Evaluating sustainability indicators employed across European arable agricultural research. A systematic literature review

Environment, Development and Sustainability
https://doi.org/10.1007/s10668-026-07521-z

Evaluating sustainability indicators employed across European arable agricultural research. A systematic literature review

Imogen Hockenhull[1] · Paul J. Burgess[2] · Sofia Kourmpetli[2] · Julian Park[1] · Gavin Shelton[3] · Alice Mauchline[1]

Received: 7 February 2025 / Accepted: 1 March 2026

Abstract
The assessment and quantification of agricultural sustainability remain disjointed with many methodological frameworks used by the research community. Defining 'indicators' as measurable variables used to assess targeted areas of sustainability, this study provides a systematic review of studies simultaneously employing indicators across social, economic, and environmental pillars of sustainability to assess the farm-level performance of European arable agriculture. Based on strict search criteria, 36 publications were identified, employing 22 different frameworks and multiple unique indicator combinations. Overall, the analysis demonstrates that whilst many existing assessment structures are similar in their overall approach, there are large differences in the total number of indicators used and a common trend towards a higher number of environmental, rather than economic or social indicators. Across the three pillars, common indicators included the treatment and accessibility of labour, production efficiency, environmental care during production, and impacts on soil quality, suggesting that improvements in these areas on farms are considered to support their sustainability. The review also identified trade-offs between the broad applicability and site specificity of sustainability assessment frameworks, suggesting that a minimal set of indicators incorporating these key areas could be used across frameworks to support comparisons. This review identifies research gaps, summarises conflicting methodologies, and provides scientific reference and guidance for the evaluation of the sustainability of European agricultural systems.

Keywords Agricultural sustainability · Sustainability assessment · Review · Indicators · PRISMA

✉ Imogen Hockenhull
i.hockenhull@pgr.reading.ac.uk

[1] School of Agriculture, Policy and Development, University of Reading, Earley Gate, Whiteknights, Reading RG6 6EU, UK

[2] Faculty of Engineering and Applied Sciences, Cranfield University, Cranfield MK43 0AL, UK

[3] COFARM Foundation, Cambridge CB2 3QJ, UK

Published online: 24 March 2026

1 Introduction

With the world population forecasted to grow to about 10 billion by 2050 (UNDESA, 2022) and the consequent pressures placed on an array of global systems (Barnosky et al., 2016; Mccauley et al., 2015; Challinor et al., 2014; Foley et al., 2005), the need for sustainable development and protection of the Earth's finite resources is paramount. The concept of sustainable development is widely recognised as the development of systems which can support the needs of today without compromising the ability to meet the needs of the future. The transition of the global food system is critical as it provides the fundamental basis of human health and well-being and is a principal cause of the exceedance of many planetary boundaries including biogeochemical flows, biosphere integrity and land-system change (Richardson et al., 2023). For example, excessive application of nitrogen (N) and phosphorus (P) in agroecosystems greatly influences the global N and P cycle, can pollute coastal marine waters and reduce biodiversity (Swaney et al., 2012). Campbell et al. (2017) suggests that agriculture may cause 80% of the decline in biosphere integrity through its role in driving deforestation, habitat fragmentation and biodiversity loss. Simultaneously, food systems are responsible for one-third of the anthropogenic greenhouse gas emissions (Crippa et al., 2021) and food inequalities are related to unequal productivity and distribution, food waste, poverty, and limits on land access (Evenson & Gollin, 2003; Papargyropoulou et al., 2014).

The publication of the Brundtland Commission (WCED) report: 'Our Common Future' (Brundtland, 1987) and the 2002 World Summit on Sustainable Development highlighted the multi-dimensional impact of agriculture (Pham & Smith, 2014; Summit, 2002; Von Frantzius, 2004). In 2023, the UN agreed a declaration on sustainable agriculture, resilient food systems and climate action at COP28 in Dubai. Three *pillars* or *dimensions* of sustainability, that is economic, environmental, and social sustainability are now commonplace in the discussion of a sustainable future. Consequently, in the effort to enable a transformed, sustainable world, many of the 17 Sustainability Development Goals (SDGs) adopted by the UN Member States align with the advancement of more sustainable food systems. This includes Responsible Consumption and Production (12), No Poverty (1), Zero Hunger (2), Gender Equality (5), Reduced Inequalities (10) and Decent Work and Economic Growth (8).

Despite an extensive literature, the assessment and quantification of agricultural sustainability remain disjointed. Many methodological frameworks, also referred to as tools, assessing the sustainability of agricultural systems have been presented by the research community (Meul et al. 2008; Leiva and Morris 2001; Gaviglio et al. 2017; Gómez-Limón and Riesgo 2009; Özden and Acar 2022; Peano et al. 2014; Feledyn-Szewczyk and Kopiński, 2015; FAO, 2014; Gerrard et al., 2011). The aims of these commonly fall under one of three areas: the self-reflection and informed practice of farmers, exploring the anticipated "ex-ante" effects of policy implementation, or collecting empirical evidence after "ex-post" policy implementation. To this end, these frameworks are presented with various formats, measures, end users, levels of stakeholder engagement and target systems. They operate using a hierarchical breakdown of sustainability, splitting into multiple *themes*, or *sub-dimensions*, then into *sub-themes*, or *categories*, and finally into multiple base-level measures known as *indicators* or *indices*. The traction each assessment framework garners is highly variable, with some being well-recognised, utilised, and reviewed including; Sustainability Assessment of Food and Agriculture Systems (SAFA); the Public Goods

Tool (PG); Indicateurs de Durabilité des Exploitations Agricoles (IDEA); and Response-Inducing Sustainability Evaluation (RISE), and others that are more singularly applicable and bespoke to the authors that originally presented them (Meul et al., 2008; Antunes et al., 2017; Corvo et al., 2021).

To date, some studies have chosen to isolate one sustainability pillar over another for the development of relevant indicators (Pham & Smith, 2014; Rasmussen et al., 2017). This isolation whilst beneficial to the sustainability pillar under study may have unintended repercussions to those pillars not considered due to the potential crossover present across key thematic areas. Further, in recent years, reference has been made to an "indicator explosion" (Riley, 2001; Bockstaller et al., 2009) whereby a substantial increase in potential indicator-based measures have been presented. The selection of meaningful indices and the complex requirements for normalisation, weighting and aggregation are methodological criteria that come with a diverse range of suggested arrangements (Al Shamsi et al., 2019; Asselt et al., 2014; Gaviglio et al., 2017). A substantial amount of research now explores the creation of both simple and composite indicators integrated within comprehensive sustainability frameworks (Lampridi et al., 2019). These frameworks have been trialled across various agricultural ventures including conventionally intensive, agroecological and (peri-) urban systems as well as across each level of the wider food system.

It is unlikely a one-size-fits-all approach will ever be optimal as the composition of a sustainability framework, for instance, assessing Flemish dairy farms (Meul et al., 2008) will deviate from one assessing the supply chain distribution of vegetables across Vietnam (Hoang, 2021) as they aim to assess distinct food systems, climates, and socioeconomic conditions. Similarly, the defining principles of a framework will influence their decision-making, prioritisation and ultimately their wider impact. For example, an agroecologically-rooted framework will tend to have a stronger focus on social aspects than a non-agroecological approach (Burgess et al., 2023) and ultimately affect such sustainability research. However, even within frameworks assessing systems of similar physical and objective characteristics, a noticeable amount of structural variation is present. Such poor methodological cohesion and a plethora of choice is a source of confusion that often leads to the application of indicators with low scientific relevance, feasibility, or applicability to the systems of interest and suggests that there could be benefits from establishing a broader collective perspective (Hansmann et al., 2012).

Existing reviews on agricultural sustainability assessment frameworks (Chopin et al., 2017; Janker & Mann, 2018; De Olde et al., 2017; Gasparatos & Scolobig, 2012; Schader et al., 2014; Binder & Feola, 2013; Marchand et al., 2014) have generally focused on established frameworks, individual pillars, or pre-selected farming systems, demonstrating the required compromise between maximising broad applicability and framework comparability. Here, a combination of refinement parameters has been selected to provide an insight into the sustainability indicators used in European arable agricultural research. These parameters were selected to allow a controlled amount of variation relating to climate, socio-economic conditions and farming systems. The review reported here presents a current systematic search of studies simultaneously utilising indicators across social, economic, and environmental pillars of sustainability to assess the farm-level performance within Europe and aims to answer four research questions:

- Is there a particular focus on the production system and location of arable farming assessed within Europe?

- What are the similarities between the assessment structures and frameworks?
- Which are the most prevalent indicators across European arable agricultural sustainability assessments?
- How does the prevalence of indicators differ across the three pillars of sustainability, and how are they characterised?

This review identifies research gaps, contributes to the summarisation of conflicting methodologies, and provides scientific reference and guidance for future sustainability evaluation developments in European agricultural systems.

2 Methodology

The systematic literature review builds on recent reviews in the field (Nadaraja et al., 2021; Chopin et al., 2017; Desiderio et al., 2022) using previous and overarching terms to investigate assessment frameworks developed and used across European arable agriculture. To ensure a level of consistency and comparability and to help bound the systematic review, research papers considered were primarily based on arable production, however the exact farming system (e.g., community-based, commercially intensive, mixed, or urban) was not defined. This review thus included research studies that were not associated with a pre-established or defined framework to aid in the assessment of previously explored arguments around scientific relevance, feasibility, applicability, and structural variation regarding indicator selection. The Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) flowchart was used to identify articles (See Liberati et al. (2009). Firstly, all combinations of the common search terms were selected: sustainab*, agricultur*, farm*, indicator*, assess* and monitor* (Table 1). These were used in combination with the overarching terms: economic, environmental, and social joined with the AND operator to ensure the combined presence of all three sustainability pillars. In order to ensure a focus on arable

Table 1 Search terms, combinations, refinements and fields

Search Terms	C1: Sustainability (sustainab*) OR Resilience
	C2: Agriculture (agricultur*) OR Farming (farm*)
	C3: Economic AND Environmental AND Social
	C4: indicator (*)
	C5: Monitoring (monitor*) OR Assessment (assess*)
	C6a: Livestock OR Dairy OR Aquaculture OR Animal (*) OR Breed (*)
	C6b: Fish OR Breeding OR Animal OR Dairy
	C7: Developing Country (developing countr*)
Combinations, Refinements and Fields	CAB Abstracts: ALL ((C1 and C2 and C3 and C4 and C5) not (C6a or C7) and LA= English)
	Web of Science: ALL ((C1 and C2 and C3 and C4 and C5) not (C6a or C7) and LA= English
	Scopus: TITLE-ABS-KEY ((C1 and C2 and C3 and C4 and C5) not (C6a or C7) and LA= English
	Google Scholar: TITLE ((C2 and C4) not C6b) [citations not included]

systems, strictly animal-based farming practices were excluded by rejecting responses with search terms including dairy, aquaculture, livestock, and breed*. Since identifying a single region (e.g., Europe) in the search terms risks excluding European studies for a variety of reasons, it was deemed necessary to remove articles using the term developing countr* instead and manually extract European studies from those that passed through. As the complete methodology was constructed to align with the PRISMA criteria the following phases were established: literature collection and eligibility, data extraction, thematic characterisation, and data analysis.

2.1 Literature collection and eligibility

This section outlines the selection of peer-reviewed articles. Given their wide range of subject fields, the databases Scopus, Web of Science and CAB Abstracts were selected to ensure a comprehensive literature representation. All literature searches were conducted on 10 January 2023 with query strings comprising the key words discussed above either within all fields or within the title, abstract and keywords of materials in each database, connected via the Operators AND, OR, and NOT (Table 1). Additionally, a complementary title search, with a more refined search string (Table 1), was applied to the Google Scholar database to assure a thorough approach. No parameters were defined regarding publication year.

The initial search identified 954 publications across all four databases, to which a series of further inclusion and exclusion criteria were applied, and duplicates (n=248) removed (Fig. 1). First, all non-European studies were removed (n=303), this criterion was considered appropriate due to the influence the agricultural product, climate, economy, and socio-political structure is known to have on defining "sustainable" practices (Ikerd, 1993; Siebrecht, 2020). Transcontinental European countries, such as Turkey, Russia, and Cyprus, were not excluded due to their geographical location at this stage. Similarly, studies includ-

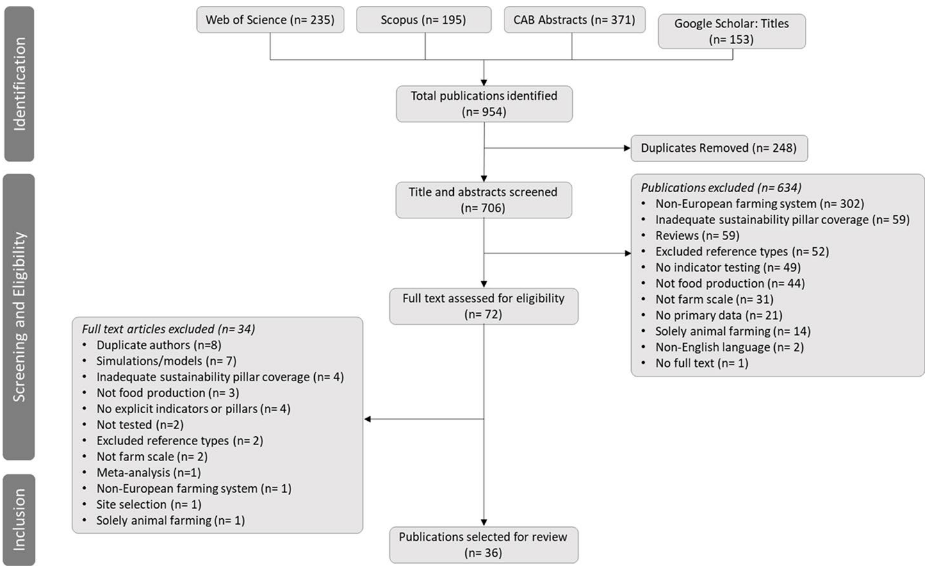

Fig. 1 Preferred Reporting Items for Systematic reviews and Meta-Analyses (*PRISMA)* flow diagram (Liberati et al., 2009) showing literature sources and inclusion/exclusion process

ing both European and non-European case studies were not excluded due to their geographical location; however, all subsequent analysis such as case study demographics (Sect. 3.1) and data extraction (Sect. 2.2) focused exclusively on the indicators applied to European case studies. Review articles, meta-analyses, other secondary-data articles, and studies which described the methodology of a framework without a case study of actual application were removed on the basis that they either had not selected, or were not employing, the measures to assess sustainability themselves ($n=186$); this was also the case for exclusively simulation-based studies ($n=7$). Additionally, for the paper to be included the case study application needed to be at farm level (Chopin et al., 2017; Fresco & Westphal, 1988), larger comparisons were allowed provided the assessment took place on an individual farming unit prior to regional comparisons, however all assessments taking place on a larger scale were removed ($n=33$).

Papers that used either no defined indicators, or indicators spanning only one or two of the sustainability pillars were removed for not fulfilling the combined-assessment requirements of this review ($n=67$). The studies included were all written in the English language and required case systems that contained at least some level of crop production, any literature which did not meet this criterion was removed ($n=66$). Finally, in some instances studies were removed to prevent a bias from prolific authors using the same framework across multiple case studies and publications ($n=8$, See Sect. 2.3). Overall, this identified 36 papers for inclusion in this analysis.

2.2 Data extraction and thematic characterisation

Bibliographic information including author, title, year of publication, publication journal, geographical location of study, and type of farm case study was extracted. Following this, information on the indicators and any associated frameworks in the publications were collated, including the number of indicators used in each study (TI) and in each sustainability pillar. This review considered any aggregation of individual indicators as themes, categories, or subcategories. Given the many ways that an indicator could be defined, new Themes, Categories and Sub-categories were assigned to each indicator by the primary author. To maintain a level of consistency and proportionality, subcategories aggregated indicators with similar names, wording, phrasing, units of measurement or ratios. Further aggregations into categories and themes, though inspired by previous publications, are acknowledged to be subjective and contextual decisions that are variable dependent on researcher's opinion and thus could reasonably be grouped in several different configurations. For this reason, analysis is predominately concentrated on the sub-categorical data collected. Information on the selected indicator groupings can be found in the supplementary codebook (https://doi.org/10.17864/1947.001491).

2.2.1 Cross pillar similarities

It has been argued that the impact any one variable or measure has will likely span multiple sustainability pillars (Schader et al., 2016), thus, it was theorised that similar indicators would be found across pillars and a further, broader comparison to identify the extent to which this was true was conducted by the primary author. Following characterisation, a keyword was assigned to each subcategory and all corresponding indicators, in this way, each indicator was counted only once. This process was systematically applied to all subcategories and pillars. Unlike the initial thematic groupings, keywords were designed to transcend individual pillars. All keyword allocations are provided in the supplementary codebook.

2.3 Data analysis and minimising bias

All data were initially collated within Excel and analysed in RStudio using the packages: tidyverse (Wickham et al., 2019) for data handling, subset creation, one-way analysis of variance (ANOVA) and data presentation as well as RColorBrewer (Neuwirth, 2022), ggh4x (van den Brand, 2024), gghalves (Tiedemann, 2022), gridExtra (Auguie, 2017) for data presentation and ggplot manipulation. With the intention of minimising bias, the following rules were used:

(i) Only unique indicators were extracted from each paper such that indicators which were repeated within the same paper under multiple subheadings were counted only once.
(ii) Multiple articles in the final list with duplicate first authors were assessed to verify their uniqueness, if they were considered too similar the most recent article with explicit indicators was selected and the rest excluded. If authors had multiple articles that were considered varied enough (i.e., several different indicators or frameworks), then both were included.
(iii) Indicators that were classified into more than the three sustainability dimensions, such as a governance dimension, were collectively split into the most appropriate of the three pillars once all indicators were extracted and themes produced. This included allocating measures of financial stability to the economic pillar, bio-physical measures into the environmental pillar and measures of urban development or influence measures into the social pillar.
(iv) This review considered an indicator as each simple measure contributing to an aggregated final score. Any larger composite groupings were broken down into their constituent measures for analysis and coding.

The presentation of indicator information in the article by (Schader et al., 2016) was not cohesive with the data collection strategy used within this review due to their complex overlapping of indicators across multiple themes and categories. Thus, while bibliographic data was extracted and incorporated ($n=36$), it was removed in all subsequent analyses, including distribution across pillars and the thematic characterisation process (Sect. 3.2.3 onward, $n=35$).

3 Results and discussion

Based on selected criteria, 36 publications simultaneously employing economic, environmental, and social indicators of sustainability in the context of predominately arable European agriculture were identified (Table 2). Throughout these documents, a combined total of 1138 indicators were extracted, 22 different frameworks used, and multiple unique indicator combinations selected. The publication date of the articles ranged from 2001 to 2022, with

Table 2 Characteristics of sustainability assessments identified through the systematic literature review. The summary attaches a Unique Identifier Number (UIN) to each study and describes corresponding case study locations, production system classifications, sustainability assessment framework(s) used, the total number of indicators, and their distribution across economic, environmental, and social pillars

UIN Author (s)	European case study location	Farming system	Associated framework(s)	Total indicators	Economic indicators	Environmental indicators	Social indicators
1 Yildirim et al. 2022	Turkey	Conventional	CH/TFSI	37	13	5	19
2 Corvo et al. 2021	France, Hungary, Switzerland, Netherlands, Serbia, Germany, Spain, Greece, Italy	Conventional, Organic	SIAT	64	20	13	31
3 Hloušková et al. 2020	Czech Republic	Conventional	MultiE	34	16	7	11
4 Stylianou et al. 2020	Cyprus	Conventional	-	41	15	9	17
5 Tapia et al. 2021	Denmark	Urban	-	24	6	9	17
6 Troiano et al. 2019	Italy	Controlled Environment	MAVT	29	12	8	9
7 Herrera et al. 2019	Germany, Greece, Spain, Finland, France, Hungary, Ireland, Netherlands, Poland	Conventional	FLINT	18	8	5	5
8 Altobelli et al. 2018	Italy	Conventional	-	3	1	1	1
9 Boggia et al. 2022	Italy	Conventional	MRP-WSCI	9	3	3	3
10 Lechenet et al. 2014	France	Conventional, Organic, Integrated	-	9	5	3	1
11 Luca et al. 2018	Italy	Conventional	-	9	3	3	3
12 Vitunskiene and Dabkiene, 2016	Lithuania	Conventional	FRSI	23	8	8	7
13 Antunes et al. 2017	Romania, Turkey, Italy, Spain	Conventional, Subsistence	SIRIUS	68	21	24	23
14 Galdeano-Gómez et al. 2017	Spain	Conventional	SAFE	14	3	5	6
15 Bachev et al. 2019	Bulgaria	Conventional	-	46	13	17	16
16 Asselt et al. 2014	The Netherlands	Peri-Urban	-	8	3	3	2

Table 2 (continued)

UIN Author (s)	European case study location	Farming system	Associated framework(s)	Total indicators	Economic indicators	Environmental indicators	Social indicators
17 Peano et al. 2015	Italy	Conventional	SAEMETH	52	10	20	22
18 Zanzi et al. 2021	Italy	Urban	SAFA	69	19	27	23
19 Reig-Martínez et al. 2011	Spain	Conventional	DEA	12	3	5	4
20 Gaviglio et al. 2017	Italy	Conventional, Organic	4agro	42	9	18	15
21 Ozden and Acar, 2022	Turkey	Community Supported Agriculture	-	45	8	20	17
22 Al Shamsi et al. 2019	Turkey	Organic	SAFA	116	28	52	36
23 Ceyhan 2010	Turkey	Conventional	Samsun	40	10	20	10
24 Gómez-Limón and Riesgo, 2009	Spain	Conventional	-	12	4	6	2
25 Alletto et al. 2022	France	Conventional	MASC 2.0, SYSTERRE	15	4	8	3
26 Iocola et al. 2021	Italy	Organic	BioDurum_MCA	30	8	20	2
27 Feledyn-Szewczyk and Kopiński, 2015	Poland	Conventional, Organic	RISE	12	3	7	2
28 Sulewski et al. 2018	Poland	Conventional	-	51	9	31	11
29 Iocola et al. 2020	France, Germany, Italy	Conventional, Organic	DiverIMPACTS, SAFA	64	16	35	13
30 Colomb et al. 2013	France	Organic	MASC-OF	29	4	20	5
31 Leiva and Morris, 2001	United Kingdom	Conventional	-	21	2	15	4
32 Rodríguez Sousa et al. 2020	Spain	Conventional, Organic	AHP	14	1	10	3
33 Roesch et al. 2021	Switzerland	Conventional	SALCAsustain	28	6	20	2
34 Thiollet-Scholtus et al. 2021	France	Conventional	-	25	2	19	4

Table 2 (continued)

UIN Author (s)	European case study location	Farming system	Associated framework(s)	Total indicators	Economic indicators	Environmental indicators	Social indicators
35 Migliorini et al. 2018	Italy	Organic	-	25	1	23	1
36 *Schader et al. 2016	Germany, Switzerland and Austria	Conventional, Organic	SMART-Farm Tool, SAFA	327	-	-	-

75% published between 2016 and 2022. Each research question in Sect. 1 was addressed by analysing the sustainability assessment structures and their focus in the selected papers.

3.1 Case study production systems and locations

The present study isolated assessment frameworks developed and applied across Europe, allowing indicators to be examined within a consistent regional context. This approach allows the review to serve as a foundational resource for further indicator selection processes as relevant context-specific characteristics such as national standards, regional challenges and social norms are reflected (Gasso et al., 2015; De Olde et al., 2016). The sample literature covered a total of 21 European countries, with Italian farming systems providing a clear sustainability framework focus (13 articles). Following this, France and Spain were observed in seven publications, Germany, and Turkey in four, the Netherlands, Poland, and Switzerland in three, Greece and Hungary in two and the remaining countries in one. International farming comparisons were a common occurrence. In most cases comparisons were made across Europe, comprising between three to nine European countries (Table 2), typically with the goal of comparing case study performance. In three articles, additional case studies were present outside of Europe. For example, Al Shamsi et al. (2019) observed the sustainability of multiple organic enterprises from Sicily (Italy) and the United Arab Emirates, which they reported had common environmental and socio-economic struggles. Similarly, Schader et al., (2016) observed additional case study locations outside Europe including Kenya, Brazil, and India, with the aim of assessing the applicability of the SMART FARM Tool in a different socio-political and environmental conditions. Ultimately, they both reflected that robust comparisons and clear goal setting such as benchmarking, or farm-advice require consistent frameworks, even though their application must remain flexible.

Some of the multi-purpose frameworks such as SAFA, PG, IDEA, and RISE have been designed for use on a range of farm types. However, of the 36 studies identified, the majority (27 articles) concentrated on conventional farming systems either exclusively (19 articles) or in comparison to an alternative, typically organic, food production system (8 articles). The exact classification of these systems can be found in Table 2.

In all cases, these all-purpose tools have been designed with flexibility in mind, recognising that agricultural systems vary in scale, aims, financial security and management structure. Despite this, their application within the selected literature is limited. Variations in project scale, funding, objectives, and timelines often drive researchers to select bespoke variables and indicators tailored to their specific research needs. As a result, although a variety of multi-purpose tools are available, their practical adoption is low. For example, Zanzi et al. (2021) reported that their study was the first of its kind to apply the SAFA tool to (peri-)urban farming systems despite the framework being accessible for almost 10 years. Though overall positive, the study highlighted subjectivity, potential for misjudgement, and lack of homogeneity between assessments and grading across systems. These observations underscore the ongoing challenge in developing widely accepted and comparable assessment frameworks and highlight the potential value of identifying a core set of indicators in collaboration with the intended end-users to address the lack of consensus and standardisation observed across assessments.

This challenge is particularly evident in alternative farming systems. Exclusive consideration of such systems was observed in nine of the selected articles, consisting of organic agriculture (4), urban (and peri-urban) agriculture (UA, 3), community supported agriculture (CSA, 1) and controlled environment systems (CE, 1). In many of these case studies, authors used bespoke indicators or developed entirely new assessment frameworks which reflect the physical, social and motivational differences inherent to these systems. It seems debatable whether the current multi-purpose frameworks can be suitably adapted to capture this alternative ethos, particularly their social capital principles, or whether a bottom-up, co-design approach as discussed above is required. However, the prolific creation of bespoke frameworks further complicates the comparability, transparency and interpretation of data, especially when actors define and evaluate sustainability on their own terms, potentially emphasising their strengths at the expense of other, less favourable dimensions.

3.2 Sustainability assessment framework characteristics

To investigate any existing trends in assessment frameworks, the following section details key technical components found in the literature, namely the combined total of indicators, the individual pillar proportions, and any associated frameworks named.

3.2.1 Associated frameworks

Across the 36 articles, 23 used at least one named assessment framework or tool, with several articles choosing to pull methodological aspects from multiple pre-established frameworks. Few frameworks were used by multiple articles, however four articles used indicators within the SAFA framework (Al Shamsi et al. 2019; Iocola et al., 2020; Zanzi et al. 2021; Schader et al.,2016), two articles used the MASC framework (Alletto et al., 2022; Colomb et al., 2013) and the remainder of frameworks were used by a single study each (Table 2). Many of the frameworks used across this review (SAFA, RISE, MASC, SMART) have already been the feature of systematic reviews, typically in relation to comparing their application, user interface and feasibility (Alaoui et al., 2022). Overall, whilst these reviews highlighted many universal characteristics, they also identified major differences associated with data collection, the expertise of the data collector and the intended use for end-users (Alaoui et al., 2022). Amongst those who selected a pre-established framework, only half provided justified reasoning behind doing so. Of those that did, the stated reasoning related to various combinations of geographic scale, target audience, indicator relevance, framework availability, methodological robustness, and proof of effectiveness (Colomb et al. 2013; Zanzi et al. 2021; Feledyn-Szewczyk and Kopiński, 2015 ; Al Shamsi et al. 2019).

Though these pre-established frameworks were used in multiple studies, authors also created and presented several other named frameworks occasionally following their own tailored review (Antunes et al., 2017; Boggia et al., 2022). Some studies operated with no presented framework at all, opting for free form indicator selection based on the case study of interest (Leiva & Morris, 2001; Altobelli et al., 2018; Antunes et al., 2017; Troiano et al., 2019). For example, (Leiva & Morris, 2001) assessed the impact that mechanisation has on the sustainability of a farming system using 21 indicators across two British farming systems. Similarly, (Altobelli et al., 2018) used three indicators, one for each dimension, relating to the blue water footprint (WFb) to provide sustainability information on irrigated farming systems. Whilst these indicator selections can improve case study relevancy, they can hinder broader comparisons outside the study in question.

Since the January 2023 search date, an additional eight relevant research papers can be identified under the same search string (Bockstaller et al., 2024; Falasco et al., 2025; Ferretti et al., 2025; Gharaei et al., 2025; Guglielmo et al., 2025; John & Artmann, 2024; Pries et al., 2026; Soulé et al., 2023, 26th January 2026). Briefly, these studies adopt a range of assessment techniques including the above-mentioned MASC 2.0 framework (Bockstaller et al., 2024; Soulé et al., 2023), bespoke or unique frameworks such as the Foodmeter 2.0 (Falasco et al., 2025) or AESIS (Ferretti et al., 2025), and using individually selected indicators (Gharaei et al., 2025), consistent with the findings listed above. Case study systems similarly vary, including conventional systems (Falasco et al., 2025), the comparison of conventional and organic systems (Bockstaller et al., 2024) and the consideration of alternative agriculture such as urban agriculture and vertical farming (John & Artmann, 2024). Despite this growing body of work, a relevant systematic synthesis of the literature as presented here has not been identified, underscoring the need for the present study. Overall, the farming systems and their applied indicators overlap strongly with the existing scope of this review therefore all following analysis is conducted on the original literature set.

3.2.2 Total number of indicators

The review suggested that factors including the time frame of data collection, user-friendliness and scientific merit affected the total number of indicators (TI) included within an assessment framework. A framework with few indicators will typically be time-efficient and enticing to end-users who are time limited, but it may present a less complete picture in terms of sustainability and impact. Conversely, whilst an indicator-heavy framework can provide a comprehensive assessment, it risks being time inefficient and can confuse the real effects that farming practices have (Gasparatos & Scolobig, 2012; Marchand et al., 2014). In this research the total number of indicators within the papers reviewed ranged from 3 to 327, with 42% of the articles having between 10 and 29. The largest total number of indicators of 327 (Schader et al., 2016) and 116 (Al Shamsi et al., 2019) were outliers, with the next largest grouping having 61–70. Interestingly, while both Schader et al. and Al Shamsi et al. reported using the SAFA framework, it has also been adapted into a condensed list of 69 (Zanzi et al., 2021) and 30 indicators (Iocola et al. 2020). An advantage of the SAFA framework is the wide applicability gained from selecting indicators from a pre-established list. However, this diversity can also lead to a lack of cohesion and incompatibility between SAFA assessments. It can be argued that perhaps a fundamental core indicator set should be present in all applications of a framework before customisation. This would have the advantage of providing a base level of comparability between farming systems, allowing a more intuitive understanding of the ratings recorded and their relative success in comparison to similar systems rather than an isolated set of results.

One limitation in some articles was that the total number of indicators reported did not match the number explicitly named. Additionally, there was variation in the definition of an indicator. This review considered any aggregation of individual indicators as themes, categories, or subcategories. In some instances, however, base level indicators themselves were the aggregation of several different measures into one. Both issues made the determination of the total number of indicators challenging, and to aid transparency are identified in the supplementary codebook when encountered.

3.2.3 Proportions allocated to sustainability pillars

Although other papers have often focused on environmental assessments of agricultural sustainability, this review only selected frameworks that considered all three pillars. The range of the proportion of total indicators associated with environmental, social, and economic pillars were 13.5–92.0%, 4.0–51.4.0.4%, and 4.0–55.6.0.6% respectively (Fig. 2). The mean proportion of the total indicators associated with the environmental pillar was

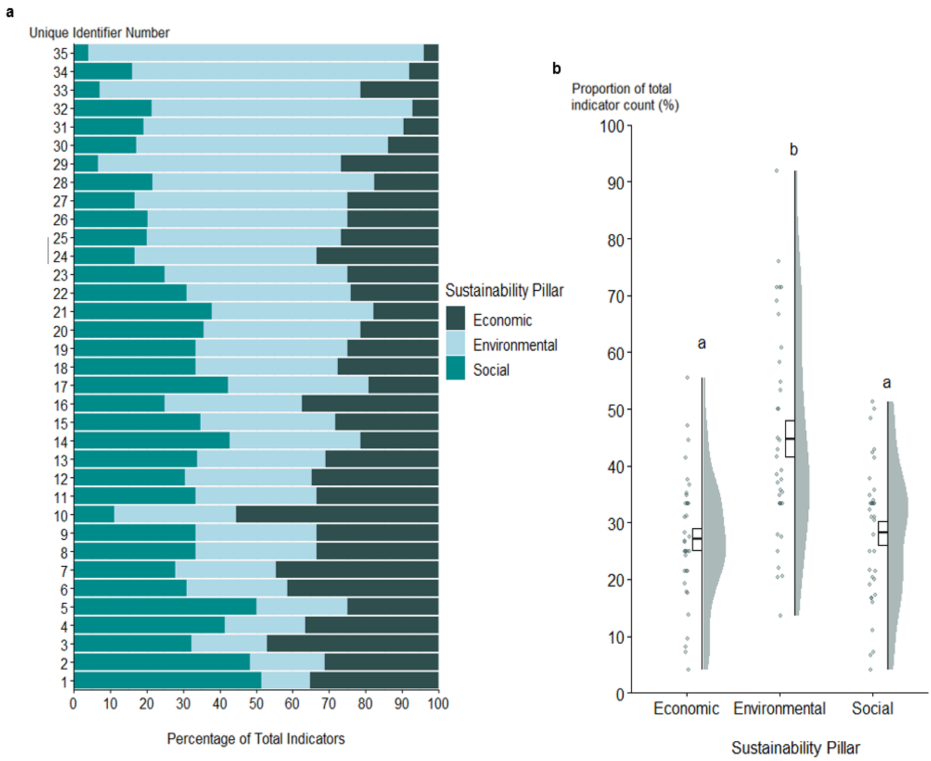

Fig. 2 (**a**) Visualisation of linked pillar proportion distribution across selected articles; allocation of the Unique Identifier Numbers (UIN) is consistent across all other data within this article i.e., Table 2. (**b**) Scatter graph of unlinked sustainability pillar proportions with violin plot, mean +- se and significance markers

greater ($p<0.001$) than the economic and social pillars, which were similar to each other ($p>0.05$). Whilst this study exclusively identified assessments that look at the wider picture, there is still an environmental focus within these methodologies.

As noted by (Janker & Mann, 2020), the social dimension is often underrepresented due to its predominately qualitative nature thereby making scalable indicators more challenging. Few social indicators provide explicitly objective, quantitative data and often result in various combinations of labour, workload and contamination indicators in frameworks that aspire to these attributes (Desiderio et al., 2022; Janker & Mann, 2020). Further, despite the economic dimension's suitability for quantitative measures and variety of indicators suggested across the literature, there is a distinct lack of discussion around its proportionally lower contribution to the identified frameworks.

Thematically, economic viability and sustainability is largely cohesive. Instead, its internal variation is a result of the variety of ratios and relational measures such as per unit of currency or labour. Comparatively, there is a larger amount of discourse concerning environmental sustainability, particularly when considering target species, best practices and end-goals. This relatively high focus on environmental themes results in a higher number of environmental variables and thus decreases the relative proportion of both social and economic indicators.

3.3 Characterisation of indicators by sustainability pillar

A process of thematic characterisation was undertaken to understand the breadth of focus of each publication given the multitude of ways any given indicator can be described, named, and categorised. Broadly summarised, similar indicators were collated in subcategories (e.g., *workload* or *risk exposure*), further grouped into larger categories (e.g., *working conditions*) and finally into broad themes (e.g., *labour*). Table 3 summarises the key themes found across the economic, environmental, and social dimensions and the following sections explore these themes within each dimension, as well as the similarities observed across them.

Table 3 Thematic distribution of sustainability indicators. The table presents the total number of indicators extracted for each theme within the environmental, economic, and social pillars of sustainability

Pillar	Theme	Total indicators
Environmental	Farmland Environment	132
Environmental	Water, Energy and Emissions	130
Environmental	Agrochemical Applications	95
Environmental	Soil Quality	80
Environmental	Farm Management	59
Economic	Business Security	86
Economic	Profitability	66
Economic	Management and Impact	58
Economic	Production	44
Economic	Operations	43
Social	Labour	144
Social	Community	84
Social	Management	65
Social	Farm Operations	52

3.3.1 Environmental sustainability

In the environmental pillar, 496 indicators were categorised into the following five themes: Farmland Environment (132 indicators, 27% of this pillar); Water, Energy and Emissions (130 indicators, 26%); Agrochemical Applications (95 indicators, 19%); Soil Quality (80 indicators, 16%); and Farm Management (59 indicators, 12%). Within these themes, 21 categories and 96 subsequent subcategories were collated (Fig. 3). Overall whilst a variety of subcategories were identified, large areas of consensus were observed including *crop diversity* within Farmland Environment (14 articles); *soil erosion* within Soil Quality (13 articles); *greenhouse gas (GHG) emissions*, *energy consumption*, and *irrigated quantity* each identified by 11 articles and collated within Water, Energy and Emissions.

Crop diversity, i.e., the number of different crop species in a given time period or area, was largely measured for the benefits that agrobiodiversity has on the local environment as opposed to the security that product diversification would offer. It related larger counts of crop species to positive scoring either directly or through use of a Simpson's index formula (Simpson 1949; Ceyhan, 2010; Iocola et al. 2021; Vitunskiene and Dabkiene 2016). In addition to absolute species counts, indicators also focused on *cropping practices* including intercropping, cover crops and rotational cropping (9 articles) and specific counts of *legumes* (5 articles). Understanding the role that crop diversity plays in local ecosystem.

functioning has been a focus of agricultural sustainability research (Hajjar et al., 2008; Smith et al., 2008; Gaudin et al., 2015; Hendrickson & Colazo, 2019; Stefan et al., 2021; Matsushita et al., 2016).

For example, increased cereal yields were associated with an increased number of crop species in annual rotations and with cover crops compared to monocropping systems with

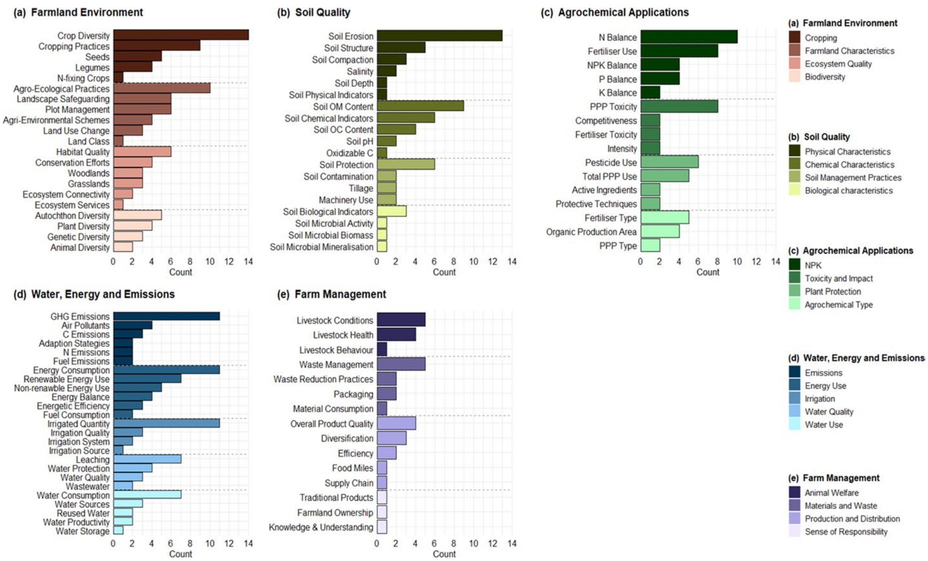

Fig. 3 Unique article counts of environmental sustainability themes, categories and subcategories ($n = 35$). Data is presented as a tiered systems across 5 sub-sections (**a-e**) that separate each environmental theme characterised and their subsequent (sub-)categories: Farmland Environment (**a**), Soil quality (**b**); Agrochemical Applications (**c**); Water, Energy and Emissions (**d**) and Farm Management (**e**)

chemical inputs (Smith et al., 2008). Positive changes in soil microbial composition were also reported in some locations (Stefan et al., 2021). McDaniel et al. (2014) and Zampieri et al. (2020) proposed that rotations or intercropping leads to more consistent, resilient, and less nutrient input-demanding yields due to its positive soil microbial impact. Many soil health and quality indicators were identified including *soil erosion* (with high values related to low soil health). *Soil erosion* indicators frequently used an annual average of bare soil (%) across the utilised agricultural area (UAA) as a measure of soil erosion risk. Such a measure is attractive due to its methodological simplicity and affordability, allowing a diverse range of assessors and providing data interpretable by a variety of end users. At a similar level of interest, *GHG emission* indicators are more methodologically intensive and complex. The description of the method for calculating GHG emissions was often limited, but it is assumed that it would commonly be determined using a commercial GHG calculator.

The consumption of energy and its source was included in many assessments. In this review indicators were divided into those that specifically identified *renewable*- and *non-renewable energy use* (7 and 4 articles, respectively) as well as overall *energy consumption* (11 articles) with no named source preference. Despite this focus, a lack of methodological cohesion was observed. For example, Corvo et al. (2021) presented the amount of non-renewable energy as a proportion of the total energy usage, such that the rating of the indicator presumably decreased with an increasing percentage. Gaviglio et al. (2017) opted for a categorical Yes/No measure of renewable energy sources and did not assess the proportion of total energy from different sources. Measures of overall *energy consumption* generally presented energy use per hectare or per crop. Of those that selected an energy related indicator, almost half used multiple indicators. For example, Al Shamsi et al. (2019); Iocola et al. (2021) and Leiva and Morris (2001) selected four indicators spanning areas of energy use. It is possible that these indicators would be better modified or condensed into a composite indicator for a more streamlined data collection and presentation process especially in cases where the total number of indicators is small to prevent one area from having a disproportionate impact on overall ratings (Talukder et al., 2017; Magrini, 2022; Gómez-Limón & Sanchez-Fernandez, 2010), however composite indicators can also reduce the transparency of the method.

Overall, the indicators identified within the environmental pillar demonstrated large areas of consensus, using many well tested performance-based measures. Performance-based indicators provide the user with immediate situational awareness of the farming (De Olde et al., 2017; Moller & MacLeod, 2013). This deviates from the application of practice-based indicators that measure the level of planned-intervention or mitigation strategies which theoretically maintain the sustainability and resilience of a system by ensuring planned actions in cases of urgency or emergency. There has been discussion on whether to prioritise one over another (De Olde et al., 2017; Moller & MacLeod, 2013), however a combination often demonstrates an ability to provide long-term sustainability and resilience.

3.3.2 Economic sustainability

In the economic pillar, 297 indicators were categorised into the following five themes: Business Security (86 indicators, 29% of this pillar); Profitability (66 indicators, 22%); Management and Impact (58 indicators, 20%); Production (44 indicators, 15%), and Operations (43 indicators, 14%). Within these, 21 categories and 94 subsequent subcategories were collated

(Fig. 4). In total, the 297 indicators within the economic pillar are 200 and 50 less than those reported for the environmental and social pillars respectively. Despite this, 94 subcategories of economic indicator were identified suggesting substantial variation between frameworks. Areas of consensus were observed as *gross margin ratios* (8 articles) and *economic efficiency* (8 articles) within Profitability; *agricultural multifunctionality* (7 articles) and *subsidies* (7 articles) within Business Security.

Gross margin indicators were subdivided into *absolute measures* calculating financial output minus variable costs (3 articles); and *ratios* relating gross margin per hectare or per product (8 articles). Functionally, standardised ratio-based indicators allow comparisons either between other systems or geographically averaged “standards” (Firth, 2002). By relating to a standardised unit such as area, product or currency, a degree of scalability is enabled. Ultimately, gross margin measures are limited by their exclusion of fixed costs, such that only short-term conclusions relating to sustainability can be articulated and the information they gather must be considered in context (Gómez-Limón & Riesgo, 2009; Nadaraja et al., 2021). Gross margin comparisons may be misleading across farms with different fixed cost structures, especially in cases where variable costs have been substituted for fixed costs. This is the case in some organic systems whereby the variable costs of pesticides are substituted by increased assignable fixed costs in terms of mechanical weeding and increased labour costs (Firth, 2002). Further, a focus on profit aligns with national targets such as economic growth and development (Welford, 2013; Barkemeyer et al., 2014).

In most cases, profitability indicators were rated positively, Huttmanová et al., 2019 argue with increasing profit with no reference toward a maximum score value. However, theoretically at a certain point the impact that growing profit has on business security plateaus and begins instead to inform growth and development (Huttmanová et al., 2019). Across the various studies, a variety of economic productivity ratios were presented relating

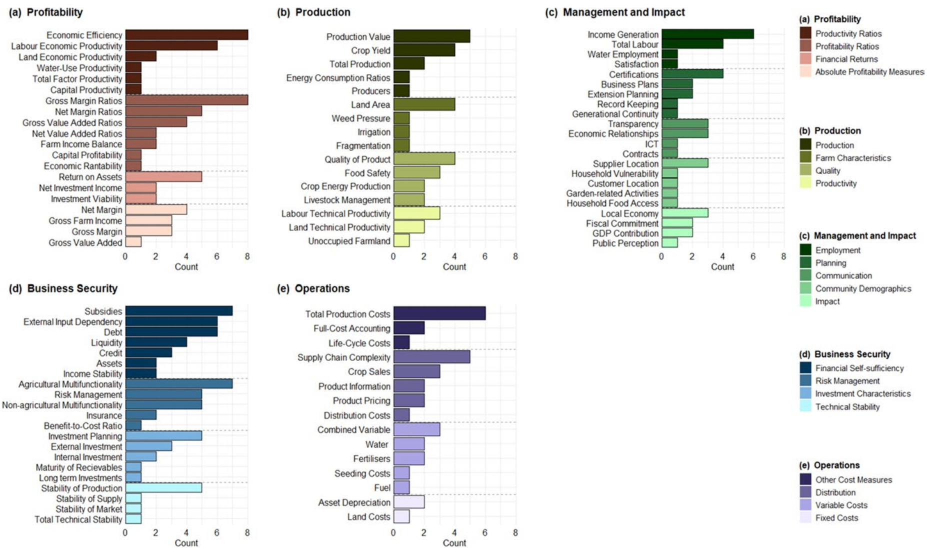

Fig. 4 Unique article counts of economic sustainability themes, categories and subcategories ($n=35$). Data is presented as a tiered systems across 5 sub-sections (**a-e**) that separate each environmental theme characterised and their subsequent (sub-)categories: Profitability (**a**), Production (**b**); Management and Impact (**c**); Business Security (**d**) Operations (**e**)

gross income or gross product to land, labour, farm capital and costs. Of these, *economic efficiency* indicators were the most frequent (8 articles) examining the ratio of gross product or gross income to operating costs. Such measures allow a system to evaluate cost-effectiveness and technical efficiency (Alletto et al., 2022).

Multifunctionality indicators were divided into measures of *agricultural multifunctionality* (*AM*, 7 articles) relating to diversification at the production level (e.g., farm product variety and on-farm processing); and *non-agricultural multifunctionality* (*non-AM*, 5 articles) identifying other gainful activities such as education or recreational services. In either case, indicator ratings typically performed better with increasing multifunctionality as a diversified income stream can provide security and economic resilience due to the portfolio effect (Tadesse & Blank, 2003; Ogundari, 2013; Abson et al., 2013). Whilst product diversification offers a level of stability greater than monoculture to factors such as nutrient deficit and disease, farmers can incur additional opportunity costs, more complex management systems and efficiency reductions for sowing multiple, less profitable crops. Hence there is typically a balance between diversification and cost management (Navarrete et al., 2015; Villa et al., 2019).

The reliance of external sources of income such as loans (*debt*, 6 articles), grants and investments (*external input dependency*, 6 articles) and government subsidies (s*ubsidies*, 7 articles) were collated into the category Financial Self-sufficiency. Indicators within these subcategories measured the proportion of each income source to the farm's total revenue, and as such their reliance. Increasing reliance on these streams negatively affected indicator ratings, with the assumption that large levels of reliance provide an unstable foundation and in the case of fund withdrawal would have major impacts on operation and stability. Though several assessments incorporated multiple indicators to inform each source (Gaviglio et al. 2017; Hlouskova et al. 2020; Stylianou et al., 2020; Sulewski et al., 2018 ; Bachev et al., 2019), no single indicator was presented to assess multiple streams and their interaction. Like multifunctionality, it can be argued that a variety of different external income streams would provide more stability than the sole reliance on one, and this benefit may not be captured by simple proportion-based measures.

3.3.3 Social sustainability

In the social pillar, 345 indicators were categorised into the following four themes: Labour (144 indicators, 42% of this pillar); Community (84 indicators, 24%); Management (65 indicators, 19%); Farm Operations (52 indicators, 15%). Within these, 14 categories and 63 subsequent subcategories were collated (Fig. 5). Overall, social sustainability indicators demonstrated the greatest uniformity, aggregating into 30 less subcategories than either of the other pillars despite having 50 more indicators than the economic pillar. Over 40% of social indicators measured personal or professional traits within the workforce and constituted the largest theme (Labour) across any pillar in both absolute and relative terms. Further, the five most common indicator subcategories fell within Labour, including *workload* (12 articles); *training and expertise* (*TE*); *job opportunities*; *income*; and *education* (9 articles each) all referring to both the farmer and their employees.

Illustrating the reflections of previous reviews (Desiderio et al., 2022; Chopin et al., 2021; Janker & Mann, 2018), these common subcategories can be classified as quantitative objective performance-based indicators. *Workload*, *income* and *TE* measure the different

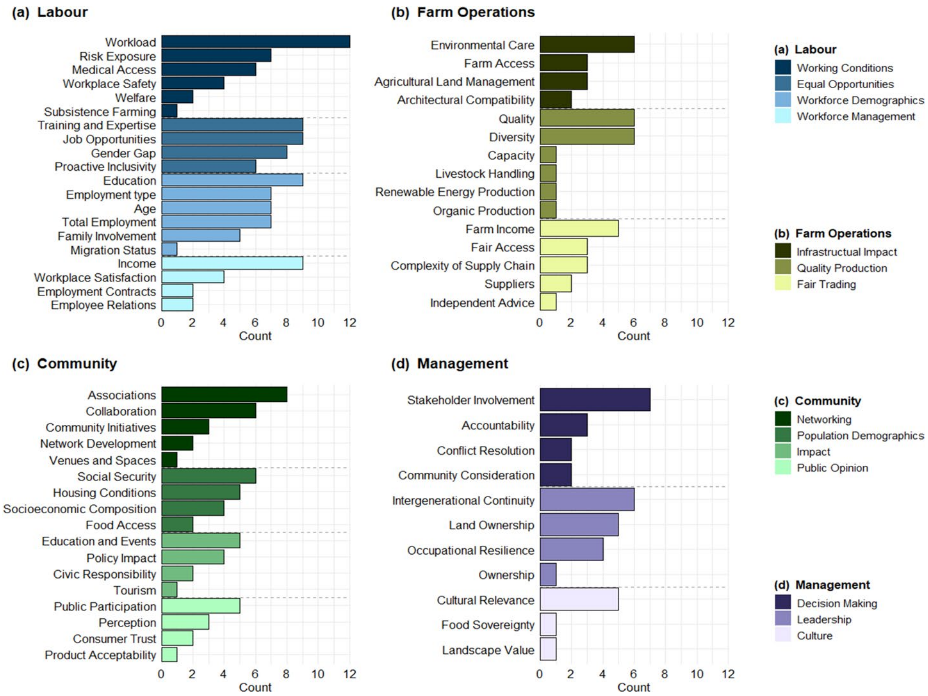

Fig. 5 Unique article counts of social sustainability themes, categories and subcategories ($n=35$). Data is presented as a tiered systems across 5 sub-sections (**a-e**) that separate each environmental theme characterised and their subsequent (sub-)categories: Labour (**a**), Farm Operations (**b**); Community (**c**); Management (**d**)

aspects of working conditions, ensuring pay, working hours and safety training fall within legal limits; *job opportunities* reflect the systems contribution to local employment and *education* categorically recording the highest academic level of qualification obtained by members of a farming system. The sensitivity of these measures differs broadly. As *workload* and *income* contain many comparative indicators that reflect not only the systems operation but its performance in relation to legal, regional or national statistics, the values depend on the period of measurement. By contrast, *education* measures that provide a count of academic achievement could be relative stable across years without a large employee turnover and would be more suited to comparisons between systems rather than the same system through time.

Subjective indicators were far broader and had little methodological cohesion such as measures of *public perception* (3 articles) and *consumer trust* (2 articles). The values for these measures were typically derived by asking relevant individuals to rate the system based on their sense of community and community relations. This method of assessment relies heavily on the interpretability of the question and the participants ability to internally reflect. As discussed by AlWaer et al. (2008), subjective measures remove a degree of precision by relying on external personal factors. However, for research assessing the impact on local communities, personal reflection measures enable a more comprehensive scoping than a reliance on just implied and extrapolated effects (Veenhoven, 2002). Many of the selected assessments used indicators which required the assessment of board agendas, contracts, minutes and interviews to evaluate indicators related to decision-making, culture, fairness and equal opportunities. This is both time-consuming and subjective. This methodology involves not only the subjective answers of interviewees but the subjective interpretation of the assessor themselves. Ensuring robust, standardised protocols and rigorous sense checking is an important factor in the use of such measures (Jones & Tanner, 2017).

Stakeholder involvement (7 articles) i.e., the identification and engagement of stakeholder groups in decision making processes and providing equal opportunities was a measure in which the methodology greatly varied both in form and clarity. (Peano et al., 2015) reported using a questionnaire format to quantitatively measure three indicators relating to decision-making, producer involvement and knowledge sharing with the aim of monitoring the strength of internal relationships. Tapia et al. (2021) reported using a categorical question to assess the types of stakeholders driving the initiative in which several weighted responses could be chosen according to their status as public or private. (Corvo et al., 2021) reported using seven separate measures including but not limited to: customer, distributor, supplier involvement in decision making processes; relationship with local actors not directly involved, and services created in collaboration with farmers. The supposed 'ideal' level of stakeholder engagement in decision-making is altered by the goals of the enterprise. Farming systems routed in community development and involvement would benefit from high and diverse stakeholder engagement levels, as opposed to conventional intensive or independent systems that usually need to account for a small number of key stakeholders such as employees, investors and customers. Given this, during framework application a process of indicator adaptation would be a useful tool of reflection, a stage that could theoretically be extrapolated across the whole framework's development.

3.3.4 Cross-pillar similarities

Understanding the impact and relevance each indicator has across the three pillars of sustainability can help create a thorough picture of the sustainability of agricultural systems. There are some indicators that have obvious effects across pillars. For instance, crop diversity can help maintain soil quality and biodiversity and improve business security by reducing catastrophic risk from the failure of a single crop. Thus, this review sought to identify areas of wider relevance and similarity through a stage of broader thematic analysis. Areas of sustainability found to fall under the jurisdiction of all three pillars included Production, Distribution and Supply Chain, Inputs, Product Quality, Livestock and Ecosystem Quality. Even so, most of these areas were primarily related to a specific pillar. For example, indicators relating to Ecosystem Quality and Inputs predominantly fell under the environmental pillar (91%) with the remaining encompassing the social (3%) and economic (6%) pillars. Similarly, whilst Business Security was the only area exclusive to economic sustainability, Income and Profitability was 90% composed of economic indicators with the remaining 10% covered by social indicators.

Interestingly, the social pillar did not have "sole rights" on any one area of sustainability, instead it was found to operate with one or both other dimensions, covering the majority of the Inclusive Labour, Ethical Governance and Population Demographic indicators. To the author's knowledge, there is no existing boundary for determining what is considered an "overlap", however, areas in which all three pillars occupied a minimum of 15% of indicators included Farmland Characteristics covering topics concerning land class, costs, usage change, infrastructure; and Product Quality indicators addressing nutrition, product safety and energy yields. Although this study focused on arable and not livestock systems, the maintenance of healthy and productive livestock was relevant to all three pillars of sustainability through areas including productivity, animal welfare rights, biodiversity, and environmental care (Rivera-Huerta et al., 2019; Cerrato et al., 2023; Tsakiridis et al., 2020).

Overall, the review demonstrates a high level of narrative overlap and interaction across the different measures of sustainability. This knowledge is helpful in framework development and application as it can allow the development of a more transparent and informed approach to the assessment of the sustainability of agricultural systems. Equally, if this overlap is not recognised and accounted for, negative implications resulting from duplicated measures may skew the broader, overall evaluations.

4 Conclusions

Overall, the analysis demonstrates that many of the existing frameworks used in research to assess the sustainability of European arable systems have a similar approach, but there are large differences in the total number of indicators used. Although this diversity is due to differing priorities regarding time frame of data collection, user-friendliness, and proven capability, it can make it difficult to compare the resulting assessments. Thus, we recommend that across similar systems, a fundamental core indicator set could be present in all applications of a framework before the customisation process. This would have the advantage of providing a base level of comparability between farming systems, allowing a more intuitive understanding of the ratings recorded and their relative success in comparison to similar systems rather than an isolated set of results. Common indicators across the economic, environmental, and social pillars included the treatment and accessibility of labour, the efficiency of- and the environmental care taken during- production and impacts on soil quality. This commonality suggests that improvement of these indicators is likely to have positive impacts to most aspects of sustainability. The type of farming systems assessed were predominately conventional systems either exclusively or in comparison to an alternative, typically organic, system. Five case studies could be classified exclusively as ‘alternative’, including (peri-)urban, community or controlled environment systems and their analysis employed a non-overlapping range of assessment frameworks and indicator sets. Across the studies reviewed, sustainability assessment frameworks show that a balance is needed between broader applicability and site-specific detail. One approach is to ensure that a minimum set of common indicators is used across assessments prior to additional modifications and adaptation. However, defining which systems this set would be appropriate for presents its own challenges. Alternative farming systems would also require additional community and socially driven indicators unidentified in the present work. Consequently, a further point of reflection on whether the current frameworks are adaptable enough to reflect this alternative ethos is warranted.

Acknowledgements The authors are grateful to FoodSEqual, the University of Reading, Cranfield University as well as the CoFarm Cambridge community for providing a platform for collaboration on this project.

Author contributions Imogen Hockenhull: conceptualization; data collection, formal analysis; writing—original draft; visualisation. Alice Mauchline: conceptualization; writing—review and editing; funding

acquisition. Julian Park: conceptualization; writing—review and editing; funding acquisition. Gavin Shelton: conceptualization; funding acquisition. Paul J. Burgess: conceptualization; writing—review and editing; funding acquisition. Sofia Kourmpetli: conceptualization; writing—review and editing; funding acquisition.

Funding This research was funded by a University of Reading studentship in collaboration with Cranfield University and the Transforming UK Food Systems project: FoodSEqual.

Data availability The datasets generated during the current study have been made open access (https://doi.org/10.17864/1947.001491).

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Conflict of interest The authors declare no competing interests.

References

Abson, D. J., Fraser, E. D. G., & Benton, T. G. (2013). Landscape diversity and the resilience of agricultural returns: a portfolio analysis of land-use patterns and economic returns from lowland agriculture. *Agriculture & Food Security*, *2*(1). https://doi.org/10.1186/2048-7010-2-2

Al Shamsi, K. B., Guarnaccia, P., Cosentino, S. L., Leonardi, C., Caruso, P., Stella, G., & Timpanaro, G. (2019). Analysis of relationships and sustainability performance in organic agriculture in the United Arab Emirates and Sicily (Italy). *Resources (Basel), 8*(1), 25. https://doi.org/10.3390/resources8010039

Alaoui, A., Barao, L., Ferreira, C. S. S., & Hessel, R. (2022). An overview of sustainability assessment frameworks in agriculture. *Land, 11*(4), 26. https://doi.org/10.3390/land11040537

Alletto, L., Vandewalle, A., & Debaeke, P. (2022). Crop diversification improves cropping system sustainability: an 8-year on-farm experiment in South-Western France. *Agricultural Systems*, 200. https://doi.org/10.1016/j.agsy.2022.103433

Altobelli, F., Cimino, O., Natali, F., Orlandini, S., Gitz, V., Meybeck, A., & Dalla Marta, A. (2018). Irrigated farming systems: Using the water footprint as an indicator of environmental, social and economic sustainability. *The Journal of Agricultural Science, 156*(5), 711–722.

AlWaer, H., Sibley, M., & Lewis, J. (2008). Different stakeholder perceptions of sustainability assessment. *Architectural Science Review, 51*(1), 48–59. https://doi.org/10.3763/asre.2008.5107

Antunes, P., Santos, R., Cosme, I., Osann, A., Calera, A., De Ketelaere, D., Spiteri, A., Mejuto, M. F., Andreu, J., Momblanch, A., Nino, P., Vanino, S., Florian, V., Chitea, M., Çetinkaya, C. P., Sakamoto, M. S., Kampel, M., Sanchez, P., Abdin, L. A., Alanasiddaiah, A. E. D., R. and, & Nagarajan, S. (2017). A holistic framework to assess the sustainability of irrigated agricultural systems. *Cogent Food and Agriculture*, *3*(1). https://doi.org/10.1080/23311932.2017.1323542

Asselt, E. D., Bussel, L. G. J., Voet, H., Heijden, G. W. A. M. v. d., Tromp, S. O., Rijgersberg, H., Evert, F., Wagenberg, C. P. A. v. and, & Fels-Klerx, H. J. v. d (2014). A protocol for evaluating the sustainability of agri-food production systems - a case study on potato production in peri-urban agriculture in The Netherlands. *Ecological Indicators*, *43*, 315–321. https://doi.org/10.1016/j.ecolind.2014.02.027

Auguie, B. (2017). 'Package 'gridExtra': Miscellaneous functions for grid graphics', 9. Available at: https://CRAN.R-project.org/package=gridExtra

Bachev, H., Bodjidar, I., & Toteva, D. (2019). 'Assessment of sustainability of agro-ecosystems in Bulgaria', *Bulgarian Journal of Agricultural Science*, 25(4), pp. 607–624. Available at: https://journal.agrojournal.org/page/en/details.php?article_id=2149

Barkemeyer, R., Holt, D., Preuss, L., & Tsang, S. (2014). What happened to the 'development' in sustainable development? Business guidelines two decades after Brundtland. *Sustainable Development, 22*(1), 15–32. https://doi.org/10.1002/sd.521

Barnosky, A. D., Ehrlich, P. R., & Hadly, E. A. (2016). Avoiding collapse: Grand challenges for science and society to solve by 2050. *Elementa: Science of the Anthropocene*, *4,* 000094. https://doi.org/10.12952/journal.elementa.000094

Binder, C. R., & Feola, G. (2013). Normative, systemic and procedural aspects: A review of indicator-based sustainability assessments in agriculture. *Methods and Procedures for Building Sustainable Farming Systems: Application in the European Context*, pp. 33–46.

Bockstaller, C., Guichard, L., Keichinger, O., Girardin, P., Galan, M.-B., & Gaillard, G. (2009). Comparison of methods to assess the sustainability of agricultural systems. A review. *Agronomy for Sustainable Development, 29*, 223–235.

Bockstaller, C., Blatz, A., Rapp, O., Koller, R., Slezack, S., & Schaub, A. (2024). Sustainable alternative to irrigated maize monoculture in a maize-dominated cropped area: Lessons learned from a system experiment. *Heliyon*, *10*(10). https://doi.org/10.1016/j.heliyon.2024.e30400

Boggia, A., Fagioli, F. F., Paolotti, L., Ruiz, F., Cabello, J. M., & Rocchi, L. (2022). Using accounting dataset for agricultural sustainability assessment through a multi-criteria approach: An Italian case study. *International Transactions in Operational Research*. https://doi.org/10.1111/itor.13141

Brundtland, G. H. (1987). Our common future—Call for action. *Environmental Conservation, 14*(4), 291–294.

Burgess PJ, Redhead J, Girkin N, Deeks L, Harris JA, Staley J. (2023) Evaluating agroecological farming practices. Report from the "Evaluating the productivity, environmental sustainability and wider impacts of agroecological compared to conventional farming systems" project SCF0321 for DEFRA. 20 February 2023. Cranfield University and UK Centre for Ecology and Hydrology

Campbell, B. M., D. J. Beare, E. M. Bennett, J. M. Hall-Spencer, J. S. I. Ingram, F. Jaramillo, R. Ortiz, N. Ramankutty, J. A. Sayer, and D. Shindell. (2017). Agriculture production as a major driver of the Earth system exceeding planetary boundaries. Ecology and Society 22(4):8 https://doi.org/10.5751/ES-09595-220408

Cerrato, M., Iasi, A., Di Bennardo, F., & Pergola, M. (2023). Evaluation of the economic and environmental sustainability of livestock farms in inland areas. *Agriculture*. https://doi.org/10.3390/agriculture13091708

Ceyhan, V. (2010). Assessing the agricultural sustainability of conventional farming systems in Samsun province of Turkey. *African Journal of Agricultural Research*, *5*(13), 1572–1583.

Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D., & Chhetri, N. (2014). A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change, 4*(4), 287–291.

Chopin, P., Blazy, J. M., Guindé, L., Tournebize, R., & Doré, T. (2017). A novel approach for assessing the contribution of agricultural systems to the sustainable development of regions with multi-scale indicators: Application to Guadeloupe. *Land Use Policy, 62*, 132–142. https://doi.org/10.1016/j.landusepol.2016.12.021

Chopin, P., Mubaya, C. P., Descheemaeker, K., Öborn, I., & Bergkvist, G. (2021). Avenues for improving farming sustainability assessment with upgraded tools, sustainability framing and indicators. A review. *Agronomy for Sustainable Development*. https://doi.org/10.1007/s13593-021-00674-3

Colomb, B., Carof, M., Aveline, A., & Bergez, J. E. (2013). Stockless organic farming: Strengths and weaknesses evidenced by a multicriteria sustainability assessment model. *Agronomy for Sustainable Development, 33*(3), 593–608. https://doi.org/10.1007/s13593-012-0126-5

Corvo, L., Pastore, L., Antonelli, A., & Petruzzella, D. (2021). Social impact and sustainability in short food supply chains: An experimental assessment tool. *New Medit, 20*(3), 175–189. https://doi.org/10.30682/nm2103l

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., & Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food, 2*(3), 198–209.

De Olde, E. M., Oudshoorn, F. W., Bokkers, E. A. M., Stubsgaard, A., Sørensen, C. A. G., & De Boer, I. J. M. (2016). Assessing the sustainability performance of organic farms in Denmark. *Sustainability, 8*(9), Article 957. https://doi.org/10.3390/su8090957

De Olde E. M., Moller, H., Marchand, F., McDowell, R. W., MacLeod, C. J., Sautier, M., Halloy, S., Barber, A., Benge, J., & Bockstaller, C. (2017). When experts disagree: The need to rethink indicator selection for assessing sustainability of agriculture. *Environment, Development and Sustainability,* 19(4), 1327–1342.

Desiderio, E., Garcia-Herrero, L., Hall, D., Segre, A., & Vittuari, M. (2022). Social sustainability tools and indicators for the food supply chain: A systematic literature review. *Sustainable Production and Consumption*, *30*, 527–540. https://doi.org/10.1016/j.spc.2021.12.015

Evenson, R. E., & Gollin, D. (2003). Assessing the impact of the Green Revolution, 1960 to 2000. *Science, 300*(5620), 758–762. https://doi.org/10.1126/science.1078710

Falasco, S., Saladini, A., Caputo, P., Mura, B., & Ferla, G. (2025). Operationalizing sustainability measurement in the agrifood sector: Insights from the foodmeter tool. *Cleaner Environmental Systems*. https://doi.org/10.1016/j.cesys.2025.100370

FAO (2014). *SAFA (Sustainability Assessment of Food and Agriculture systems) Tool. User manual (version 2.2.40)*: Food and Agriculture Organization of the United Nations (FAO) [Manual]. Available at: https://openknowledge.fao.org/handle/20.500.14283/i4113e (Accessed: Aug 05 2024).

Feledyn-Szewczyk, B., & Kopiński, J. (2015). The comparison of sustainability of agricultural production of organic and conventional farms using the RISE model. *Journal of Research and Applications in Agricultural Engineering, 60*(3), 28–32.

Ferretti, L., Di Blasi, S., Landers, L., Elli, F., O'Connor, R., & Pacini, G. (2025). Agroecology in wine production: Assessing the environmental, productive and social sustainability pillars of conventional, organic and biodynamic vineyard management through the AESIS framework. *Ecological Solutions and Evidence*. https://doi.org/10.1002/2688-8319.70101

Firth, C. (2002). The use of gross and net margins in the economic analysis of organic farms. *Proceedings of the UK Organic Research 2002 Conference*, Organic Centre Wales, Institute of Rural Studies, University of Wales Aberystwyth, 285–288.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., & Gibbs, H. K. (2005). Global consequences of land use. *Science, 309*(5734), 570–574.

Fresco, L., & Westphal, E. (1988). A hierarchical classification of farm systems. *Experimental Agriculture, 24*(4), 399–419.

Galdeano-Gómez, E., Aznar-Sánchez, J. A., Pérez-Mesa, J. C., & Piedra-Muñoz, L. (2017). Exploring synergies among agricultural sustainability dimensions: An empirical study on farming system in Almería (Southeast Spain). *Ecological Economics, 140*, 99–109. https://doi.org/10.1016/j.ecolecon.2017.05.001

Gasparatos, A., & Scolobig, A. (2012). Choosing the most appropriate sustainability assessment tool. *Ecological Economics*, *80*, 1–7.

Gasso, V., Oudshoorn, F. W., de Ol, E., & Sørensen, C. A. G. (2015). Generic sustainability assessment themes and the role of context: The case of Danish maize for German biogas. *Ecological Indicators, 49*, 143–153. https://doi.org/10.1016/j.ecolind.2014.10.008

Gaudin, A. C., Tolhurst, T. N., Ker, A. P., Janovicek, K., Tortora, C., Martin, R. C., & Deen, W. (2015). Increasing crop diversity mitigates weather variations and improves yield stability. *PLoS ONE, 10*(2), Article e0113261.

Gaviglio, A., Bertocchi, M., & Demartini, E. (2017). A tool for the sustainability assessment of farms: Selection, adaptation and use of indicators for an Italian case study. *Resources (Basel), 6*(4), 21. https://doi.org/10.3390/resources6040060

Gerrard, C. L., Smith, L., Padel, S., Pearce, B., Hitchings, R., & Cooper, N. (2011). 'OCIS public goods tool development'.

Gharaei, M., Gliesmi, B., & Roig, J. (2025). From metrics to insights: Evaluating cereal farming sustainability in Catalonia using composite index approach. *Agricultural Economics-Zemedelska Ekonomika*, *71*(11), 592–603. https://doi.org/10.17221/462/2024-agricecon

Gómez-Limón, J. A., & Riesgo, L. (2009). Alternative approaches to the construction of a composite indicator of agricultural sustainability: An application to irrigated agriculture in the Duero basin in Spain. *Journal of Environmental Management, 90*(11), 3345–3362.

Gómez-Limón, J. A., & Sanchez-Fernandez, G. (2010). Empirical evaluation of agricultural sustainability using composite indicators. *Ecological Economics, 69*(5), 1062–1075.

Guglielmo, S., Pietro, D., Andrea, C., Narote, A., Guidetti, R., Bocchi, S., & Vaglia, V. (2025). Sustainability assessment of rice farming: Insights from four Italian farms under climate stress. *Agriculture-Basel*. https://doi.org/10.3390/agriculture15171797

Hajjar, R., Jarvis, D. I., & Gemmill-Herren, B. (2008). The utility of crop genetic diversity in maintaining ecosystem services. *Agriculture, Ecosystems & Environment, 123*(4), 261–270.

Hansmann, R., Mieg, H. A., & Frischknecht, P. (2012). Principal sustainability components: Empirical analysis of synergies between the three pillars of sustainability. *International Journal of Sustainable Development & World Ecology, 19*(5), 451–459. https://doi.org/10.1080/13504509.2012.696220

Hendrickson, J., & Colazo, J. C. (2019). 'Using crop diversity and conservation cropping to develop more sustainable arable cropping systems', *Agroecosystem Diversity*: Elsevier, pp. 93–108.

Herrera, B., Gerster-Bentaya, M., Tzouramani, I., & Knierim, A. (2019). Advisory services and farm-level sustainability profiles: An exploration in nine European countries. *Journal of Agricultural Education and Extension, 25*(2), 117–137. https://doi.org/10.1080/1389224X.2019.1583817

Hlouskova, Z., Lekesova, M., Hlavacova, M., & Pankova, L. (2020). Multicriteria assessment of Czech farms. *Agricultural Economics - Zemědělska Ekonomika, 66*(3), 101–111. https://doi.org/10.17221/193/2019-agricecon

Hoang, V. (2021). Modern short food supply chain, good agricultural practices, and sustainability: A conceptual framework and case study in Vietnam. *Agronomy*, *11*(12), 2408.

Huttmanová, E., Valentiny, T., Novotný, R., & Nováková, M. (2019). Evaluation of the green growth and sustainable development in the European union countries. *International Multidisciplinary Scientific GeoConference: SGEM*, *19*(5.3), 327–334.

Ikerd, J. E. (1993). The need for a system approach to sustainable agriculture. *Agriculture, Ecosystems & Environment, 46*(1–4), 147–160.

Iocola, I., Angevin, F., Bockstaller, C., Catarino, R., Curran, M., Messéan, A., Schader, C., Stilmant, D., Stappen, F., Vanhove, P., Ahnemann, H., Berthomier, J., Colombo, L., Guccione, G. D., Mérot, E., Palumbo, M., Virzì, N., & Canali, S. (2020b). An actor-oriented multi-criteria assessment framework to support a transition towards sustainable agricultural systems based on crop diversification. *Sustainability*. https://doi.org/10.3390/su12135434

Iocola, I., Angevin, F., Bockstaller, C., Catarino, R., Curran, M., Messéan, A., Schader, C., Stilmant, D., Van Stappen, F., Vanhove, P., Ahnemann, H., Berthomier, J., Colombo, L., Dara Guccione, G., Mérot, E., Palumbo, M., Virzì, N. and Canali, S. (2020) 'An Actor-Oriented Multi-Criteria Assessment Framework to Support a Transition towards Sustainable Agricultural Systems Based on Crop Diversification', Sustainability, 12(13), pp. 5434. https://doi.org/10.3390/su12135434

Iocola, I., Colombo, L., Guccione, G. D., De Vita, P., Palumbo, M., Ritunnano, V., Sciacca, F., Virzi, N., & Canali, S. (2021). A multi-criteria qualitative tool for the sustainability assessment of organic durum wheat-based farming systems designed through a participative process. *Italian Journal of Agronomy, 16*(1), 15. https://doi.org/10.4081/ija.2021.1785

Janker, J., & Mann, S. (2018). 'The social dimension of sustainability in agriculture', *A review of sustainability assessment tools. Ettenhausen, Switzerland: Agroscope*.

Janker, J., & Mann, S. (2020). Understanding the social dimension of sustainability in agriculture: A critical review of sustainability assessment tools. *Environment, Development and Sustainability, 22*(3), 1671–1691.

John, H., & Artmann, M. (2024). Introducing an integrative evaluation framework for assessing the sustainability of different types of urban agriculture. *International Journal of Urban Sustainable Development*, *16*(1), 35–52. https://doi.org/10.1080/19463138.2024.2317795

Jones, L., & Tanner, T. (2017). 'Subjective resilience': Using perceptions to quantify household resilience to climate extremes and disasters. *Regional Environmental Change, 17*(1), 229–243. https://doi.org/10.1007/s10113-016-0995-2

Lampridi, M. G., Sørensen, C. G., & Bochtis, D. (2019). Agricultural sustainability: A review of concepts and methods. *Sustainability, 11*(18), Article 5120.

Lechenet, M., Bretagnolle, V., Bockstaller, C., Boissinot, F., Petit, M. S., Petit, S., & Munier-Jolain, N. M. (2014). Reconciling pesticide reduction with economic and environmental sustainability in arable farming. *PLoS ONE, 9*(6), Article e97922. https://doi.org/10.1371/journal.pone.0097922

Leiva, F. R., & Morris, J. (2001). Mechanization and sustainability in arable farming in England. *Journal of Agricultural Engineering Research, 79*(1), 81–90. https://doi.org/10.1006/jaer.2000.0686

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P., Clarke, M., Devereaux, P. J., Kleijnen, J., & Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration. BMJ (Clinical research ed.), 339: b2700 https://doi.org/10.1136/bmj.b2700

Luca, A. I., Falcone, G., Stillitano, T., Iofrida, N., Strano, A., & Gulisano, G. (2018). Evaluation of sustainable innovations in olive growing systems: A life cycle sustainability assessment case study in southern Italy. *Journal of Cleaner Production, 171*, 1187–1202. https://doi.org/10.1016/j.jclepro.2017.10.119

Magrini, A. (2022). Assessment of agricultural sustainability in European Union countries: A group-based multivariate trajectory approach. *AStA Advances in Statistical Analysis, 106*(4), 673–703. https://doi.org/10.1007/s10182-022-00437-9

Marchand, F., Debruyne, L., Triste, L., Gerrard, C., Padel, S., & Lauwers, L. (2014). 'Key characteristics for tool choice in indicator-based sustainability assessment at farm level'. *Ecology and Society*, *19*(3): 46 . http://dx.doi.org/10.5751/ES-06876-190346

Matsushita, K., Yamane, F., & Asano, K. (2016). Linkage between crop diversity and agro-ecosystem resilience: Nonmonotonic agricultural response under alternate regimes. *Ecological Economics*, *126*, 23–31.

Mccauley, D., Pinsky, M., Palumbi, S., Estes, J., Joyce, F., & Warner, R. (2015). Marine Defaunation: Animal Loss in the Global Ocean. Science, 347, Article ID: 1255641.

McDaniel, M. D., Grandy, A. S., Tiemann, L. K., & Weintraub, M. N. (2014). Crop rotation complexity regulates the decomposition of high and low quality residues. *Soil Biology & Biochemistry, 78*, 243–254.

Meul, M., Passel, S., Nevens, F., Dessein, J., Rogge, E., Mulier, A., & Hauwermeiren, A. (2008). MOTIFS: A monitoring tool for integrated farm sustainability. *Agronomy for Sustainable Development, 28*(2), 321–332. https://doi.org/10.1051/agro:2008001

Migliorini, P., Galioto, F., Chiorri, M., & Vazzana, C. (2018). An integrated sustainability score based on agro-ecological and socioeconomic indicators. A case study of stockless organic farming in Italy. *Agroecology and Sustainable Food Systems*, *42*(8), 859–884. https://doi.org/10.1080/21683565.2018.1432516

Moller, H., & MacLeod, C. J. (2013). *Design criteria for effective assessment of sustainability in New Zealand's production landscapes*.

Nadaraja, D., Lu, C., & Islam, M. M. (2021). The sustainability assessment of plantation agriculture - A systematic review of sustainability indicators. *Sustainable Production and Consumption, 26*, 892–910. https://doi.org/10.1016/j.spc.2020.12.042

Navarrete, M., Dupré, L., & Lamine, C. (2015). Crop management, labour organization, and marketing: Three key issues for improving sustainability in organic vegetable farming. *International Journal of Agricultural Sustainability, 13*(3), 257–274. https://doi.org/10.1080/14735903.2014.959341

Neuwirth, E. (2022). 'RColorBrewer: ColorBrewer Palettes', *ColorBrewer palettes*, 991. Available at: https://CRAN.R-project.org/package=RColorBrewer

Ogundari, K. (2013). Crop diversification and technical efficiency in food crop production. *International Journal of Social Economics*, *40*(3), 267–287. https://doi.org/10.1108/03068291311291536

Özden, B., & Acar, S. (2022). Sustainability assessment for Asparagus Farms that work with a Community-Supported Agriculture Model in Turkey. *Future of Food: Journal on Food, Agriculture and Society, 10*(3), 1–16. https://doi.org/10.17170/kobra-202204136010

Papargyropoulou, E., Lozano, R., Steinberger, J., Wright, N., & Ujang, Z. (2014). The food waste hierarchy as a framework for the management of food surplus and food waste. *Journal of Cleaner Production, 76*, 106–115. https://doi.org/10.1016/j.jclepro.2014.04.020

Peano, C., Migliorini, P., & Sottile, F. (2014). A methodology for the sustainability assessment of agri-food systems: An application to the Slow Food Presidia project. *Ecology and Society, 19*(4), Article art24. https://doi.org/10.5751/ES-06972-190424

Peano, C., Tecco, N., Dansero, E., Girgenti, V. and Sottile, F. (2015) 'Evaluating the Sustainability in Complex Agri-Food Systems: The SAEMETH Framework', Sustainability, 7(6), pp. 6721–6741. Available at: https://www.mdpi.com/2071-1050/7/6/6721

Pham, L. V., & Smith, C. (2014). Drivers of agricultural sustainability in developing countries: A review. *Environment Systems and Decisions, 34*(2), 326–341. https://doi.org/10.1007/s10669-014-9494-5

Pries, M., Zeug, W., & Thrän, D. (2026). Holistic and integrated life cycle sustainability assessment of community supported agriculture: A case study of school catering in Leipzig, Germany. *Cleaner and Responsible Consumption*. https://doi.org/10.1016/j.clrc.2025.100372

Rasmussen, L. V., Bierbaum, R., Oldekop, J. A., & Agrawal, A. (2017). Bridging the practitioner-researcher divide: Indicators to track environmental, economic, and sociocultural sustainability of agricultural commodity production. *Global Environmental Change, 42*, 33–46. https://doi.org/10.1016/j.gloenvcha.2016.12.001

Reig-Martínez, E., Gómez-Limón, J. A., & Picazo-Tadeo, A. J. (2011). Ranking farms with a composite indicator of sustainability. *Agricultural Economics, 42*(5), 561–575. https://doi.org/10.1111/j.1574-0862.2011.00536.x

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., … Rockström, J. (2023). Earth beyond six of nine planetary boundaries. *Science Advances, 9*(37), Article eadh2458. https://doi.org/10.1126/sciadv.adh2458

Riley, J. (2001). Indicator quality for assessment of impact of multidisciplinary systems. *Agriculture Ecosystems & Environment*, *87*(2), 121–128.

Rivera-Huerta, A., Rubio Lozano, M. D., Padilla-Rivera, A., & Güereca, L. P. (2019). Social sustainability assessment in livestock production: A social life cycle assessment approach. *Sustainability*. https://doi.org/10.3390/su11164419

Rodríguez Sousa, A. A., Parra-López, C., Sayadi-Gmada, S., Barandica, J. M., & Rescia, A. J. (2020). A multifunctional assessment of integrated and ecological farming in olive agroecosystems in southwestern Spain using the analytic hierarchy process. *Ecological Economics*. https://doi.org/10.1016/j.ecolecon.2020.106658

Roesch, A., Nyfeler-Brunner, A., & Gaillard, G. (2021). Sustainability assessment of farms using SALCA-sustain methodology. *Sustainable Production and Consumption*, *27*, 1392–1405. https://doi.org/10.1016/j.spc.2021.02.022

Schader, C., J. Grenz, M. S. Meier, and M. Stolze. (2014). Scope and precision of sustainability assessment approaches to food systems. Ecology and Society 19(3): 42 http://dx.doi.org/10.5751/ES-06866-190342

Schader, C., Baumgart, L., Landert, J., Muller, A., Ssebunya, B., Blockeel, J., Weisshaidinger, R., Petrasek, R., Mészáros, D., Padel, S., Gerrard, C., Smith, L., Lindenthal, T., Niggli, U. and Stolze, M. (2016) 'Using the Sustainability Monitoring and Assessment Routine (SMART) for the Systematic Analysis of Trade-Offs and Synergies between Sustainability Dimensions and Themes at Farm Level', Sustainability, 8(3), pp. 274. Available at: https://www.mdpi.com/2071-1050/8/3/274

Siebrecht, N. (2020). Sustainable agriculture and its implementation gap—Overcoming obstacles to implementation. *Sustainability*. https://doi.org/10.3390/su12093853

Simpson, E. H. (1949). Measurement of diversity. *Nature, 163*(4148), 688–688.

Smith, R. G., Gross, K. L., & Robertson, G. P. (2008). Effects of crop diversity on agroecosystem function: Crop yield response. *Ecosystems, 11*, 355–366.

Soulé, E., Charbonnier, R., Schlosser, L., Michonneau, P., Michel, N., & Bockstaller, C. (2023). A new method to assess sustainability of agricultural systems by integrating ecosystem services and environmental impacts. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2023.137784

Stefan, L., Hartmann, M., Engbersen, N., Six, J., & Schöb, C. (2021). Positive effects of crop diversity on productivity driven by changes in soil microbial composition. *Frontiers in Microbiology, 12*, Article 660749.

Stylianou, A., Sdrali, D. and Apostolopoulos, C. D. (2020) 'Integrated Sustainability Assessment of Divergent Mediterranean Farming Systems: Cyprus as a Case Study', Sustainability, 12(15), pp. 6105. Available at: https://doi.org/10.3390/su12156105

Sulewski, P., Kłoczko-Gajewska, A. and Sroka, W. (2018) 'Relations between Agri-Environmental, Economic and Social Dimensions of Farms' Sustainability', Sustainability, 10(12), pp. 4629. Available at: https://doi.org/10.3390/su10124629

Summit, J. (2002). World summit on sustainable development. *Johannesburg South Africa*, *9*(3), 67–69.

Swaney, D. P., Hong, B., Ti, C., Howarth, R. W., & Humborg, C. (2012). Net anthropogenic nitrogen inputs to watersheds and riverine N export to coastal waters: A brief overview. *Current Opinion in Environmental Sustainability, 4*(2), 203–211.

Tadesse, D., & Blank, S. C. (2003). Cultivar diversity: A neglected risk management strategy. *Journal of Agricultural and Resource Economics, 28*(2), 217–232.

Talukder, B., Hipel, K. W., & vanLoon, G. W. (2017). Developing composite indicators for agricultural sustainability assessment: Effect of normalization and aggregation techniques. *Resources*. https://doi.org/10.3390/resources6040066

Tapia, C., Randall, L., Wang, S., & Aguiar Borges, L. (2021). Monitoring the contribution of urban agriculture to urban sustainability: An indicator-based framework. *Sustainable Cities and Society, 74*, Article 103130. https://doi.org/10.1016/j.scs.2021.103130

Thiollet-Scholtus, M., Muller, A., Abidon, C., Grignion, J., Keichinger, O., Koller, R., Langenfeld, A., Ley, L., Nassr, N., Rabolin-Meinrad, C., & Wohlfahrt, J. (2021). Multidimensional assessment demonstrates sustainability of new low-input viticulture systems in north-eastern France. *European Journal of Agronomy*. https://doi.org/10.1016/j.eja.2020.126210

Tiedemann, F. (2022). 'gghalves: Compose half-half plots using your favourite geoms'. Available at: https://CRAN.R-project.org/package=gghalves

Troiano, S., Novelli, V., Geatti, P., Marangon, F., & Ceccon, L. (2019). Assessment of the sustainability of wild rocket (*Diplotaxis tenuifolia*) production: Application of a multi-criteria method to different farming systems in the province of Udine. *Ecological Indicators, 97*, 301–310. https://doi.org/10.1016/j.ecolind.2018.10.013

Tsakiridis, A., O'Donoghue, C., Hynes, S., & Kilcline, K. (2020). A comparison of environmental and economic sustainability across seafood and livestock product value chains. *Marine Policy, 117*, Article 103968. https://doi.org/10.1016/j.marpol.2020.103968

UNDESA (2022). *Key Messages, World Population Prospects. 2022.* Available at: https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/undesa_pd_2022_wpp_key-messages.pdf (Accessed: Aug 05 2024).

van den Brand, T. (2024). 'ggh4x: Hacks for 'ggplot2''. Available at: https://CRAN.R-project.org/package=ggh4x

Veenhoven, R. (2002). Why social policy needs subjective indicators. *Social Indicators Research, 58*(1), 33–46. https://doi.org/10.1023/A:1015723614574

Villa, G., Adenso-Díaz, B., & Lozano, S. (2019). An analysis of geographic and product diversification in crop planning strategy. *Agricultural Systems*, *174*, 117–124.

Vitunskiene, V., & Dabkiene, V. (2016). Framework for assessing the farm relative sustainability: A Lithuanian case study. *Agricultural Economics (Zemědělská Ekonomika), 62*(3), 134–148.

Von Frantzius, I. (2004). World Summit on Sustainable Development Johannesburg 2002: A critical analysis and assessment of the outcomes. *Environmental Politics, 13*(2), 467–473. https://doi.org/10.1080/09644010410001689214

Welford, R. (2013). *Hijacking environmentalism: Corporate responses to sustainable development.* Routledge.

Wickham, A. M., Bryan, J., Chang, W., McGowan, L. D., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Pedersen, K. M., Miller, T. L., Bache, E., Müller, S. M., Ooms, K., Robinson, J., Seidel, D. DP, and, Spinu, V., Vaughan, T. K., Wilke, D., Woo, C., & Yutani, K. H (2019). Welcome to the Tidyverse. *Journal of Open Source Software*, *4*(43), 1686. https://doi.org/10.21105/joss.01686

Yildirim, C., Turkten, H., & Boz, I. (2022). Assessing the sustainability index of part-time and full-time hazelnut farms in Giresun and Ordu Province, Turkey. *Environmental Science and Pollution Research*, *29*(52), 79225–79240. https://doi.org/10.1007/s11356-022-20966-9

Zampieri, M., Weissteiner, C. J., Grizzetti, B., Toreti, A., van den Berg, M., & Dentener, F. (2020). Estimating resilience of crop production systems: From theory to practice. *Science of the Total Environment, 735*, Article 139378.

Zanzi, A., Vaglia, V., Spigarolo, R., & Bocchi, S. (2021). Assessing agri-food start-ups sustainability in peri-urban agriculture context. *Land*. https://doi.org/10.3390/land10040384