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ARTICLE

RESEARCH ARTICLE

Assessing the sensitivity of global sustainability indicators to different composite index methods: application to cereal farming in Catalonia

Evaluación de la sensibilidad de la sostenibilidad global con diferentes métodos de índice compuesto: aplicación al sector de los cereales en Cataluña

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Abstract: *Aim of study:* Forward-thinking farming must become more efficient and sustainable to address the multitude of challenges it faces. This study examines the sensitivity of sustainability assessments to different composite index construction methodologies. *Area of study:* We compare five distinct approaches to composite sustainability index (CSI) construction using Farm Accountancy Data Network (FADN)-EU data from 2012 to 2022. Environmental, economic, and social dimensions are incorporated to provide comprehensive sustainability assessments for cereal farming in Catalonia, Spain. *Material and methods:* Through random effects generalized least squares regression and variance-based sensitivity analysis, we demonstrated that methodological choices significantly influence sustainability outcomes, with some methods showing greater robustness and theoretical consistency than others. Our analysis operated within the weak sustainability paradigm using additive aggregation methods. *Main results:* Our findings revealed that expert weighting produced results remarkably similar to equal weighting in this context, while factor analysis with min-max normalization offered the most theoretically consistent results. Principal component analysis provided strong statistical stability but had limitations for quantitative data applications. *Research highlights:* This study provides the first systematic integration of variance-based sensitivity analysis with econometric validation for agricultural sustainability indices, developing a quantitative robustness scoring framework that enables evidence-based method selection. The methodological insights contribute to enhanced transparency and reliability in agricultural sustainability assessment within the weak sustainability framework.

Keywords: cereal farming; FADN; sensitivity analysis; sustainability performance.

Resumen: *Objetivo del estudio:* La visión de futuro de la agricultura debe volverse más eficiente y sostenible para hacer frente a los múltiples desafíos que enfrenta. Este estudio analiza la sensibilidad de las evaluaciones de sostenibilidad con diferentes metodologías de construcción de índices compuestos. *Área de estudio:* Comparamos cinco enfoques distintos para la construcción de un índice compuesto de sostenibilidad (ICS), utilizando datos de la Red de Información Contable Agraria (RICA)-UE entre 2012 y 2022. Las dimensiones ambiental, económica y social se incorporan para proporcionar evaluaciones integrales de sostenibilidad en la agricultura cerealista de

Cataluña, España. *Material y métodos:* A través de regresiones de mínimos cuadrados generalizados con efectos aleatorios y un análisis de sensibilidad basado en varianza, demostramos que las elecciones metodológicas influyeron significativamente en los resultados de sostenibilidad, siendo algunos métodos más robustos y coherentes teóricamente que otros. Nuestro análisis operó dentro del paradigma de sostenibilidad débil utilizando métodos de agregación aditiva. *Resultados principales:* Nuestros hallazgos revelaron que la ponderación por expertos produjo resultados notablemente similares a la ponderación equitativa en este contexto, mientras que el análisis factorial con normalización min-max ofreció los resultados más coherentes desde una perspectiva teórica. El análisis de componentes principales proporcionó una gran estabilidad estadística, pero presentó limitaciones para la aplicación con datos cuantitativos. *Aspectos destacados de la investigación:* Este estudio proporciona la primera integración sistemática del análisis de sensibilidad basado en varianza con validación econométrica para índices de sostenibilidad agrícola, desarrollando un marco cuantitativo de puntuación de robustez que permite la selección de métodos basada en evidencia. Los conocimientos metodológicos contribuyen a mejorar la transparencia y confiabilidad en la evaluación de sostenibilidad agrícola dentro del marco de sostenibilidad débil.

Palabras clave: agricultura cerealista; análisis de sensibilidad; desempeño en sostenibilidad; RICA.

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Supplementary information ↓

1. INTRODUCTION

The increasing global population, the negative impacts of climate change, and intensified international competition are placing significant pressure on agriculture and natural resource use. Growing concerns about global food security, alongside various social issues prevalent in large-scale agricultural operations worldwide, have prompted calls for international measures to address the sector's challenges (González-García et al., 2019; McNeill, 2019; Pandey, 2020). Within this context, there is widespread recognition of the need for developing sustainable, resilient, and adaptable agricultural production systems (Darnhofer et al., 2010; Chopin et al., 2021).

Achieving sustainability in agricultural production systems requires a comprehensive evaluation of environmental, social, and economic conditions, an evaluation which can enhance understanding of how these systems can be reoriented toward greater sustainability (Malak-Rawlikowska et al., 2019; Tiwari & Khan, 2019). The inherent complexity and interdependence of these three dimensions have historically complicated the creation of composite sustainability indices as practical tools for guiding agricultural development (Gómez-Limón & Sanchez-Fernandez, 2010; Cardillo et al., 2023). While significant progress has been made in developing sustainability indicators, a critical research gap remains in terms of understanding how methodological choices in constructing composite indices affect sustainability assessments and subsequent decision-making processes.

To address these challenges, a pragmatic approach has emerged that advocates the empirical evaluation of sustainability based on three dimensions: economic viability, social equity, and environmental stewardship. This approach enables the operationalization of sustainability through indicator systems encompassing these dimensions (Latruffe et al., 2016). Given that sustainability assessment involves measuring progress toward targets or alignment with desired development paths, several primary steps should be undertaken before selecting composite sustainability index construction methods. These steps include defining the purpose of the final composite index, determining the spatial and temporal scales of the study, and evaluating the intended individual indicators that will form the composite index (OECD, 2008).

This paper addresses the pressing need for forward-thinking approaches to farming by analyzing cereal cultivation in Catalonia, Spain, as a representative case study. To assess sustainability comprehensively, we explore the sensitivity of sustainability assessments to various composite index construction methods, specifically comparing equal weighting, principal component analysis (PCA), and factor analysis (FA) approaches. Our study integrates key indicators across environmental, economic, and social dimensions using Farm Accountancy Data Network (FADN)-European Union data from 2012 to 2022. The weighting and aggregation of index components are critically important steps in any sustainability assessment. Weights reflect the relative importance of different dimensions in terms of their contributions to the sustainability performance of a system, while aggregation essentially reflects the substitutability of different dimensions (Nardo et al., 2005; Gan et al., 2017). Therefore, the main objectives of this study are to: (1) assess whether different composite index construction methods using the same underlying indicators produce significantly different sustainability rankings; (2) quantify the magnitude of these differences and their impact on sustainability assessments; and (3) determine which methodological approach provides the most robust and reliable evaluation of agricultural sustainability in the context of Catalonian cereal farming.

By examining the sensitivity of sustainability indices to methodological choices through integrated econometric and statistical validation, this research makes three specific methodological contributions that advance beyond existing comparative studies. First, we provide the first systematic integration of variance-based sensitivity analysis with econometric validation to assess composite sustainability index methods using identical farm-level data. Unlike previous methodological reviews (Gan et al., 2017; Gómez-Limón et al., 2020) that focus on descriptive comparison, our approach simultaneously evaluates statistical stability, theoretical consistency, and practical robustness. Second, we develop and apply a quantitative robustness scoring framework that combines the coefficient of variation analysis with inter-method agreement assessment, enabling evidence-based ranking of composite index methods rather than purely qualitative recommendations. Third, we provide systematic econometric evidence of how methodological choices affect the relationship between individual sustainability indicators and composite outcomes, demonstrating that methodological choices fundamentally alter what composite indices measure beyond simple ranking differences.

The structure of this paper is as follows: Section 2 provides a comprehensive literature review on agricultural sustainability assessment and composite index methodologies. Section 3 details the materials and methods, including data sources, indicator selection, and the specific composite index construction approaches employed. Section 4 presents the empirical results and sensitivity analysis. Section 5 concludes with key insights and recommendations for future research.

2. BACKGROUND

Significant efforts have been made to conceptualize and quantify agricultural sustainability. To capture its multifaceted nature, a diverse set of indicators has been employed, ranging from those applicable at the population level (e.g., countries) to those specific to individual units (e.g., farms) (Böhringer & Jochem, 2007; Kelly et al., 2018; Caccavale & Giuffrida, 2020). The achievement of the Sustainable Development Goal (SDG) with regard to promoting sustainable agriculture (United Nations, 2015) depends on measurement using multiple indicators, illustrating the multidimensional nature of sustainability and the need to decompose it into distinct components for effective assessment.

However, the operationalization of agricultural sustainability assessment faces a fundamental theoretical tension that is rarely acknowledged in empirical applications. The distinction between strong and weak sustainability paradigms fundamentally shapes methodological choices in terms of composite indicator construction (Usubiaga-Liaño & Ekins, 2024). Strong sustainability posits that different forms of capital (natural, human, manufactured, social) are largely non-substitutable, implying that composite indices should employ non-compensatory aggregation methods. Conversely, weak sustainability assumes perfect substitutability between different capitals, justifying the additive aggregation methods commonly employed in most sustainability assessments including established frameworks.

Several comprehensive frameworks have emerged to operationalize sustainability assessment in agricultural systems, yet each exhibits the theory-practice disconnect prevalent in the field. The Food and Agricultural Organization's (FAO) Sustainability Assessment of Food and Agriculture (SAFA) Guidelines (FAO, 2014) provide a holistic framework across governance, environmental, economic, and social dimensions, yet relies on additive aggregation despite conceptual commitment to non-substitutable sustainability dimensions. The RISE methodology (Grenz et al., 2009) attempts to balance compensatory and non-compensatory elements through hierarchical structure, while the SAFE framework (Van Cauwenbergh et al., 2007) integrates stakeholder participation but leaves substitutability assumptions implicit. The Environmental Footprint methodology (Sala et al., 2018) employs sophisticated distance-to-target weighting but focuses primarily on environmental dimensions.

The methodology for synthesizing these indicators into meaningful composite measures has evolved substantially. Comprehensive research by Gan et al. (2017) reviewed existing composite index approaches and concluded that each method has its own strengths, weaknesses, and contextual applicability, emphasizing the importance of understanding when to use particular approaches. This methodological diversity is evident in the numerous approaches used to assess farm sustainability, including hierarchical evaluation, critical point identification, spatial models, product lifecycle analysis, and integrated assessments (Nchanji et al., 2017; Thies et al., 2019). Of particular relevance to our study, composite indices have become increasingly common for evaluating economic, social, and environmental sustainability in agriculture (Sachs et al., 2019; Karimian et al., 2022).

While composite indices have proven valuable for policymaking (Nardo et al., 2005) and as a method for integrating individual indicators (González-García et al., 2019), the variation in their construction methodology requires greater attention to ensure robust results. Understanding the theoretical implications of constructing sustainability indices within the strong sustainability framework is crucial, as methodological choices can significantly impact final index scores and their interpretations (Usubiaga-Liano & Ekins, 2024). These methodological concerns are typically addressed through uncertainty and sensitivity analyses: uncertainty analysis examines how different methodological choices affect the index's structure and outcomes, while sensitivity analysis assesses the impact of each choice on output variance (Talukder et al., 2017).

Although many sustainability indices have undergone uncertainty assessments (Pollesch & Dale, 2016; Gómez-Limón et al., 2020), a gap remains in the literature regarding integrated sensitivity analyses that combine variance-based statistical approaches with econometric validation with regard to comprehensive agricultural sustainability indices that encompass environmental, economic, and social dimensions. Moreover, existing analyses are often not interpreted within explicit theoretical frameworks regarding substitutability between different capital forms. Most critically, the widespread use of additive aggregation methods in agricultural sustainability assessment —including this study— implicitly adopts weak sustainability assumptions assuming perfect substitutability between sustainability dimensions. Yet this theoretical positioning is rarely acknowledged or justified.

This theoretical grounding is essential, as different methodological choices can fundamentally alter what the index measures and how sustainability is conceptualized. By examining how different composite index methods affect sustainability assessment outcomes in this specific context, this article addresses both the practical need for reliable sustainability measurement and the methodological requirement for systematic robustness assessment, while explicitly acknowledging that the use of additive aggregation operates within the weak sustainability paradigm.

3. MATERIAL AND METHODS

Sustainability assessments in agricultural systems face numerous methodological and empirical challenges that this study addresses through a systematic comparative approach. A primary challenge identified by Deytieux et al. (2016) and Moreno-Miranda et al. (2020) involves resolving apparent conflicts between sustainability dimensions and appropriately weighting different indicators to reflect their relative importance. The need for standardized measurement approaches in agricultural systems, as argued by Boas et al. (2016), further complicates the development of reliable assessment frameworks. Additionally, Halbe & Adamowski (2019) highlight limitations in simultaneously managing multiple variables within sustainability assessments, while Doré et al. (2011) emphasize that an insufficient comparison of practices and inadequate verification of results undermines the credibility of such assessments. To address these challenges and enhance the robustness of sustainability measurement in Catalonian cereal farming, this study implements a comprehensive sensitivity analysis across multiple composite index methodologies. This approach enables systematic evaluation of how methodological choices influence sustainability assessments and provides critical insights into the reliability and interpretation of composite sustainability indicators.

3.1. Data

The Spanish FADN follows European Union regulations with regard to farm selection, employing stratified random sampling based on farm size, type of farming, and geographic region. Farms are selected to represent the agricultural holdings that contribute to at least 90% of the total Standard Output in each stratum. This analysis encompasses an unbalanced panel of 521 cereal farms in Catalonia observed over the period 2012-2022. Table 1 presents descriptive characteristics of the farm sample.

Table 1. Descriptive statistics of farm-level variables for cereal farms in the study period

Year	Number of farms	Average farm (ha)	Average yield (Kg/ha)	Average income (€/ha)
2012	56	54	7081	1036
2013	58	55	8104	998
2014	57	74	7409	775
2015	53	72	6553	700
2016	53	68	6648	779
2017	45	69	6195	692
2018	40	82	6355	774
2019	30	68	6088	719
2020	29	100	7152	849
2021	37	85	6605	883
2022	63	87	5588	1042

We reviewed existing FADN-based sustainability studies (e.g., Ryan et al., 2016; Kelly et al., 2018; Dabkiene et al., 2021) and established frameworks (Wu and Wu, 2012) to identify candidate indicators across economic, social, and environmental dimensions. From this literature base, we selected indicators that: (a) appeared consistently across multiple studies, (b) could be calculated using available FADN variables, and (c) were relevant to cereal production contexts. Table 2 provides definition of selected sustainability indicators.

Table 2. Definitions of sustainability indicators by environmental, economic, and social dimensions

Name	Dimension	Effect[4]	Description	FADN code
Profitability (PI)	Economic	+	Net income divided by total revenue	SE131,420
Benefit cost (BC)		+	Total revenue divided by total cost	SE131,270
Land productivity (LDP)		+	Total revenue divided by total hectare	SE025,131
Profit ratio (PR)		+	Total output minus total intermediate cost divided by total output	SE131,275
Remuneration of factors (RF)		+	Payment to the fixed factors of production (work, land and capital) divided by total hectare	SE025,415
Investment Intensity (II)		+	Gross farm investment divided by total hectare	SE025,516
Subsidy ratio (SUB)[1]		-	Total subsidies divided by gross income	SE410,605
Employment (EL)	Social	+	Total farm labor input divided by total hectare	SE010,025
Risk management (RMI)[2]		+	Diversification on activities	SE022
Rural development (RD)		+	Rural development payment divided by total hectare	SE025,624
Insurance ratio (INS)		+	Insurance payment divided by total hectare	SE025, insurance**
Age profile (AGE)		+	Age profile (1) young farmers (<40 years), (2) middle-aged farmers (40-55 years), and (3) older farmers (>55 years)	Age**
Education (EDU)		+	Education level of farmer (1) no education, (2) basic education, and (3) higher education	Education**
Family labor (FL)		-	Unpaid farm labor divided by total labor	SE010,015
Water intensity (WI)	Environmental	-	Water consumption cost divided by total output value	SE131, water usage**
Permanent Woodland (PW)		+	Permanent woodland hectare divided by total hectare	SE025, SE075
Eco-efficiency (EER)		+	Output value divided by total environmental input value (energy, water, and land)	SE131, SE025, SE345, water usage, land price*
Shannon Weaver (SH)[3]		+	Crop acreage to total acreage	SE035,041,041,046,050,054,055,060,065,071
Energy intensity (EI)		-	Energy consumption divided by total hectare	SE025,345
Fertilizer intensity (FERT)		-	Fertilizer consumption divided by total hectare	SE025,295
Pesticide intensity (PEST)		-	Crop protection consumption divided by total hectare	SE025,300

1 The total subsidies include all farm subsidies on crops, including compensatory payments, set-aside premiums, aid under Art 68 and other coupled support except rural development.

2 The risk management indicator of each farm is calculated according to its income share of all other activities in comparison to cereal farming.

3 The Shannon Weaver indicator is Hs=, p=crop acreage/total acreage, i different crop then SH=Hs/lnL, L number of crop.

4 Positive effect means the bigger number of that indicator would improve related sustainability dimension and vice versa.

* Land prices are based on annual value evaluation reports of Agriculture Department of Generalitat de Catalonya.

** This extra information is extracted from FITXA which is the agent for farm accounting data network (FADN) based indicator computation in Catalonia.

In term of the economic dimension, seven indicators were selected based on their demonstrated relevance to agricultural sustainability. Jane Dillon et al. (2016) identified profitability as essential for ensuring business viability, while the benefit-cost ratio indicates return on investment efficiency. Land productivity measures the efficiency of land utilization in production processes (World Bank, 2013). Ehrmann (2008) emphasized investment as critical for economically sustainable growth, while Arendonk (2015) highlighted factor remuneration as a key measure of agricultural economic contribution. Additionally, the profit ratio provides a comprehensive assessment of financial health and operational efficiency. The subsidy share ratio indicates dependency on external support systems. Multiple studies identify both profit and subsidy measures as crucial indicators for evaluating long-term economic viability (Kelly et al., 2015; Sulewski & Kłoczko-Gajewska, 2018).

The social dimension is represented by seven indicators that capture diverse aspects of social sustainability in agricultural systems. Ryan et al. (2016) emphasized risk management as essential for ensuring farm stability, while targeted initiatives for rural development and comprehensive insurance coverage address economic disparities and enhance social stability (Fisher et al., 2019; Sahoo et al., 2020). While these mechanisms involve economic tools, their primary function extends beyond financial optimization to encompass social sustainability through enhanced farm continuity, rural employment maintenance, and community stability. Education level demonstrates a strong relationship with social stability, reflecting capacity for succession planning and knowledge transfer (Ryan et al., 2016). Farmer age has been shown to have an inverse relationship with the adoption of sustainable agricultural practices (Mishra et al., 2018). Employment level and share of family labor represent key drivers for increased productivity, enhanced food security, and poverty reduction in agricultural communities (Colnago & Dogliotti, 2020).

Environmental sustainability is assessed using seven indicators that address the ecological impacts of agricultural practices. Energy usage, fertilizer application, and crop protection input levels were selected due to their significant environmental implications (Ehrmann, 2010). The Shannon-Weaver diversity index provides a measure of agricultural biodiversity, while water efficiency, eco-efficiency, and woodland area indicators address critical aspects of climate impact, ecosystem health, and resource conservation (Dabkiene et al., 2021). The water intensity indicator is calculated as water consumption cost per unit of output value production, representing the environmental burden of water use relative to productive output. For rainfed farms, the water intensity value equals zero, reflecting the absence of irrigation-related environmental impacts. For irrigated farms, higher water intensity values indicate greater environmental burden per unit of production, effectively differentiating between production systems based on their water consumption impacts. These environmental indicators collectively enable a comprehensive assessment of ecological balance and sustainable resource management in cereal farming systems. Following the OECD (2008) Pressure-State-Response model, our environmental indicators are classified as: Pressure indicators (human activities that stress the environment) take the form of: Energy intensity, Fertilizer intensity, Pesticide intensity, and Water intensity. State indicators (current environmental condition) consist of: Shannon-Weaver index and Permanent Woodland. Response indicators (management responses) include: Eco-efficiency, though response indicators are limited due to FADN data constraints that primarily capture economic rather than environmental management variables.

3.2. Methods

This study systematically examines different composite index methodologies, recognizing the sensitivity of each stage in the index creation process. Through comparative analysis and validation using regression equations, the research aims to elucidate the implications of methodological choices, contributing valuable insights for informed decision-making and policy formulation. Although numerous methodological options exist for each step of composite index construction, we selected the most applicable and relevant approaches based on previous works that evaluated various methods (Gan et al., 2017; Sala et al., 2018). Table 3 provides a brief description of the different composite sustainability indices (CSIs) employed.

Table 3. Methodological framework for constructing the composite sustainability indexes

Composite Sustainability Indexes	Indicators normalizing	Indicators weightings	Indicators aggregation
CS_1	Min-max and rescaling	Equal weights	Row means
CS_2	Standardizing	Factor analysis	weighted arithmetic mean additive
CS_3	Min-max and rescaling	Factor analysis	weighted arithmetic mean additive
CS_4	Min-max and rescaling	Principal component	weighted arithmetic mean additive
CS_5	Min-max and rescaling	Experts' opinion	weighted arithmetic mean additive

While a concise explanation for each method is provided, the final step of the methodology focuses on examining different approaches using the 21 selected indicators through a random effect generalized least squares (GLS) regression technique. The diversity in units across indicators necessitates normalization of the selected sustainability indicators for the three dimensions in four of the CSIs using a two-step process. First, all indicators are normalized to a 0-1 scale using Equation (1):

$$\mathrm{X}_{\mathrm{ik}\ normalized} = \mathrm{X}_{\mathrm{ik}} - Min\mathrm{X}_{\mathrm{k}} / Max\mathrm{X}_{\mathrm{k}} - Min\mathrm{X}_{\mathrm{k}} \quad (1)$$

where is the value of farm i for indicator k, is the lowest value of indicator k, and is the highest value of indicator k. Equation (1) transforms all selected indicators to a 0–1 scale, where a value of 0 is assigned to the farm with the lowest value of the sustainability indicator, and a value of 1 is assigned to the farm with the highest value (Nardo et al., 2005).

Although min-max normalization is sensitive to extreme values. Our outlier treatment involved: (1) initial data screening to remove farms with missing or implausible values, (2) identification and removal of extreme outliers representing data recording errors, and (3) reliance on ratio and relative indicators rather than absolute values, which inherently reduces outlier sensitivity by normalizing for farm size and scale differences.

Second, the normalized indicators are converted to a 1–6 scale with appropriate polarity adjustment using Equations (2) and (3):

Positive index $$\mathrm{X}_{\mathrm{ik}\ rescaled} = 5^{*}\mathrm{X}_{\mathrm{ik}\ normalizedi} + 1 \quad (2)$$

Negative index $$\mathrm{X}_{\mathrm{ik}\ rescaled} = -5^{*}\mathrm{X}_{\mathrm{ik}\ normalizedi} + 6 \quad (3)$$

where positive indicators follow Equation (2), while negative indicators are inverted through Equation (3) to ensure that higher rescaled values consistently represent better sustainability performance across all indicators. The final scale ranges from 1 (worst sustainability condition) to 6 (best sustainability condition).

In the case of standardizing is used as a different methodology for normalizing based on Equation (4):

$$X_{ik\ standarized} = X_{ik} - \mu X_k / \delta X_k \quad (4)$$

where is the value of farm i for indicator k, is the mean value of indicator k, and is the standard deviation value of indicator k (Nardo et al., 2005).

Principal Component Analysis (PCA) for CSI_4, following Kristjanpoller & Minutolo (2018), is employed as a multivariate technique to reduce data dimensionality. Data adequacy is confirmed using the Kaiser-Meyer-Olkin test and Bartlett's sphericity test. In addition, components with eigenvalues > 1.0

were retained, explaining 70% of total variance. Indicator weights are calculated based on component loadings weighted by the proportion of variance explained by each retained component.

Factor Analysis (FA) is used for CSI_2 and CSI_3 and implemented following Yong and Pearce (2013) to achieve linear transformation without significant information loss. Maximum likelihood extraction with varimax rotation is applied to identify the underlying factor structure. Therefore, optimal factors are retained based on eigenvalue criteria. Indicator weights are derived from communalities, representing the proportion of variance in each indicator explained by the retained factors. For the equal weighting approach, where equal weights of one are assigned to all indicators, the composite index is computed using the Row Means method according to Equation (5):

$$CSI_{1i} = 1/n \sum_{j=1}^{n} X_{ij} \quad (5)$$

where is the normalized value of the j-th indicator for the i-th unit, and n is the total number of indicators.

For the expert weighting approach, a survey containing 21 questions ranking indicators on a scale from 0 (not important) to 10 (very important) was conducted using the Qualtrics platform. The survey was distributed to 20 professional experts in sustainability and cereal crop production from four different institutions: CREDA[1], IRTA[2], DAAC[3], and ISST[4], all of whom have relevant experience in the field. The experts were purposively selected based on two criteria: (1) research experience in sustainability assessment, (2) disciplinary expertise spanning economic, environmental, and social dimensions of sustainability. The final sample consisted of 10 valid responses, yielding a response rate of 50%. Using the Row Means method, the weights from the various experts were aggregated, and the final weights for each indicator were computed.

As the final step in constructing the CSIs, except for the first approach (CSI_1), we employed the additive aggregation method to construct the composite indices. Additive aggregation methods use functions that sum the normalized values of sub-indicators to form a sustainability index. The weighted arithmetic mean is one of the most widely used additive methods (Jain & Mohapatra, 2023). The continuity property of the weighted arithmetic mean ensures that the bounds for the sustainability index can be precisely defined when the relative measurement error of the indicator set is known (Pollesch & Dale, 2015). The CSIs are calculated using Equation (6):

$$\text{CSIs} = \sum W_i X_i \,/ \sum W_i \quad (6)$$

where is a weight for index i and is the normalized and rescaled indicator.

The use of additive aggregation methods (Equation 6) operates within the weak sustainability paradigm, which assumes perfect substitutability between different sustainability dimensions and their constituent indicators. This theoretical positioning means that poor performance in environmental indicators can be fully compensated by excellence in economic or social indicators, and vice versa. While this approach contrasts with strong sustainability principles that emphasize non-substitutability between different forms of capital, it enables systematic comparison of technical approaches within a consistent analytical framework. This methodological choice has important implications for interpretation. Thus, our composite sustainability indices measure overall farm performance under the assumption that sustainability dimensions are substitutable, rather than assessing whether farms meet minimum thresholds across all sustainability dimensions. This distinction is crucial for understanding the results they represent, and their applicability to different policy contexts.

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2 Institute of Agri-Food Research and Technology, Spain.
3 Department of Climate Action, Food and Rural Agenda, Spain.
4 Institute for Sustainability Science and Technology, Spain.

To obtain a comparative view of alternative methods, the sensitivity of CSIs to their main components is analyzed using an econometric regression model (Chatterjee & Hadi, 2009). Equation (7) is estimated through random effects GLS regression:

$$\text{CSIs} = \beta_0 + \beta_i \sum_{i=1}^{21} I_i + \varepsilon \quad (7)$$

This part of the methodology gives important information about the significance of individual indices when it comes to making each CSIs. Then with regard to comparing different CSIs, the last part is designing a sensitivity analysis to identify the output variables of interest. To assess the robustness of different composite sustainability index methods, we conducted a variance-based sensitivity analysis following OECD (2008) recommendations. This approach avoids endogeneity issues by evaluating how each method responds to variations in input parameters. Our analysis examined descriptive statistics, between-method correlations, dimensional balance, and rank stability across all five CSI methods. Robustness scores are calculated based on the coefficient of variation and agreement with other methods.

4. RESULTS

Table 4 presents the basic descriptive statistics for the calculated indicators. The economic indicators display considerable variation across farms. Profitability averages 0.31 with a standard deviation of 0.37, ranging from -3.12 to 1.45. The benefit-cost ratio averages 1.21 with a standard deviation of 0.48. Land productivity exhibits variation, averaging €1,456 per hectare but ranging from €135 to €6,323.

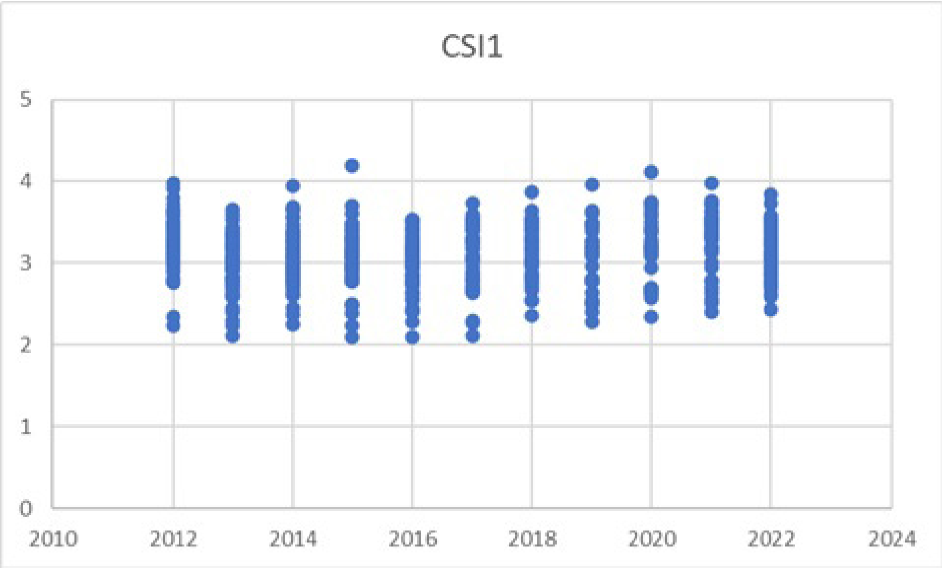
Table 4. Descriptive statistics of indicators used in the composite sustainability index

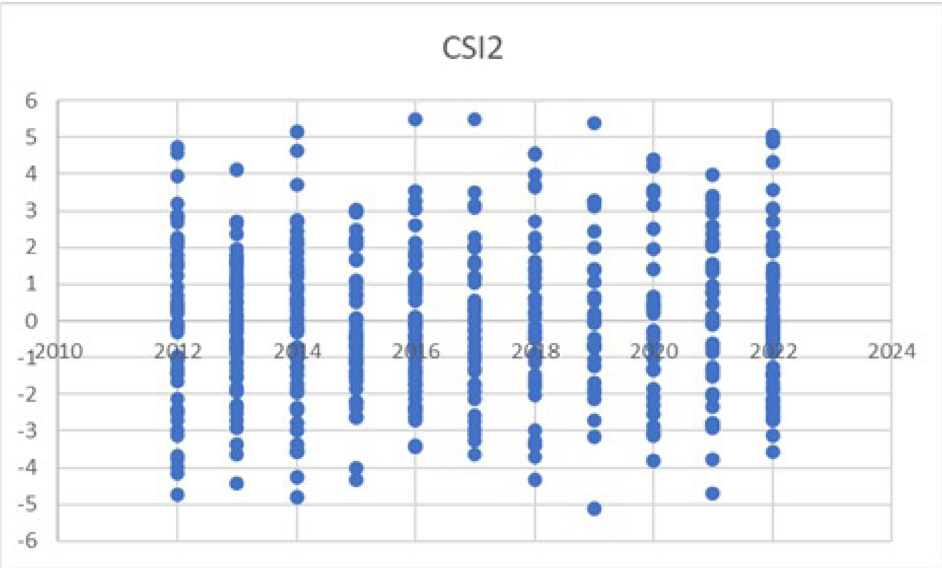
Index	Unit	Mean	Std	Min	Max
Profitability (PI)	Ratio	0.31	0.37	-3.12	1.45
Benefit cost (BC)	Ratio	1.21	0.48	0.32	3.43
Land productivity (LDP)	Euro per ha	1,456	966	135	6,323
Profit ratio (PR)	Ratio	0.32	0.27	-1.61	0.87
Remuneration of factors (RF)	Euro per ha	605	591	-1117	4909
Investment Intensity (II)	Euro per ha	260	847	0	9,005
Subsidy ratio (SUB)	Ratio	0.68	1.09	0	6
Employment (EL)	Work unit per ha	0.03	0.03	0.00	0.18
Risk management (RMI)	Categorical	3.79	20.29	0	273.35
Rural development (RD)	Euro per ha	12	39	0	625
Insurance ratio (INS)	Euro per ha	31	30	0	231
Age profile (AGE)	Categorical	2.36	0.63	1	3
Education (EDU)	Categorical	1.8	0.76	1	3
Family labor (FL)	Ratio	0.90	0.25	0	1
Water intensity (WI)	Ratio	0.04	0.05	0	0.30
Permanent Woodland (PW)	hectare	4.17	13.42	0	89
Eco-efficiency (EER)	Ratio	2.11	1.02	0.28	7.40
Shannon Weaver (SH)	Ratio	0.39	0.30	0	1.27
Energy intensity (EI)	Euro per ha	129	141	0	1275
Fertilizer intensity (FERT)	Euro per ha	160	140	0	892
Pesticide intensity (PEST)	Euro per ha	85	65	0	519

Among social indicators, family labor shows a mean of 0.90, while employment level averages 0.03 work units per hectare. Risk management exhibits high variability with a standard deviation of 20.29. The categorical indicators for age profile and education show means of 2.36 and 1.8 respectively.

Environmental indicators show energy intensity and fertilizer intensity averaging €129 and €160 per hectare respectively, while pesticide intensity averages €85 per hectare. The Shannon-Weaver diversity index averages 0.39. Permanent woodland exhibits high variation with a standard deviation of 13.42 hectares.

Figure 1 illustrates the outcomes obtained from different CSI methodologies across 2012-2022. CSI_1 (equal weights with row means) displays values primarily ranging between 2.0 and 4.0. CSI_2 (standardized indicators with factor analysis weights) exhibits values ranging from approximately -5.0 to 6.0. CSI_3 (min-max normalized with factor analysis weights) produces values predominantly between 1.0 and 6.0. CSI_4 (min-max normalized with principal component weights) displays values primarily between 2.0 and 4.0. CSI_5 (expert-weighted arithmetic mean) shows values nearly identical to CSI_1.





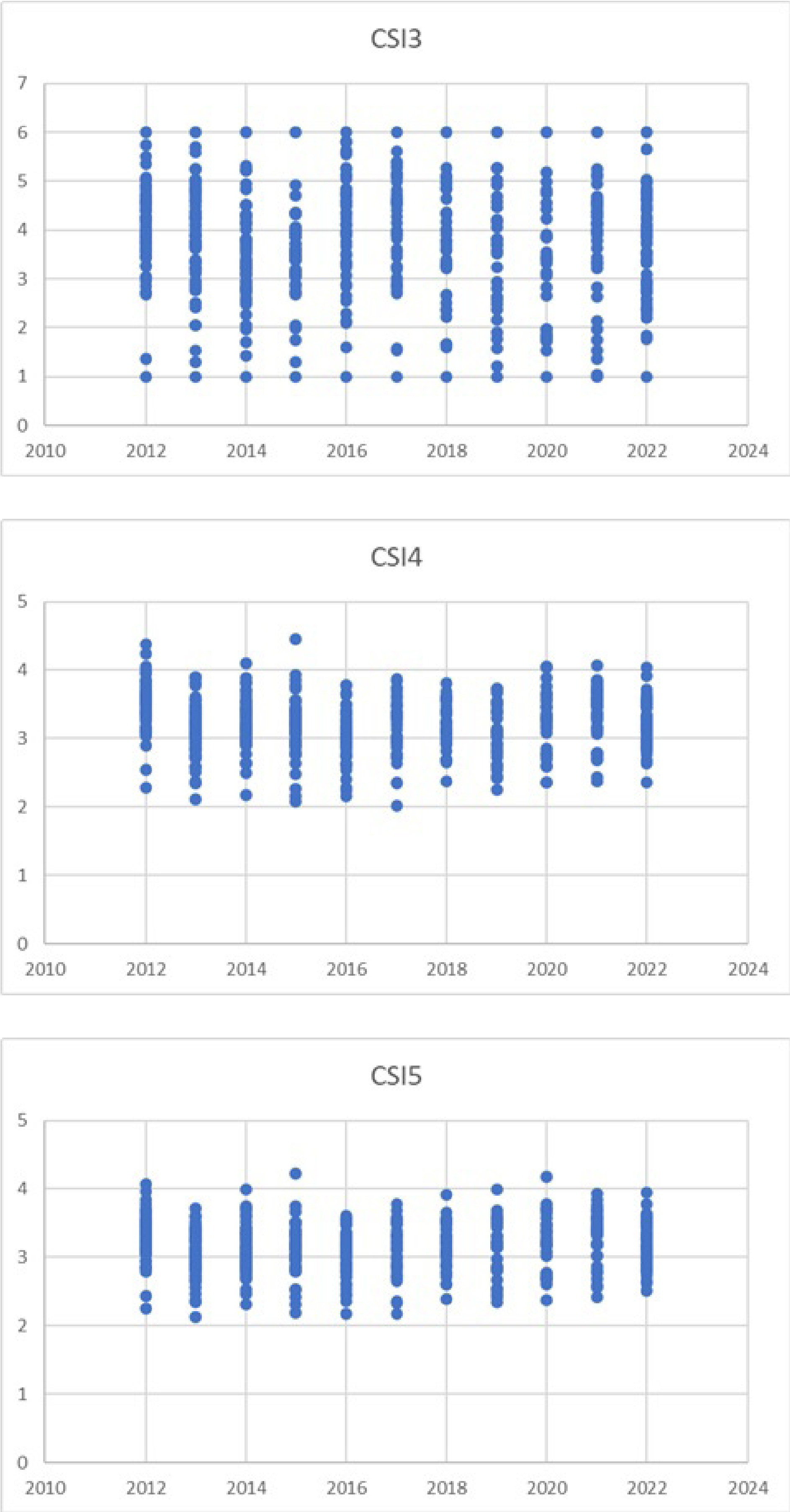


Figure 1. Comparison of Composite Sustainability Index (CSIs) scores under alternative methodological approaches.

The pairwise comparison matrix (Figure 2) shows the relationship between all five CSI methods through scatter plots (lower triangle), correlation coefficients (upper triangle), and individual distributions (diagonal). The plot reveals that CSI_1, CSI_3, CSI_4, and CSI_5 are highly correlated ($r > 0.93$), while CSI_2 shows weaker correlations and a distinctly different distribution pattern compared to other approaches.

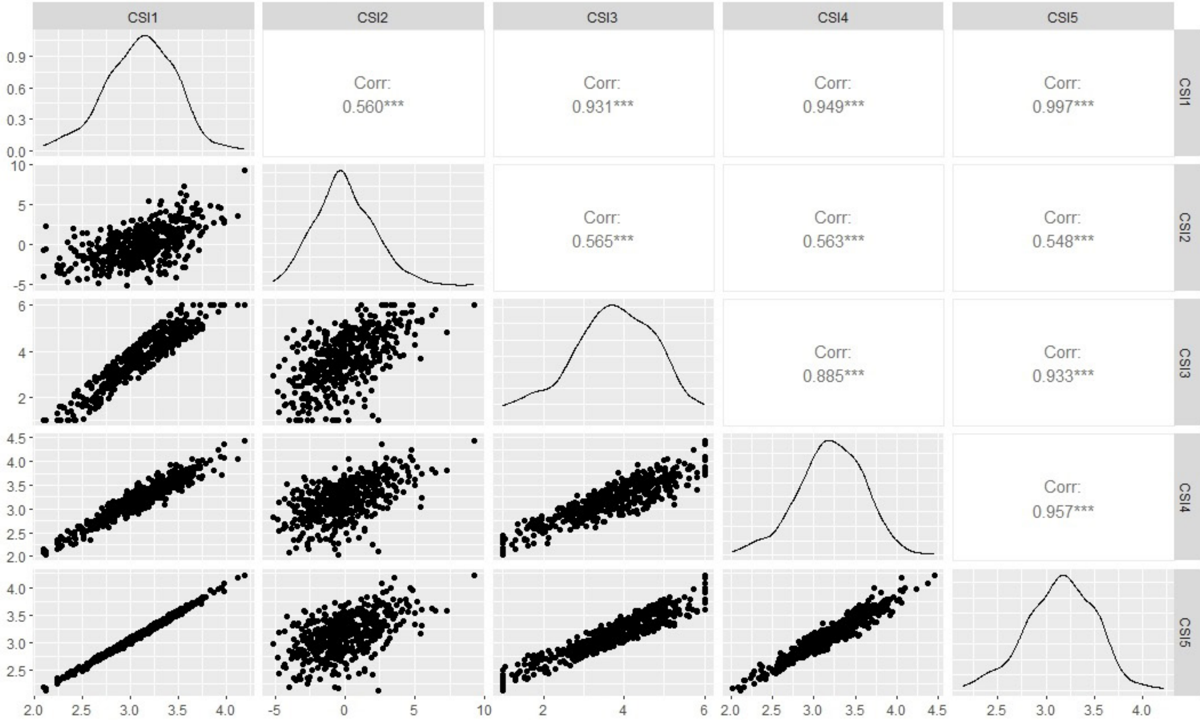


Figure 2. Pairwise correlations among Composite Sustainability Index (CSIs) specifications.

Table 5 presents the random effects GLS regression results for all five CSI methodologies. The overall explanatory power (R-squared values) ranges from 0.80 to 0.90 across methods.

Table 5. Results of random-effects general least square (GLS) regression models across specifications

Variables	CSI_1	CSI_2	CSI_3	CSI_4	CSI_5
Profitability (PI)	0.06** (0.03)	1.11*** (0.15)	0.41*** (0.11)	0.09** (0.04)	0.06** (0.03)
Benefit cost (BC)	0.08*** (0.02)	0.50*** (0.12)	0.25*** (0.09)	0.11*** (0.03)	0.09*** (0.02)
Land productivity (LDP)	-5.4×* (0.00)	-2.2×* (0.00)	-2.1×* (0.00)	-8.5×** (0.00)	-4.4×* (0.00)
Profit ratio (PR)	0.24*** (0.04)	1.35*** (0.23)	0.71** (0.16)	0.28*** (0.06)	0.24*** (0.04)
Remuneration of factors (RF)	1.4×*** (0.00)	2.7×** (0.00)	2.3×*** (0.00)	1.4×*** (0.00)	1.4×*** (0.00)
Investment Intensity (II)	4.3×*** (0.00)	2.8×*** (0.00)	1.1×*** (0.00)	4.4×*** (0.00)	3.9×** (0.00)
Subsidy ratio (SUB)	-0.04*** (0.00)	0.27*** (0.04)	-0.12*** (0.03)	-0.04*** (0.01)	-0.03** (0.00)
Employment (EL)	1.91*** (0.27)	16.07*** (1.44)	6.58*** (1.02)	2.30*** (0.38)	1.79*** (0.26)
Risk management (RMI)	0.15*** (0.01)	0.65*** (0.08)	0.41*** (0.06)	0.14*** (0.02)	0.14*** (0.01)
Rural development (RD)	8.7×*** (0.00)	4.5×*** (0.00)	1.4×*** (0.00)	6.1×*** (0.00)	8.4×*** (0.00)
Insurance ratio (INS)	1.3×*** (0.00)	0.01*** (0.00)	3.7×** (0.00)	1.2×*** (0.00)	1.1×*** (0.00)
Age profile (AGE)	0.12*** (0.00)	0.66*** (0.05)	0.38*** (0.04)	0.06*** (0.01)	0.12*** (0.01)
Education (EDU)	0.10*** (0.00)	0.25*** (0.04)	0.22*** (0.03)	0.05*** (0.01)	0.09*** (0.00)
Family labor (FL)	-0.22*** (0.02)	1.50*** (0.13)	-0.70*** (0.09)	-0.17*** (0.03)	-0.17*** (0.02)
Water intensity (WI)	-0.82*** (0.13)	7.44*** (0.71)	-2.07*** (0.50)	-0.81*** (0.19)	-0.97*** (0.13)
Permanent Woodland (PW)	3.4×*** (0.00)	0.02*** (0.00)	8.2×*** (0.00)	1.9×*** (0.00)	3.7×*** (0.00)
Eco-efficiency (EER)	0.10*** (0.02)	0.77*** (0.12)	0.43*** (0.08)	0.15*** (0.03)	0.10** (0.02)
Shannon Weaver (SH)	0.20*** (0.02)	0.84*** (0.11)	0.23*** (0.05)	0.13*** (0.03)	0.20*** (0.02)
Energy intensity (EI)	-1.3× (0.00)	3.7×*** (0.00)	-7.3× (0.00)	8.5× (0.00)	-6.1× (0.00)
Fertilizer intensity (FERT)	-3.5×*** (0.00)	1.8×*** (0.00)	-1.2×*** (0.00)	-3.8×*** (0.00)	-3.9×*** (0.00)
Pesticide intensity (PEST)	-7.5×*** (0.00)	3.9×*** (0.00)	-2.4×*** (0.00)	-7.9×** (0.00)	-8.3×*** (0.00)
Constant	2.19*** (0.05)	-9.99*** (0.26)	1.09*** (0.18)	2.41*** (0.07)	2.25*** (0.05)
R^2	0.88	0.90	0.82	0.80	0.88
Wald $\chi^2(21)$	3720***	4757***	2294***	2058***	3779***

*, *, *** indicate significance at 10%, 5%, and 1% levels respectively.

The variance-based sensitivity analysis results are presented in Table 6. CSI_1 and CSI_5 demonstrated the highest overall robustness scores (0.93), while CSI_2 showed the lowest robustness (0.28).

Table 6. Sensitivity and robustness results for alternative Composite Sustainability Index (CSI) specifications

Methods	Normalized CV	Agreement	Overall robustness
CSI_1	0.78	0.86	0.93
CSI_2	0.89	0.56	0.28
CSI_3	0.75	0.83	0.91
CSI_4	0.70	0.84	0.92
CSI_5	0.76	0.86	0.93

5. DISCUSSION

5.1. Interpretation of individual indicators

The significant variation in profitability across the sample indicates substantial heterogeneity in farm performance in the Catalonian cereal farming context. Most of the indicators being expressed as ratios represent relative relationships between two components, where values near zero typically indicate neutrality, positive values suggest good performance, while negative values imply losses or poor performance. For indicators measured in euros per hectare, the values demonstrate financial performance normalized by farm size to enable meaningful comparison across operations of different scales.

The high reliance on family workforce (mean FL of 0.90) combined with low employment levels (EL averaging only 0.03 work units per hectare) reflects the relatively low labor intensity characteristic of cereal farming. The particularly high variability in risk management suggests diverse approaches to risk across farms, while the categorical indicators for age profile and education show greater uniformity in farmer characteristics compared to other measures.

The wide range and diverse units across indicators necessitated normalization in subsequent steps to enable comparability and integration into composite sustainability indices. This normalization process was essential for developing meaningful composite measures that could effectively capture the multidimensional nature of agricultural sustainability.

5.2. Methodological comparison and implications

The choice of methodology substantially influences both the range and distribution of sustainability scores. The dramatic differences observed between methods stem directly from differences in computational approaches, highlighting the critical importance of methodological choices in sustainability assessment.

The CSI_2's extreme range and negative values, resulting from standardization that centers data around zero, reflect how this approach can amplify differences between farms and highlight outliers more prominently. However, this method exhibits several concerning characteristics, including a large negative intercept (-9.99) and contradictory signs relative to theoretical expectations. Most notably, water intensity, fertilizer intensity, and pesticide intensity —all considered negative sustainability indicators— exhibit positive coefficients, which contradicts expected relationships and raises significant concerns about the validity of this methodology.

The CSI_3 demonstrates the most theoretically consistent results with a smaller intercept (1.09), suggesting that this index may be more effective at capturing relationships between individual variables and overall sustainability. The coefficients maintain expected directional effects while showing higher magnitudes, indicating greater sensitivity to changes in individual indicators.

The remarkable similarity between CSI_1 and CSI_5 (correlation of 0.997) suggests that expert weighting in this case effectively approximates an equal weighting scheme, raising questions about whether the additional complexity of expert elicitation provides substantial benefits for this particular indicator set.

5.3. Key findings and consistent patterns

Despite methodological differences, several indicators consistently emerge as highly significant across all CSI methods. Employment level shows the largest positive coefficient across all methods, highlighting the critical importance of labor input to agricultural sustainability in the region. The consistent positive relationships of profitability, benefit-cost ratio, and profit ratio with sustainability scores reinforce the essential role of economic viability. Risk management, age profile, and education consistently display positive relationships with sustainability, emphasizing the importance of human capital and risk mitigation strategies.

Water intensity shows substantial negative coefficients in four of the five methods (with the exception of CSI_2), reflecting the critical importance of water conservation in sustainable cereal farming practices.

5.4. Methodological recommendations

Based on the comparative econometric assessment and robustness analysis, CSI_3 emerges as the most theoretically consistent and analytically useful methodology for assessing agricultural sustainability in this context. Its coefficients maintain expected directional effects while demonstrating sufficient sensitivity to changes in individual indicators.

The robustness analysis revealed that CSI_1 and CSI_5 demonstrated the highest overall robustness scores (0.93), but their similarity suggests that the added complexity of expert elicitation may not provide substantial benefits. CSI_4 achieved the lowest normalized coefficient of variation (0.70), indicating superior stability across input variations, making it particularly valuable for sustainability assessment in contexts where data quality or completeness may vary.

The CSI_2 should be approached with caution given its significantly lower robustness (0.28), poor agreement with other methods (0.56), and theoretical inconsistencies. These findings validate and extend the regression analysis results, confirming that while expert and equal weighting yield nearly identical outcomes in this context, both principal component and factor analysis approaches can provide effective alternative weighting schemes with strong statistical properties when properly implemented.

5.5. Implications for practitioners

These findings provide important methodological insights for sustainability assessment practitioners. When selecting appropriate indexing methods, practitioners should consider both theoretical consistency and robustness characteristics. The consistency between certain methods versus the distinctive patterns of others reinforces the need for thorough sensitivity analysis when developing composite indices for policy formulation or decision-making purposes.

Even when using identical underlying data and the same set of indicators, different computational approaches can lead to substantially different sustainability evaluations and rankings, emphasizing the critical importance of methodological transparency and validation in sustainability assessment research.

6. CONCLUSIONS

Our empirical findings provide valuable insights into composite sustainability index (CSI) assessment using different methodologies. The results highlight significant variations across calculation methods, underscoring the importance of careful methodological selection when evaluating agricultural sustainability. The comparison of different composite index construction methods reveals substantial variations in the sustainability assessment of cereal farming practices in Catalonia. Each stage of the index creation process proves critical, with methodological choices significantly influencing final results. Through econometric analysis, this research validates the chosen indicators and methodologies, while illuminating the strengths and limitations of each approach.

The sensitivity analysis demonstrates that CSI_1 (equal weights) and CSI_5 (expert weights) exhibit the highest degree of robustness, with nearly identical performance profiles despite their methodological differences. This finding suggests that the added complexity of expert elicitation may not substantially improve assessment outcomes in this particular context. Meanwhile, CSI_3 (factor analysis with min-max normalization) emerges as the most theoretically-consistent and analytically-useful approach, with coefficients maintaining expected directional effects while demonstrating sufficient sensitivity to changes in individual indicators. CSI_4 (principal component analysis) offers strong statistical properties with the lowest coefficient of variation, making it particularly valuable for contexts with variable data quality.

This study contributes to an enhanced understanding of sustainability assessment methodologies, facilitating informed decision-making, sustainable agricultural policy development, and collaborative efforts within Catalonia and beyond. The research demonstrates that factor analysis as a weighting method provides more theoretically consistent results compared to other approaches examined in this study. Additionally, we found that expert weighting produces remarkably similar results to equal weighting, questioning the cost-benefit analysis of complex expert elicitation processes.

While this study aimed to compare different methods using identical inputs, several limitations emerged. The social dimension assessment is limited by FADN data constraints, lacking key social sustainability aspects such as gender equity and community engagement (Brennan et al., 2023). These limitations may affect our findings and should be addressed in future research through more comprehensive indicator selection and methodological refinements. In addition, limited size of experts used for the weighting approach may limit the generalizability of expert-derived weights. Future studies should explore additional composite index methodologies and their applicability to different agricultural systems and regions to further validate and extend these findings.

Supplementary information ↑

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Supplementary material

Table S1: accompanies the paper on SJAR’s website.

Data availability

Due to privacy of farm level data, data only will be made available on reasonable request from correspondence author.

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Authorship contribution statement

Mahdieh Khezri-nejad-gharaei: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing.

Bouali Gusemi: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Validation, Writing – review & editing, Project administration.

Jose M. Gil-Roig: Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation.

Competing interests

The authors have declared that no competing interests exist.

Statement on the use of Artificial Intelligence

The author(s) used sed OpenAI, ChatGPT GPT-4o mini (2025) to translate the title, abstract, and keywords from English into Spanish. Following their use, the author(s) assumed full responsibility for the publication's content.

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