assessments. To accurately model this uncertainty, a fuzzy logic-based approach is necessary. Traditional crisp methods may oversimplify expert input, whereas fuzzy approaches allow for more nuanced modeling of expert opinions using linguistic variables and ranges of values.

3. Precision through GIVTFNs:

The use of GIVTFNs enhances precision in representing expert uncertainty compared to simpler fuzzy numbers. This is particularly important when dealing with multidimensional indicators and limited sample sizes, as is often the case in expert-based research. GIVTFNs offer a flexible structure to express hesitation and variability in judgments, which improves the reliability of the resulting causal analysis.

To illustrate the feasibility of the proposed approach, a preliminary structure of the fuzzy-DEMATEL framework is outlined. In a future empirical phase, the sustainability and resilience indicators identified through the literature review would form the basis of an expert evaluation matrix. Selected indicators would be grouped into sustainability and resilience domains, and experts would assess the degree of influence among them using linguistic variables. These evaluations would be converted into Generalized Interval-Valued Trapezoidal Fuzzy Numbers (GIVTFNs) to account for uncertainty. The resulting direct-relation matrix (Z) would then be normalized to obtain matrix (X), followed by the computation of the total-relation matrix $T = X\ (I - X)^{-1}$, capturing both direct and indirect relationships among indicators. From this analysis, prominence (D + R) and relation (D−R) values would be derived to determine the relative importance and causal roles of indicators. Finally, a threshold value would be applied to construct the cause–effect diagram. This process provides a structured basis for examining how sustainability-related factors may influence resilience-related factors, and vice versa, without assuming predefined causal relationships.

To capture the uncertainty and subjectivity inherent in expert evaluations, linguistic variables are represented using Generalized Interval-Valued Trapezoidal Fuzzy Numbers (GIVTFNs). This approach allows for a more flexible and accurate representation of imprecise judgments compared to crisp values. The linguistic evaluation scale adopted in this study follows the framework proposed by Sahu et al. (2023), where each linguistic term is expressed as a pair of lower and upper trapezoidal fuzzy numbers with associated membership degrees. In this context, fuzzy logic is used to transform qualitative expert judgments into quantitative representations, allowing uncertainty and variability in evaluations to be explicitly incorporated into the analysis.

To further clarify the application of the proposed fuzzy-DEMATEL framework, a simplified illustrative example is provided using indicators identified in this study. Consider the relationship between the sustainability indicator “resource efficiency” and the resilience indicator “adaptive capacity” within a biodistrict. Resource efficiency refers to the efficient use of inputs such as water, energy, and raw materials, while adaptive capacity reflects the ability of the system to adjust to environmental, economic, or social disruptions.

In a future empirical phase, expert evaluations would be collected through semi-structured interviews and expert-based assessments involving researchers, policymakers, biodistrict managers, and other stakeholders with practical experience in agri-food systems. Experts would evaluate the degree of influence between indicators using linguistic terms such as “low,” “medium,” or “high influence,” instead of assigning precise numerical values.

These linguistic evaluations would then be converted into Generalized Interval-Valued Trapezoidal Fuzzy Numbers (GIVTFNs) based on the linguistic scale presented in Table 7, allowing uncertainty and subjectivity in expert judgments to be represented more accurately. For example, a “high influence” assessment would be transformed into a fuzzy interval reflecting both the possible range of influence and the confidence level associated with the evaluation.

Although this example is illustrative and based on simulated expert evaluations, it demonstrates how the proposed fuzzy-DEMATEL framework can systematically translate qualitative expert knowledge into a structured analysis of interdependencies between sustainability and resilience indicators in biodistricts, without assuming predefined causal relationships.

4. Discussion

4.1. Systematic literature review

The primary aim of the literature search was to identify studies that explicitly engage with the concepts of sustainability and resilience in the context of biodistricts and agri-food systems. The final selection of 30 articles reflects a focused body of research that meets this objective. While the initial number of records was high, a rigorous screening process revealed that relatively few studies directly addressed the mutual relationship between sustainability and resilience within biodistrict frameworks.

This outcome highlights a notable research gap, suggesting that although biodistricts are increasingly mentioned in sustainability literature, comprehensive investigations into their resilience dimensions remain limited. The final corpus of articles, however, provides a solid foundation for analyzing how these two concepts intersect and are operationalized in practice. It also underscores the need for more

Table 7
Linguistic scale.

term	abbrev	a1	a2	a3	a4	wL	b1	b2	b3	b4	wU
no influence	NI	0	0	0	0	0.8	0	0	0.01	0.02	1
very low	VL	0	0	0.02	0.07	0.8	0	0	0.03	0.09	1
low	L	0.04	0.1	0.18	0.23	0.8	0.02	0.09	0.19	0.25	1
medium	M	0.32	0.41	0.58	0.65	0.8	0.3	0.4	0.59	0.67	1
high	H	0.72	0.78	0.92	0.97	0.8	0.7	0.77	0.93	0.99	1
very high	VH	0.93	0.98	1	1	0.8	0.91	0.97	1	1	1

integrative research that captures the systemic interplay between environmental, social, and economic aspects in biodistricts.

4.2. Content analysis

The keyword analysis highlights that while sustainability and resilience are central themes in agri-food system literature, references to biodistricts remain limited. Their co-occurrence in 22 articles indicates frequent parallel discussion, though not within integrated frameworks. The findings underscore a gap in applying interdisciplinary methods to assess their mutual effects, guiding the next phase toward selecting a suitable methodology for evaluating their interlinkages in biodistricts.

The results from the analysis of the codes related to resilience and sustainability reveal several key insights into the relationships between various sustainability goals and their associated actions. As shown in Fig. 2, the code "Responding to Shocks and Disruptions" emerged as the most frequently applied across the analyzed articles, appearing 365 times. This code, closely associated with SDGs 13 (Climate Action), 2 (Zero Hunger), and 3 (Good Health and Well-being), emphasizes the importance of preparedness and adaptability in addressing shocks and disruptions, particularly in relation to climate change and its impacts on food systems and public health.

Following closely was the "Organic Agriculture" code, linked to SDG 12 (Responsible Consumption and Production), which was mentioned 261 times. This result highlights the growing recognition of organic farming as a critical strategy for sustainable food production. In contrast, the "Fair Trade and Employment" code, associated with SDG 8 (Decent Work and Economic Growth), had the lowest frequency of 10 mentions. This suggests that while fair trade practices and employment are acknowledged in the literature, they might not be as prominently discussed in the context of resilience and sustainability within the analyzed articles.

These findings reveal an important gap in the literature on biodistricts and territorial agri-food systems. While environmental and production related themes, such as organic agriculture, climate change adaptation, biodiversity conservation, and waste reduction, are relatively well represented, social and economic dimensions related to fair trade, employment, and access to clean energy remain underrepresented. This is particularly relevant because biodistricts are not only ecological or organic production models, but also territorial governance systems intended to support local development, social participation, fair economic relations, and sustainable rural livelihoods.

The limited representation of fair trade dimensions may also be related to the fact that most biodistricts currently operate within developed economies and are strongly oriented toward short supply chains and local markets, where fair trade practices are generally less emphasized than in globally oriented agri-food trade systems. Similarly, access to clean energy and alternative energy systems appears to receive limited attention within the current biodistrict literature. Therefore, the limited presence of fair trade, employment, and energy related dimensions suggests that the social justice, labor, and energy transition aspects of biodistrict sustainability require further investigation, particularly in view of the possible expansion of biodistrict models to the Global South.

These findings are consistent with previous studies on territorial agri-food systems and biodistricts, which emphasize organic agriculture, local governance, social impact assessment, short supply chains, and territorial monitoring as central components of biodistrict development. However, compared with these studies, the present review shows that some SDG related dimensions remain less integrated into indicator-based assessment frameworks, particularly SDG 7 on affordable and clean energy and SDG 8 on decent work and economic development. This suggests that future biodistrict assessment models should move beyond environmental performance and organic production alone and include a more balanced set of indicators addressing energy access, employment quality, fair trade, and local economic resilience.

In the subsequent phase of the analysis, which explored the co-occurrenceliterature between resilience and sustainability codes (as presented in Table 2) the most significant co-occurrence occurred between resilience codes and the "Climate Change Adaptation" code. This was followed by co-occurrence with the "Health and Well-being" and "Organic Agriculture" codes. These results emphasize the interconnectedness of resilience and sustainability, particularly in the context of climate change, public health, and sustainable agricultural practices.

The co-occurrence between "Organic Agriculture" and other sustainability codes was particularly notable. As seen in Table 4, "Organic Agriculture" had a high co-occurrencewith "Education and Awareness" (SDG 4), reflecting the importance of knowledge dissemination and capacity-building in promoting sustainable agricultural practices. Additionally".

On the other hand, some codes, such as "Fair Trade and Employment" and "Affordable and Clean Energy," had minimal co-occurrence with other codes, which may indicate that these concepts are less integrated into the literature on resilience and sustainability. Specifically, the "Fair Trade and Employment" code had no co-occurrence with other sustainability codes in the corpus, suggesting a potential gap in the literature or a need for more focused discussions on these topics within the broader framework of sustainable development.

4.3. Indicators

The relationship between sustainability and resilience has been conceptualized in different ways in literature. According to Marchese et al. (2018), three main configurations can be identified: (i) resilience as a component of sustainability, (ii) sustainability as a component of resilience, and (iii) both as complementary but conceptually distinct system properties. In the context of agri-food systems and biodistricts, the present study adopts the third configuration, treating sustainability and resilience as complementary but distinct dimensions. This perspective is particularly appropriate given that sustainability indicators primarily assess long-term environmental, social, and economic performance, while resilience indicators capture dynamic system properties such as robustness, adaptability, and recovery capacity. Adopting this framework provides a theoretical basis for interpreting the relationships identified in this study, allowing the analysis to examine how these two sets of indicators are associated within the literature without assuming direct causal or directional relationships.

Overall, the literature suggests that sustainable practices may strengthen resilience by improving adaptability, reducing vulnerabilities, and supporting continuity in agri-food systems. The analysis of the identified sustainability and resilience indicators indicates potential interconnections between the two domains within agri-food systems and biodistricts. Sustainability indicators such as resource efficiency, waste reduction, emissions reduction, and climate change adaptation seem to align with resilience goals like flexibility, redundancy, and robustness. For instance, efforts aimed at resource efficiency and waste management could enhance the system's capacity to withstand and recover from environmental disruptions by reducing vulnerability to resource scarcity.

Social sustainability indicators, including labor safety, community well-being, stakeholder welfare, and social responsibility, appear to relate to resilience indicators like trust-based networks, local governance, and social equity.

Moreover, economic sustainability indicators such as profitability, cost efficiency, and market competitiveness may support resilience characteristics like agility, information flow, and operational continuity. Financially sustainable systems might be better positioned to absorb disruptions and maintain performance during crises.

The relationships identified between sustainability and resilience indicators in this study should be interpreted with caution. The results are based on co-occurrence and thematic coding of the literature, which capture patterns of association rather than causal mechanisms. While these patterns suggest that certain sustainability dimensions are frequently discussed alongside resilience related concepts, they do not demonstrate that one directly causes or determines the other. Instead, they highlight potential areas of interconnection that require further investigation through empirical methods or expert based approaches.

4.4. Introducing the model and tools

In this study, GIVTFNs were selected to flexibly capture expert opinions under uncertainty by transforming linguistic evaluations into useable fuzzy data, making it easier to address the complexity of sustainability and resilience relationships. Meanwhile, DEMATEL was chosen for its strength in identifying direct and indirect cause-effect relationships between indicators, fitting the multidimensional and interdependent nature of the study's focus.

The combination of GIVTFNs and DEMATEL aligns with the research goal of understanding how sustainability impacts resilience and vice versa, offering both mathematical rigor and flexibility to accommodate expert uncertainty.

The method will be implemented using R programming, which provides a robust environment for handling fuzzy arithmetic, constructing relation matrices, and performing DEMATEL calculations, ensuring accuracy and efficiency in the analysis.

Given the multidimensional nature of sustainability and resilience indicators in biodistricts, modeling expert judgment requires an approach that can simultaneously account for uncertainty and the need for precision. On one hand, expert assessments are often expressed in linguistic or approximate terms, making a fuzzy approach necessary to preserve the inherent vagueness and hesitation in their evaluations. On the other hand, decision-making in complex socio-ecological systems also demands a sufficient degree of precision to distinguish subtle differences among indicators and ensure reliable causal analysis. The integration of Generalized Interval-Valued Trapezoidal Fuzzy Numbers (GIVTFNs) with the DEMATEL method achieves this balance: it captures the ambiguity of expert input while providing the mathematical rigor needed for precise cause-effect modeling. For this reason, the fuzzy-DEMATEL framework proposed by (Sahu et al., 2023) was selected as the most suitable methodology for the present study.

In this study, the fuzzy-DEMATEL approach is proposed as a conceptual and methodological framework for future research. Its purpose is to enable the analysis of potential influence relationships between sustainability and resilience indicators based on expert judgment. However, the method is not empirically applied in the present study, and therefore no causal conclusions are drawn. Instead, the framework is introduced to demonstrate how such relationships could be systematically analyzed in subsequent research.

5. Conclusion

This study clarifies how sustainability and resilience interact within biodistricts, a largely underexplored field. Using a PRISMA-guided literature review and SDG-based content analysis, the study identified key challenges, classified different categories of sustainability and resilience indicators, and evaluated analytical frameworks for assessing their interdependencies.

The results show strong convergence in themes such as climate change adaptation, organic farming, and health, while lower representation was observed in dimensions related to fair trade, employment, and access to clean energy. Environmental and production-related dimensions appear to be more extensively represented in the literature, reflecting the strong orientation of biodistricts toward organic agriculture, ecosystem protection, local governance, and territorial sustainability.

The relatively limited presence of fair trade dimensions in the reviewed literature may also be related to the fact that most biodistricts currently operate within developed economies and are primarily oriented toward short supply chains and local markets, where fair trade practices are generally less emphasized than in globally oriented agri-food trade systems. Similarly, the limited consideration of energy-related dimensions may reflect the still limited integration of alternative energy systems within existing biodistrict models.

The findings further suggest that sustainability and resilience are closely associated within agri-food systems; however, these associations should be interpreted as conceptual interconnections rather than direct causal relationships. In this context, the study proposes a fuzzy-DEMATEL framework combined with Generalized Interval-Valued Trapezoidal Fuzzy Numbers (GIVTFNs) as a methodological approach for analyzing potential interdependencies between sustainability and resilience indicators.

While the proposed framework is not empirically implemented in the present study, it provides a structured basis for future research based on expert evaluation and interview- or questionnaire-based data collection.

Overall, this study contributes to future empirical research on biodistricts by supporting the assessment of the relative importance and interconnections of sustainability and resilience indicators across different territorial contexts. Furthermore, the findings may support policymakers and biodistrict managers in designing more sustainable, adaptive, and resilient agri-food systems.

CRediT authorship contribution statement

Elham Kakaei: Conceptualization, Data curation, Investigation, Methodology, Software, Writing – original draft. **Cesare Zanasi:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing. **Cosimo Rota:** Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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