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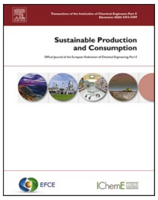

Assessment of the sustainability of the European agri-food sector in the context of the circular economy

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ABSTRACT

Quantifying the sustainability of the agriculture, livestock, and agri-food industry under a homogeneous criterion is essential to strategize the implementation of sustainable development in the agri-food sector and increase the commitment of stakeholders using aids to reduce the socio-economic impact of the expansion of sustainability. In order to homogenize the quantification methodology in the European context, a composite indicator was developed from a system of indices of the European agri-food system. Results unveiled a moderate level of sustainability in the food production and processing in the European Union. The French agri-food system (0.46) had the highest overall sustainability according to the composite indicator of this study, followed by Austria (0.44), Italy (0.43), Estonia (0.43), Germany (0.42), Belgium (0.40), Finland (0.40), Denmark (0.40), Spain (0.40), Latvia (0.39), Czech Republic (0.39), Sweden (0.38), Greece (0.38), Netherlands (0.38) and Slovakia (0.38), all of them above the EU-27 average (0.37). The more significant economic and social progress of agricultural activity was associated with a lower quality of environmental indicators. Overall agri-food system sustainability can be predicted from ten indicators. The results suggest the necessity of implementing a policy that prioritizes the development of Local Productive Systems based on the framework of the circular economy to favor territorial balance.

1. Introduction

The 2030 Agenda, signed by United Nations (UN) Member States, identifies 17 Sustainable Development Goals (SDGs) and 169 targets that address the most relevant social, environmental, and economic issues on a global scale. The sustainability of all activities included in the agri-food sector (i.e., agriculture, livestock and agri-food industry) is embedded in several SDGs. In this context, sustainable development has become a fundamental pillar for the progress of society (UN, 2015).

Negative externalities generated by anthropogenic activities have led to the emergence of an expansive environmental and social awareness among States, which aims to reduce the impacts caused by their economic progress and thus combat the effects of global warming (Cifuentes-Faura, 2022; Tremblay et al., 2020; UN, 2015). Climate change has pushed countries to modify their structural policies to neutralize their environmental footprint (Castillo-Díaz et al., 2022a, 2022b; Cifuentes-Faura, 2022; Davies et al., 2021). Nowadays, some movements call for systematic or generalized degrowth to combat the

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Abbreviations: CAP, Common Agricultural Policy; CPI, Consumer Price Index; EU, European Union; FAO, Food and Agriculture Organization of the United Nations; GDP, Gross Domestic Product; GHG, Greenhouse gas; gl, degrees of freedom; ICEX, ICEX Spain Export and Investment; LPS, Local Productive Systems; LSD test, the least significant difference test; MAPA, Ministry of Agriculture, Fisheries and Food of the Government of Spain; n.a., not available; OECD, The Organization for Economic Co-operation and Development; OIV, International Organization of Vine and Wine; PCU, livestock population correction; PSR, Pressure-State-Response; R^2, coefficient of determination; SDC, Sustainable Development Commission; SDGs, Sustainable Development Goals; UN, United Nations; WHO, World Health Organization.

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externalities caused by anthropogenic activities since the unlimited expansion of economic activity is a utopian goal given that the planet's resources are limited. This trend poses a major challenge to fulfil different the objectives of some organizations (Belmonte-Ureña et al., 2021; Keyber and Lenzen, 2021; Plaza-Úbeda et al., 2020).

The transformation experienced by agricultural and agri-food industries since the 1950s has generated diverse environmental impacts on ecosystems (Goyette et al., 2022; Tian et al., 2019; Vanthoor et al., 2012). The advent of the Green Revolution expanded the carrying capacity of the planet through the genetic improvement of plant species positioned at the base of the food pyramid. However, this caused an intensification of productive activity, which resulted in an increased demand for energy and agrochemicals (FAO, 2017, 2019). This scenario entailed the origin of externalities, both negative and positive, derived from food production, either in developed or developing countries. In the latter, implementing an industrial system to produce high-added-value food (e.g., palm oil production) has improved some essential services (e.g., transport infrastructure, hospitals, education) and increased employment and territorial wealth. However, it has increased the consumption of natural resources and the generation of conflicts among residents (Abram et al., 2017; Austin et al., 2017; Ayompe et al., 2021). Agri-food products are exported to other markets of high economic interest, such as the European one. This behavior can alter the sustainability and territorial balance of the origin systems (European Commission, 2022a; Maudos and Salamanca, 2022b; Moyo, 2011).

In both the European and international contexts, food production has generated various environmental impacts due to poor fertilization management, excessive consumption of phytosanitary and zoo-sanitary products (Gil et al., 2018; Martínez-Francés et al., 2009; Taylor et al., 2022), inadequate management of agricultural and industrial organic and inorganic waste (Castillo-Díaz et al., 2022a, 2022b; Duque-Acevedo et al., 2020; Le Moine and Ferry, 2019), excessive water consumption and high energy demand, among others (Aznar-Sánchez et al., 2021; López-Serrano et al., 2022; Vanthoor et al., 2012). Such negative impacts can damage ecosystems of high environmental value and their flora and fauna, besides increasing the net emission of greenhouse gases, which promotes climate change (Tian et al., 2019). It is expected that the temperature will rise 1.5 °C in the next century due to human activity. Therefore, it is necessary to implement production techniques that mitigate such trends (Keyber and Lenzen, 2021), but this requires quantitative information to facilitate decision-making. Therefore, it is of crucial importance to quantify the economic, social and environmental sustainability of the agrifood value chain in order to develop action strategies that may limit negative externalities, while favoring socio-economic development (Carvalho et al., 2022; Cirone et al., 2023; Streimikis and Baležentis, 2020). Previous research has focused on characterizing the sustainability of food production and processing based on theoretical reasoning. The results of those studies may be influenced due to the use of unofficial indices (Carvalho et al., 2022), or because they tried to characterize the sustainability of specific activities within the agri-food value chain or specific management activities under diverse methodologies (Maesano et al., 2021; MAPA, 2016; Suresh et al., 2022). Therefore, it is beneficial to characterize the sustainability of all agri-food activities through a composite indicator. This indicator should be constructed from a system of indices obtained from official databases. Further, its variables should have undergone a standardization procedure to offer comparable results between different agrosystems to develop strategies. The composite indicator helps to illustrate a complex and multidimensional reality, such as sustainability, and also provides an overall view for better decision-making (OECD and European Commission, 2008). Practical information on this subject is not abundant.

On an international scale, the European Union (EU) is one of the most proactive territories implementing initiatives to protect the environment from the impacts generated by anthropogenic activities (Cifuentes-Faura, 2022). Europe's concern for the natural environment emerged at the end of the 20th century, and the signing of Agenda 2030 has accelerated Europe's green transition. In 2015, the European Commission published the first Circular Economy Strategy (Comisión Europea, 2015; Davies et al., 2021; European Commission, 2018). This paper proposes transforming the current linear economic system, based on consuming natural resources, into a model based on reducing input consumption, reusing by-products, recycling waste, and repairing the damage caused (Duque-Acevedo et al., 2022; Kalmykova et al., 2018; Prados-peña et al., 2022). In this context, it is key to measure the degree of implementation of the circular economy and sustainability in the agri-food chain (Alonso-Muñoz et al., 2022; Carvalho et al., 2022; Cirone et al., 2023) to identify the commitment of EU Member States to implement these policies in the agri-food sector and to establish an objective criterion for establishing legislative and business measures.

In 2018, the EU proposed progressive, ambitious environmental milestones subdivided into decades through the European Green Pact. To meet these targets, the environmental footprint of its Member States must be neutral without altering the wealth and employment of the territories. This goal implies a major effort for their economic activities in the face of the total change of direction proposed (European Comission, 2019). The European territory has developed various strategies to be implemented among its various economic activities to achieve the aforementioned goal: reducing agrochemicals and antimicrobials in food production by 2030 preserving and improving the biodiversity of ecosystems since 50 % of the world's GDP depends on them (European Comission, 2020a, 2020b). The EU is tightening its legislation, including and expanding in its new regulatory reformulations the principles of the circular economy (Castillo-Díaz et al., 2022a, 2022b), as well as providing the stakeholders in the agri-food sector with the means to facilitate this transition. The Next Generation EU Funds are intended to modernize the productive structure of the EU Member States. Digital tools can reduce the demand for inputs through better use and treatment of the information gathered by sensors from artificial intelligence systems. The Common Agricultural Policy (CAP) has reinforced the importance of the sustainability and modernization of agricultural and livestock farms (MAPA and Cajamar, 2022).

In this context, the numerical quantification of sustainability is of clue to distinguish between sustainable and unsustainable activities (Suresh et al., 2022). This information can help to take corrective measures and decisions regarding financing by States and private companies. For example, the banking sector needs tools to qualify the sustainability of activity when deciding favorably or unfavorably on granting credit (Azahara and González, 2021). The sustainability of each agricultural model depends on its characteristics. Such sustainability depends on the interaction between society, the economy, environment, and technology used in the system, although there are indicators that allow comparison between different production models (Vanthoor et al., 2012).

Several studies have identified the need to measure the sustainability of the European agricultural system, livestock farming, and agri-food industry. However, there is little information available on the numerical calculation of the sustainability of European food production using a composite indicator that facilitates a comparison between countries and whose disaggregation allows the development of action plans and strategies that guarantee compliance with EU and non-EU environmental agreements while facilitating the decision-making of the business sector. This is due to the theoretical nature of most of the previous studies. In addition, the methodology and taxonomy used are diverse, so it is necessary to establish a common and practical criterion based on previous research. Therefore, to fill the existing experimental gap, the following objectives are proposed:

- Select a system of indicators obtained from official sources to enable the construction of a composite indicator suitable for making comparisons between the EU Member States and adapt it to the specific characteristics of the agri-food sector.

- To quantify the economic, social, and environmental sustainability of the agri-food sector in each EU Member State to generate a base of knowledge on its current status. This information will help in developing action plans and to establish criteria to determine which agri-food activities are sustainable.

With the objective of meeting these goals, this work begins by describing and justifying the selection of the indicators system and the methodology followed for the standardization of the source indicators and for the construction of the composite indexes (i.e., economic, social, environmental, and global). Then, results derived from this research have been displayed and finally, conclusions along with limitations, and possible future lines of research have been presented.

2. Materials and methods

2.1. Main characteristics of the European agri-food sector

This study evaluated the sustainability of all the activities that make up the agri-food system (i.e., agriculture, livestock, and agri-food industry) in each State Member of the EU. This system includes 10,282,700 farms and 293,576 agri-food industries (EUROSTAT, 2022b). Imports from the European agri-food sector amounted to 130.158 billion euros, while exports amounted to 198.068 billion euros. The EU-27 had a trade balance of 67.910 billion euros. The most commonly imported products are tropical fruits (fresh or dried), nuts, and spices. Wine, vermouth, cider, and vinegar are the most exported products (European Commission, 2022a; Maudos and Salamanca, 2022b). The consumption of fertilizers, phytosanitary and antimicrobial products was 11,219,420 t, 348,095.2 t, and 101.23 mg/PCU, respectively (EUROSTAT, 2022b). Table 1 identifies the details of the main characteristics of the EU-27 agri-food system.

Table 1
Main indicators of the EU-27 agri-food system.

Main indices			
Number of farms[a]	10,282,700	CAP spending	35 % of the EU budget
Number of agri-food industries[b]	293,576	Employment in agribusiness[b]	4.54 %
Imports (billions of European euros)[d]	13 0.158	Employment agri-food industry[b]	2.21 %
Exports (billions of European euros)[d]	198,068	Fertilizer consumption (t)[c]	11,219,420
Trade balance (billions of European euros)[d]	67,910	Pesticide consumption (t)[c]	348,095.2
Agricultural GDP[d]	3.0 %	Antimicrobial consumption (mg/PCU)[c]	101.23
Agri-food industry GDP[d]	2.4 %	Agricultural GHG (t)[c]	382,449.7

Detail exports (millions of €)[d]		Detail imports (millions of €)[d]	
Wine, vermouth, cider and vinegar	17,162	Tropical fruit, fresh or dried; nuts and spices	12,949
Pasta, pastry, biscuits and bread	9495	Oilcakes	7776
Chocolate, confectionery and ice cream	9197	Palm & palm kernel oils	6842
Pigmeat, fresh, chilled and frozen	9141	Unroasted coffee, tea in bulk & mate	6802
Spirits and liqueurs	8405	Soybeans	6669
Food preparations, not specified	8317	Fruit, fresh or dried, excl. citrus & tropical fruit	6467
Infant food and other cereals, flour, starch or milk preparations	7974	Oilseeds, other than soyabeans	4919
Preparations of vegetables, fruit or nuts	7695	Vegetables, fresh, chilled and dried	4752
Remaining agri-Food products	113,568	Remaining Agri-Food products	73,182

PCU: livestock population correction unit established in by the European Medicines Agency to calculate antibiotic consumption in food animals (Veterinary Medicines Directorate, 2016). Source: own elaboration based on Eurostat (2022a), European Commission (2022a), Maudos and Salamanca (2022a, 2022b).

[a] 2016.
[b] 2019.
[c] 2020.
[d] 2021.

2.2. Selection of indicators

The first stage of this research consisted of selecting a battery of measurable and relevant indicators to evaluate the economic, social, and environmental aspects of the sustainability of the agri-food system (i.e., agriculture, livestock, and agri-food industry) of the EU Member States.

The indicators studied here have been chosen based on the well-established relationship between the environmental, social, and economic dimensions of sustainability and the development of agricultural activities within the framework of the circular economy (Silvestri et al., 2022). Their election relies on previous relevant but recent research and review papers where the sustainability of the agri-food sector has been connected with the circular economy or the above-mentioned dimensions (Abbate et al., 2023; Correia et al., 2020; Orou et al., 2023; Ruiz-almeida and Rivera-ferre, 2019; Scandurra et al., 2023; Silvestri et al., 2022). Table S1 extends the number of sources consulted. In selecting the methodology, careful consideration has been given to the most widely used and relevant indicators according to the state of the art of this field (Gallo et al., 2023). These selected indicators are not only extensively used but also strongly aligned with the objectives of this paper (Falkenberg et al., 2023; Silvestri et al., 2022). Special relevance has been given to the indicators of Life Cycle Assessments (LCA) because of the importance they have shown in assessing and improving the agri-food industry in terms of social and environmental impacts (Esposito et al., 2020). Additionally, indicators used in Life Cycle Sustainability Assessment (LCSA) models have been included since they cover not only social and environmental dimensions but also the economic one, thus giving to this research a holistic approach (Arcese et al., 2023). Likewise, recent challenges and gaps already identified in this research field by previous studies have been considered and included. Furthermore, the initial sample of indicators was evaluated by professionals from the agri-food sector and various researchers.

Next, the indicators were obtained from those available in official databases of the EU. It was ensured that the information had been standardized among the EU Member States (European Commission, 2022c; Eurostat, 2022a). From the information available in the repositories, the time scale was limited to the period between 2015 and 2019 to select a similar number of values among each indicator and avoid the influence of COVID-19. The databases consulted were Eurostat and the CAP performance indicators section of the Agriculture and Rural Development section of the European Commission website (European Commission, 2022c; Eurostat, 2022a). The final availability of the indicators in the official databases finally determined the specific indicator and its units. Table S1 identifies the list of indicators with their respective source. In the first stage, the indicators had to meet the following criteria: measurable, understandable, reliable, official, accessible, long-term, related to sustainability, and not affected by the COVID-19 pandemic (OECD and European Commission, 2008; Opon and Henry, 2019; Fig. 1).

Subsequently, it was verified that they complied with the principles of the methodological proposal described in the Pressure-State-Response (PSR) model for being one of the most internationally accepted protocols to select sustainability indicators (Claudia et al., 2016; Lai et al., 2022; Wang and Wang, 2021). The PSR method is also recommended by entities such as the Organization for Economic Cooperation and

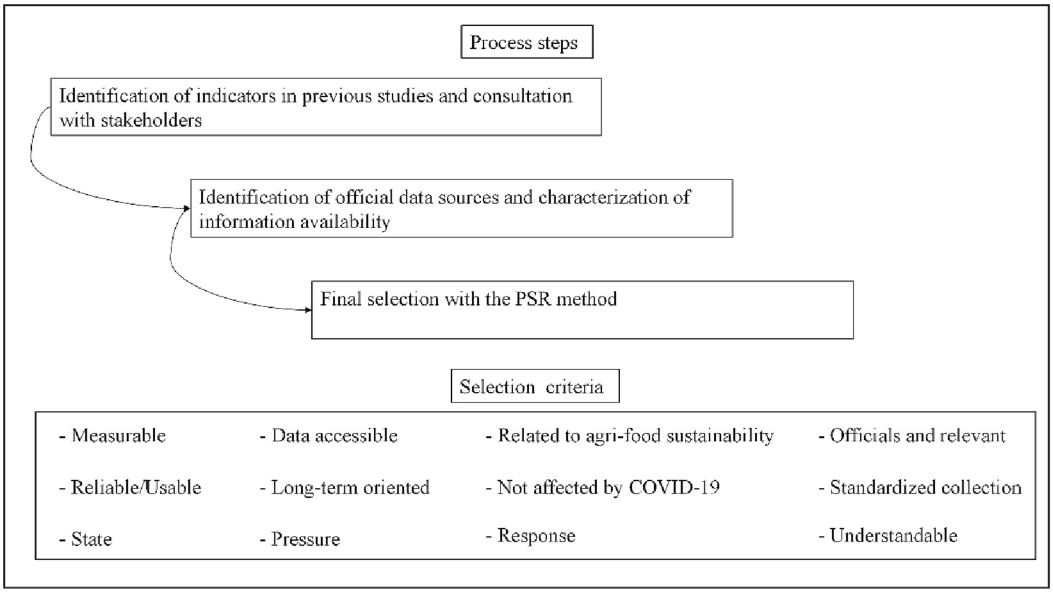


Fig. 1. Stages and criteria for selecting indicators.

Development (OECD) and the United Nations Sustainable Development Commission (SDC) (Martínez, 2009). The PSR model is based on the principle of causality, i.e., anthropogenic activities put pressure on ecosystems and change their state (quality). It was derived from the definition of the production system and its stress, vulnerability, and management (Fig. 2). The PSR method indicates that the events produced on natural environments can be observed through causal chains, where there is a cause-effect relationship between anthropogenic activities and the state of the environment, thus organizing the indicators between those that reflect human pressure on natural spaces, those that reflect the state of the environment, and those that indicate the responses of societies to pressures and changes in the state of the environment (Suresh et al., 2022; Woodhouse et al., 2000). In the second stage, indicators had to meet the criteria of pressure (they cause pressure on the system), state (they characterize the state of the system to be evaluated), and response (they indicate what actions are taken to solve the problem and improve the state of the system) (Martínez, 2009; Fig. 1).

Table 2 identifies the indicators used. Each indicator was assigned a positive or negative sustainability impact on ecosystems.

2.3. Standardization of values

In the second stage of this study, the source indicators were normalized to obtain dimensionless magnitudes that would make it possible to construct a composite index of the economic, social, environmental, and global sustainability of the agri-food system of each EU Member State. The aggregation simplifies the interpretation of the results, making it easier to synthesize complex or multidimensional issues into an overall view that allows a complete study of the system, which promotes communication and allows us to judge the efficiency of the system. This is why this type of representation was used (Fig. 3). However, aggregation can also lead to compensate for the negative state of certain indicators (Nardo et al., 2005; OECD and European Commission, 2008; Opon and Henry, 2019; Saisana, 2004; Fig. 4). Therefore, the disaggregated data for each simple value were also presented to observe

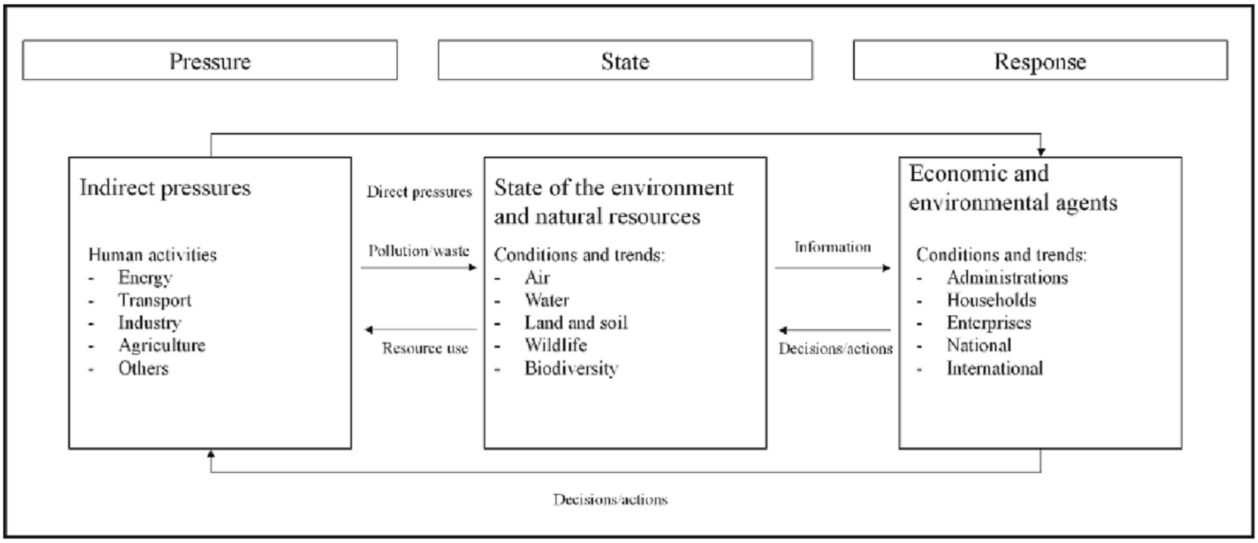


Fig. 2. Conceptual framework of the Pressure-State-Response (PSR) model.
Source: own elaboration adapted from Woodhouse et al. (2000).

Table 2
Selected official indicators to evaluate the sustainability of the agri-food system of the EU Member States.

Code	Index	Unit	Impact on sustainability[a]
Economic subcomponent			
E.1	Farm income	Euros per unit of annual work	+
E.2	Weight of subsidies in farm income	%	−
E.3	Variability of farm income	%	−
E.4	Share of agriculture, livestock and forestry resources in GDP	%	+
E.5	Weight of the food industry in GDP	%	+
E.6	Exports	Billions of euros	+
E.7	Trade balance	Billions of euros	+
E.8	Agriculture and livestock productivity	Euros per unit of annual work	+
E.9	Food industry productivity	Euros per person	+
E.10	Annual Consumer Price Index (CPI)	%	−
E.11	Protected Designation of Origin	Number	+
E.12	Protected Geographical Indication	Number	+
E.13	Traditional Specialty Guaranteed	Number	+
Social subcomponent			
S.1	Total CAP investment	Billions of euros	+
S.2	Direct payment, CAP	Euros per farm	+
S.3	Young farmer support, CAP	Euros per farm	+
S.4	Small producer support, CAP	Euros per farm	+
S.5	Market measures, CAP	Euros per farm	+
S.6	Farms subsidized to participate in local market quality programs and short circuits	%	+
S.7	Farms subsidized to modernize their facilities	%	+
S.8	Employment in the agricultural and livestock sector	%	+
S.9	Employment in the forestry sector	%	+
S.10	Employment in the agri-food industry	%	+
S.11	Poverty rate in rural areas	%	−
S.12	Imbalance between the overall poverty rate and the general poverty rate	%	−
S.13	Generational turnover. Employment in the agricultural, livestock, and forestry sector between 15 and 39 years of age	%	+
S.14	Generational replacement. Employment in the food industry between 15 and 39 years of age	%	+
S.15	Producer organizations	Number	+
Environmental subcomponent			
En.1	Green payment, CAP	Euros per farm	+
En.2	NH_3 emissions from agriculture and livestock farming	Thousands of tons of NH_3 per farm	−
En.3	Greenhouse gas emissions per agricultural operation	Tons CO_2 equivalent per agricultural operation	−
En.4	CO Emissions per agri-food industry	Tons of CO per food industry	−
En.5	Subsidized farms to reduce their NH_3 footprint	%	+
En.6	Grassland in Useful Agricultural Area	%	+
En.7	Organic farming	%	+
En.8	Heads of organic livestock	%	+
En.9	Organic farming operators	Number	+
En.10	Water footprint per agricultural holding	Cubic hectometers per agricultural holding	−
En.11	Agricultural areas subsidized to improve their water efficiency	%	+
En.12	Agricultural area under crop diversification	%	+
En.13	Subsidized farms to improve soil quality	%	+
En.14	Index of birds on farms	%	+
En.15	Forestry area subsidized to improve soil fertility	%	+
En.16	Subsidized agricultural land to improve its biodiversity	%	+
En.17	Sales of antimicrobials in food-producing animals	Milligrams per unit population	−
En.18	Sale of plant protection products per unit of surface area	Kilograms per hectare	−
En.19	Consumption of nitrogen fertilizers per unit of surface area	Kg per hectare	−
En.20	Consumption of phosphate fertilizers per unit of land area	Kg per hectare	−
En.21	Energy consumption per unit area in agriculture, livestock and forestry	Euro per kilogram of oil equivalent	−

[a] Positive or negative effect on the economic, social, and environmental stability of the system evaluated as a result of the action defined by the indicator. +: indicates a positive effect on the agri-food system; −: indicates a negative effect on the agri-food system.

the specific status of each index.

The standardization protocol used is widely accepted by institutions such as the UN, the OECD, and the European Commission, as well as by previous research that have evaluated the sustainability of different economic activities in the face of climate change, where the study identified rural activities and food production (Bao et al., 2022; Hahn et al., 2009; Nasrnia and Ashktorab, 2021; Omerkhil et al., 2020; Pandey and Jha, 2012; Suresh et al., 2022).

Eq. (1) was used for indicators that contributed positively to the sustainability of the agri-food system. Eq. (2) was used for indicators that contributed negatively to the sustainability of the agri-food system. The mathematical formulas used during the transformation procedure were as follows:

$$Index_{sd} = S_d - S_{min} / S_{max} - S_{min} \tag{1}$$

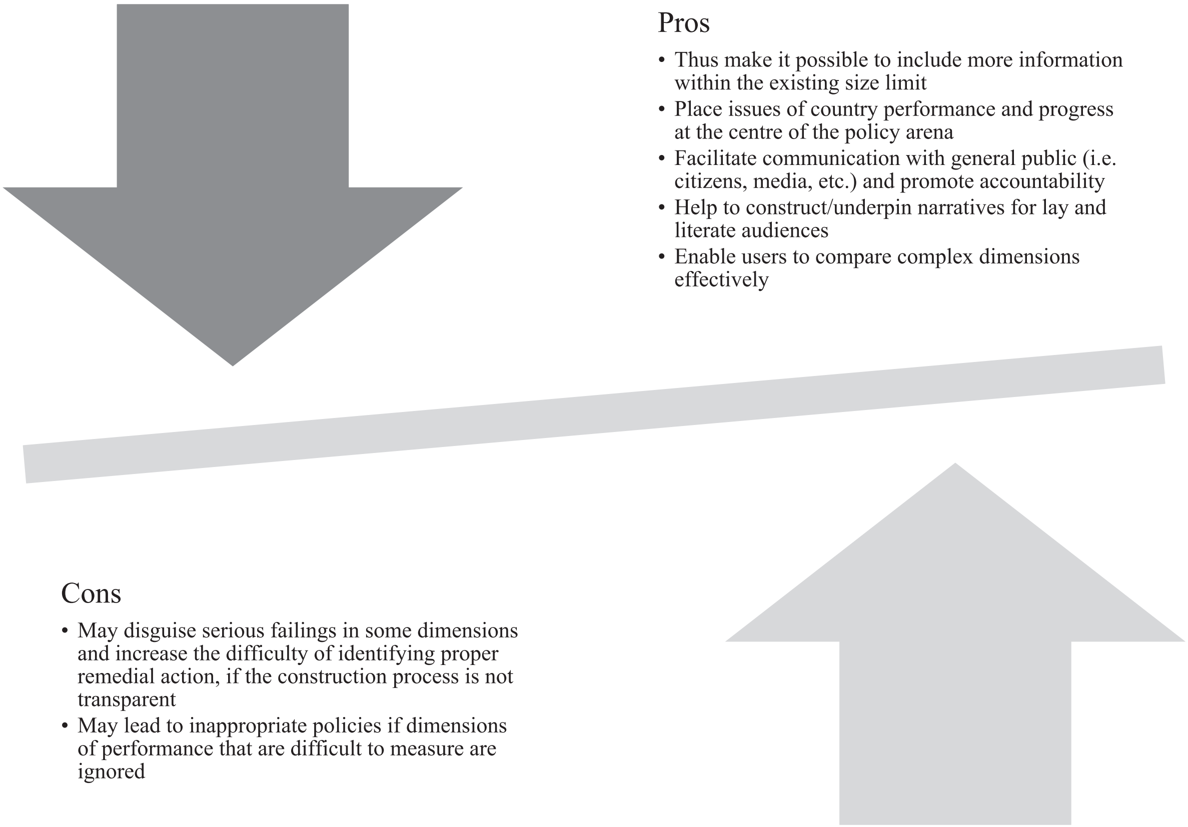
$$Index_{sd} = S_{max} - S_{sd} / S_{max} - S_{min} \tag{2}$$

$0 \leq \mathrm{Index}_{sd} \leq 1$

where,

S_d represents the value of each indicator
S_{max} and S_{min} are the maximum and minimum values of each selected indicator during the period comprised between 2015 and 2019.

After normalizing the indicators, the value of each subcomponent of sustainability was calculated from the average value of the set of indicators of each group of indexes (Table 2). For the calculation of overall sustainability, similar importance was assigned to the economic, social,



Pros

- Thus make it possible to include more information within the existing size limit
- Place issues of country performance and progress at the centre of the policy arena
- Facilitate communication with general public (i.e. citizens, media, etc.) and promote accountability
- Help to construct/underpin narratives for lay and literate audiences
- Enable users to compare complex dimensions effectively

Cons

- May disguise serious failings in some dimensions and increase the difficulty of identifying proper remedial action, if the construction process is not transparent
- May lead to inappropriate policies if dimensions of performance that are difficult to measure are ignored

Fig. 3. Pros and cons of using composite indicators.
Source: own elaboration based on OECD and European Commission (2008).

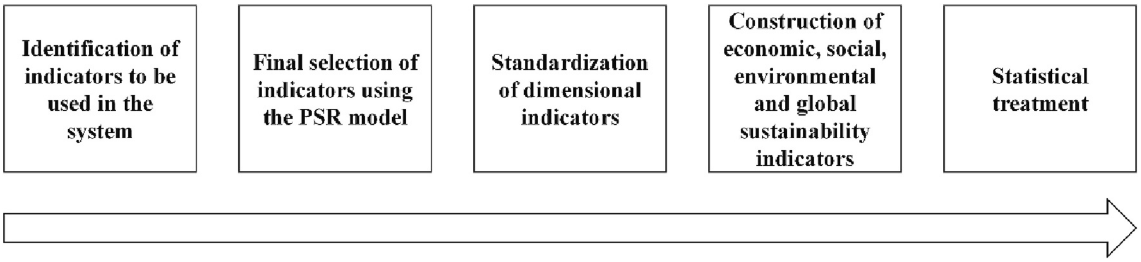


Fig. 4. Methodological stages followed in the research.

and environmental aspects of sustainability given the EU's desire to build a resilient economic system, decoupled from the consumption of natural resources and capable of generating wealth and employment in its Member States (European Comission, 2019). Several authors have also recommended that sustainability should be calculated through the average value of the identified subcomponents (Ćulibrk et al., 2021; Nasrnia and Ashktorab, 2021; Suresh et al., 2022). The mathematical formula used was as follows:

$$IS = \sum_{i=1}^{n} Index_{sd} \Big/ n \tag{3}$$

where,

IS is the index of economic, social, environmental and global sustainability of the agri-food system of each State Member of the EU
$Index_{sd}$ is the partial index calculated through Eqs. (1) and (2)
n is the number of subcomponents of the composite index.

2.4. Statistical treatment

The third stage of the research consisted of applying different statistical treatments to the results. First, an analysis of variance (one-way ANOVA) was performed on the composite sustainability index to observe the behavior of each Member State on the study variable. Previously, the assumptions of normality and homoscedasticity were checked. Subsequently, the least significant difference test (LSD test) was performed to establish subgroups at a confidence level of 95 %.

Secondly, the stepwise linear regression method was used. Through this procedure, the behavior of a significant dependent variable can be predicted from a set of predictor magnitudes (unstandardized β) and their weight in the model by means of the standardized β coefficients (Marín-Guirao et al., 2019; Pope and Webster, 1972). The stepwise linear multiple regression model conforms to the following mathematical expression:

$$y_j = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \xi \tag{4}$$

where,

y_j is the model's dependent variable
β_0 is a constant value
β_1, β_2 and β_n are the set of unstandardized predictor values
ξ is the residual.

In this study, the dependent variable was annual sustainability of the agri-food system of each EU Member State, and the independent variables were the indexes identified in Table 2. The adjusted R^2 value, unstandardized β coefficient, standardized β coefficient, and *t*-test were calculated for each model. Before applying the model, the assumptions of normality, heterogeneity, multicollinearity, and independence of the residuals were checked to verify that the variables used to construct the model met the aforementioned requirements. Variables E.6, E.12, En.9, En.18, and S.15 were excluded because they did not meet the multicollinearity assumption.

Third, a hierarchical-type cluster analysis was applied using Ward's clustering method to determine a similarity between the sustainability of the agri-food system of the EU Member States (Saraçli et al., 2013). The maximum number of clusters was limited according to the maximum number of combinations (binomial coefficient) given by the three subcomponents of sustainability (i.e., economic, social, and environmental).

The first statistical analysis was performed with the STATGRAPHIC CENTURION XVIII software (Manugistic Incorporate, Rockville, Maryland) for Windows, while the next two statistical studies were performed with the SPPS v.28 package for Windows.

Fig. 4 shows the different methodological steps followed in the research.

3. Results

3.1. Economic, social, and environmental sustainability of the European agri-food system

Figs. 5, 6 and 7 show the detail of the economic, social, and environmental aspects of the sustainability of the agri-food system of the 27 Member States of the EU during the period of 2015–2019. There is a different trend between each subcomponent of sustainability.

France (0.60), Italy (0.54), the Netherlands (0.54), Spain (0.52), and Germany (0.44) achieved the highest economic prosperity in the European agri-food sector during the period of study. However, this is only partially related to the development of the social component of the system. Some Member States, such as the Czech Republic, Romania, Latvia, and Sweden, showed a higher value for the social index than other EU countries, such as Ireland or Greece, whose economic sustainability was higher than the EU-27 average.

The environmental sustainability of Estonia (0.69) and Austria (0.67) stood above the rest of the EU Member States, while the Netherlands (0.32) and Malta (0.37) recorded the lowest environmental sustainability. Some of the States at the bottom of the environmental scale are at the forefront of the transition to a system based on the principles of the circular economy. However, as our study shows, the environmental sustainability of its agri-food system displays a different behavior compared to that of the overall economy (Mazur-Wierzbicka, 2021).

3.2. Compound sustainability index

Fig. 8 shows the compound sustainability index of the agri-food sector of the EU Member States. The overall sustainability of the French agri-food system was significantly higher than that of the other Member States during the period of study (one-way ANOVA; $p \leq 0.05$). Austria (0.44), Italy (0.43), Estonia (0.43), Germany (0.42), Belgium (0.40), Finland (0.40), Denmark (0.40), Spain (0.40), Latvia (0.39), Czech Republic (0.39), Sweden (0.38), Greece (0.38), Netherlands (0.38) and Slovakia (0.38) exceeded the average sustainability of the EU-27 agri-food sector. Although Sweden, Greece, the Netherlands, and Slovakia did not experience significant differences with Slovenia, the first Member State after the EU-27 average (one-way ANOVA; $p \leq 0.05$).

In the proposed model, no Member State reached the maximum value. This could be due to the disparate records for the selected indicators in different territories, with one Member State leading in one set of indices, while lagging in others.

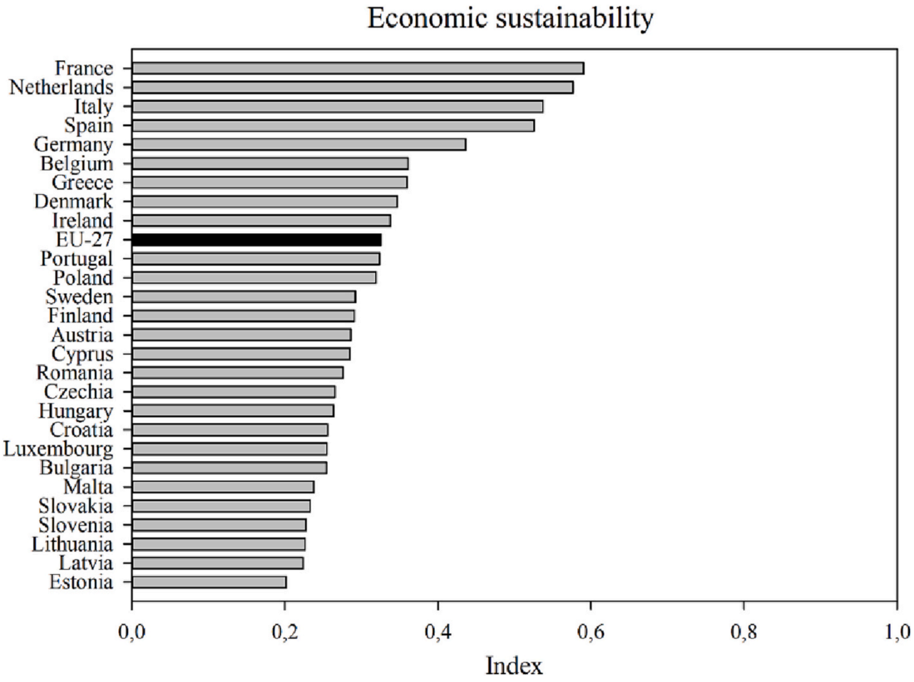


Fig. 5. Economic sustainability of the agri-food system of the EU Member States.

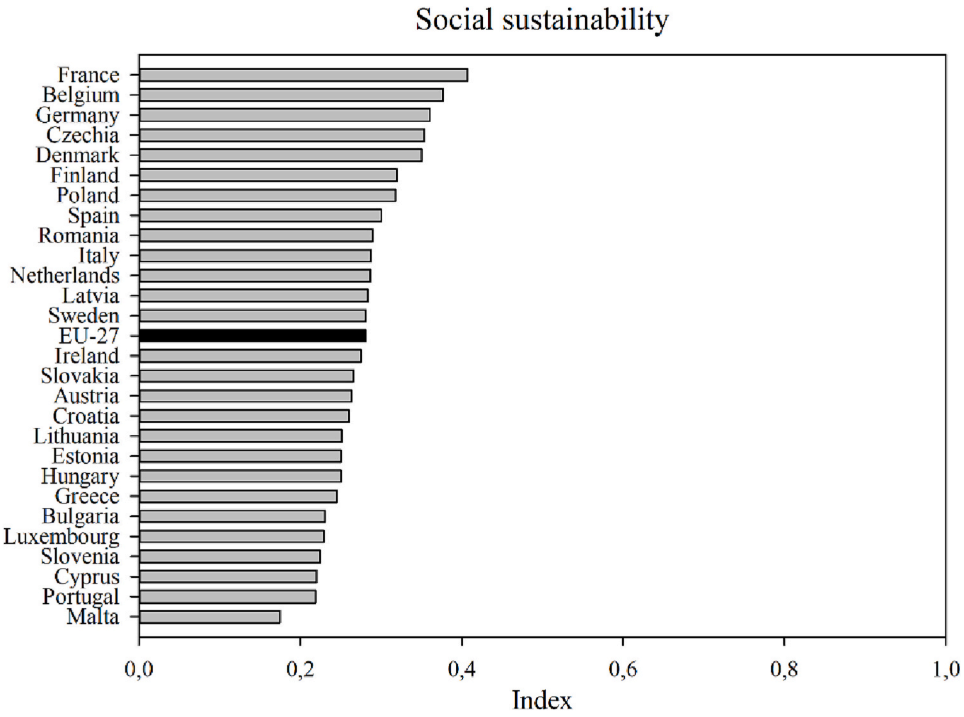


Fig. 6. Social sustainability of the agri-food system of the EU Member States.

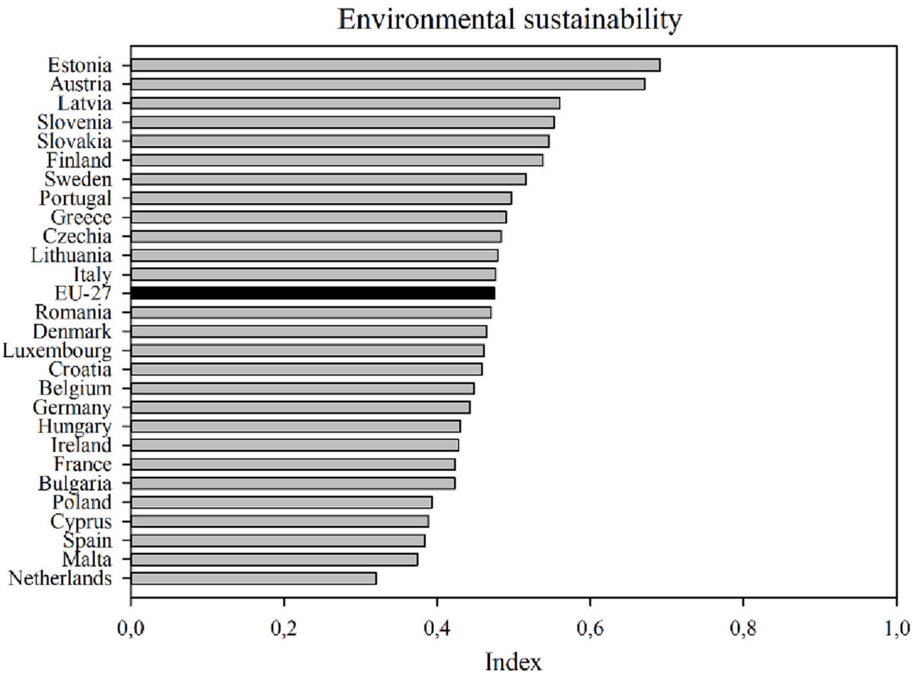


Fig. 7. Environmental sustainability of the agrifood system of the EU Member States.

3.3. Cluster analysis

Table 3 shows the results of the cluster analysis. The six pre-set groups, based on the binomial coefficient of the three aspects of sustainability, made it possible to classify the behavior of the 27 EU Member States:

- Group I comprised the Member States with high environmental sustainability.
- Group II includes the States with the highest social sustainability despite their low average value.
- Group III comprises Member States with low economic, social, and environmental sustainability.
- Group IV consists of Member States with moderate social and environmental sustainability.
- Group V identifies Member States with high economic and social sustainability, but low environmental sustainability.
- Group VI includes States with moderate economic and environmental sustainability, but low social sustainability.

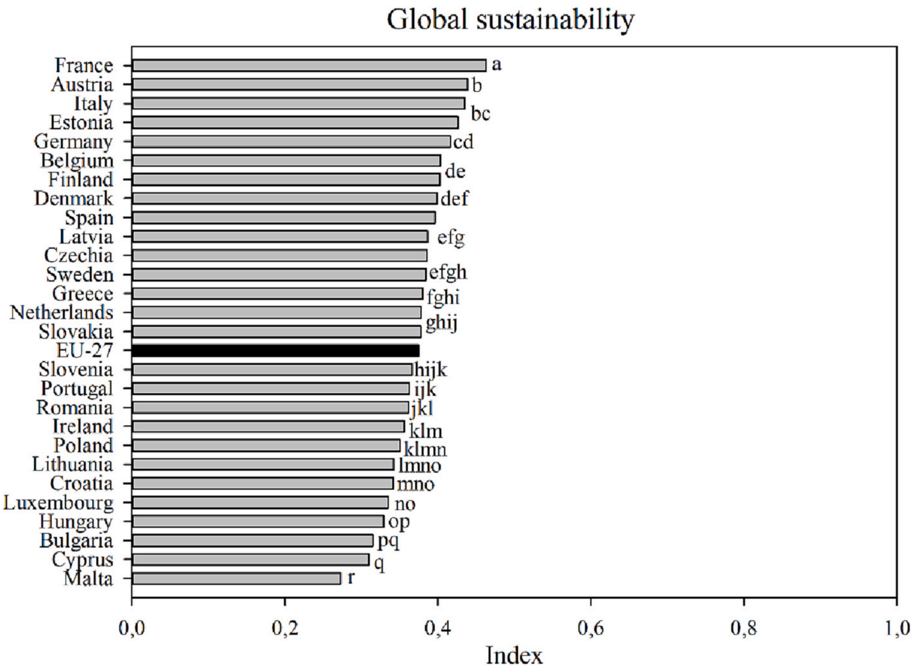


Fig. 8. Overall sustainability of the agrifood system of the EU Member States. Different letters indicate significant differences ($p \leq 0.05$; Test LSD).

Table 3
Description of the average value of the groups established by the cluster analysis.

Cluster	Cluster size	Member state	SE	SS	SEN
I	2	Austria and, Estonia	0.24	0.26	0.68
II	5	Belgium, Denmark, Germany, Ireland, and Poland	0.36	0.34	0.44
III	8	Bulgaria, Croatia, Cyprus, Hungary, Lithuania, Luxembourg, Malta, and Romania	0.26	0.24	0.44
IV	6	Czechia, Finland, Latvia, Slovakia, Slovenia, and Sweden	0.26	0.29	0.53
V	4	France, Italy, Netherlands, and Spain	0.56	0.32	0.40
VI	2	Greece, and Portugal	0.34	0.23	0.49

SE: economic sustainability; SS: social sustainability; SEN: environmental sustainability.

Table 4
Stepwise multiple linear regression model that evaluates the prediction of the synthetic sustainability index from the indicators selected by the PSR model.

Adjusted R^2	s^2, gl	Predicted variable	β not standardized	β standardized	Partial *t*-test, p-value
0.945	0.00828, 55	Constant	0.382 ± 0.008	–	<0.001
		En.20	−0.022 ± 0.005	−0.226	<0.001
		E.5	0.003 ± 0.001	0.311	<0.001
		En.11	0.000 ± 0.000	0.223	<0.001
		S.5	$2.289 \cdot 10^{-5}$ ± 0.000	0.381	<0.001
		S.1	$8.280 \cdot 10^{-8}$ ± 0.000	0.380	<0.001
		En.8	0.001 ± 0.000	0.244	<0.001
		En.12	0.000 ± 0.000	0.095	0.033
		En.19	−0.006 ± 0.001	−0.426	<0.001
		S.12	0.001 ± 0.000	0.210	0.001
		En.15	236.397 ± 105.732	0.132	0.030

En.20: Consumption of phosphate fertilizers per unit area; E.5: Weight of food industry in GDP; En.11: Agricultural area subsidized to improve its water efficiency; S.5: Market measures, CAP; S.1: Total investment in CAP; En.8: Heads of organic livestock; En.12: Agricultural area undergoing crop diversification; En.19: Consumption of nitrogen fertilizers per unit area; S.12: Imbalance between overall poverty rate and overall poverty rate; En.15: Forestry area subsidized to improve soil fertility; gl: degrees of freedom.

3.4. Multiple linear regression analysis

Table 4 shows the main results of the stepwise multiple linear regression that took the composite sustainability index as the dependent variable and the economic, social, and environmental indicators selected through the PSR model as independent variables. The model (adjusted R^2: 0.945; $p < 0.001$) detected ten predictor variables: phosphate fertilizer consumption per unit area, agri-food industry GDP rate, rate of farms with contracts to improve water footprint, market measures established by the CAP, CAP expenditure, organic livestock rate, agricultural area with crop diversification, nitrogen fertilizer consumption per unit area, the difference between national poverty and rural poverty, and forest area subsidized to improve its biodiversity.

Only the consumption of nitrogenous (adjusted β: −0.426) and phosphate fertilizers (adjusted β: −0.226) per unit area had a negative influence on the composite index of the sustainability of the agri-food system of the EU Member States (Table 4). The demand for nitrogen fertilizers had the strongest influence on the predictor model (adjusted β: −0.426). In this case, the overfertilization of European fields led to a law limiting the addition of nutrients in regions declared to be at risk (Consejo Europeo, 1991). However, intensive agriculture has contaminated natural areas of high ecological value, which has led to the adoption of local initiatives for their protection (Alcon and Zabala, 2022; Región de Murcia, 2019). The addition of fertilizers can also increase the concentration of heavy metals in the soil (Gil et al., 2018). In the framework of the circular economy, the use of by-products offers inputs that allow similar yields to those shown by the conventional system, favoring the adherence of the organic production system while reducing high-value inputs, such as water. This makes it possible to meet the objectives of the 2030 Agenda and those established by the EU (Castillo-Díaz et al., 2022a, 2022b; Krav̌, 2022; Salinas et al., 2020).

3.5. Simple indicators

Table 5 shows the normalized indices selected by the stepwise linear regression model to represent the sustainability of the agri-food system of the EU Member States during the period 2015–2019.

In Germany, France, Italy, Spain, and the Netherlands, the agri-food industry contributed the most to the overall GDP of each country. The EU's major players were the countries that made the biggest contribution to CAP spending. The Netherlands achieved the highest rate of imbalance between State poverty and rural poverty.

The consumption of nitrogen and phosphate fertilizers per farm was elevated in all European territories. The Netherlands was the Member State with the highest demand for nitrogen fertilizers per unit area, while Cyprus excelled in the expenditure of phosphate fertilizers.

Austria led in the number of livestock holdings with European organic certification and the rate of farms subsidized to improve their water footprint during the period studied.

Spain was at the bottom regarding the forestry area subsidized to improve its biodiversity. In this last indicator, Belgium is the country that has made the firmest commitment to enhance the biodiversity of its forests. Denmark stands out in terms of crop diversification in its agricultural area, which improves the biodiversity of the agriculture field. Ranking in Table 5 is related to the position of the Member States according to the economic, social, and environmental aspects of the sustainability of the agri-food system and its composite sustainability index (Figs. 5, 6, 7 and 8).

Tables S2 and S3 show the normalized indices not selected by the stepwise linear regression model. Overall, the environmental indicators showed a higher mean value.

The Netherlands' trade balance and exports were the highest in the EU due to the country's high trade openness. Its re-export of goods and services to third countries accounts for 42 % of all its foreign sales. The Netherlands' main trading partners, including the sale of agri-food products, are the Member States of the EU (ICEX, 2020; Maudos and Salamanca, 2022b).

Italy, Germany, and Spain stood out regarding the possession of Protected Designations of Origin, Protected Geographical Indications, and Traditional Specialties Guaranteed. Austria showed the highest rate of organic area, while Italy had the highest number of operators specialized in organic farming.

The social importance of the agri-food system in the Eastern European Member States was high. However, these countries also had the highest poverty rate in rural environments, where food production usually articulates the territorial balance, perhaps due to the lower economic prosperity of the countries and the lower economic productivity of food production and processing.

Central and Northern Europe showed the lowest rural poverty rate. France, Germany, Italy, and Spain presented the highest number of producer organizations. These entities have a key social relevance because they can help producers to achieve effective management and leadership, provide mechanisms for conflict resolution, assistance for better market access, higher incomes, and the creation of supportive institutions and regulations (Tirivayi et al., 2018). The large disparity between the selected social indicators of the Member States may have triggered the lower average value of the composite index of sustainability.

In terms of the energy demanded in food production, the Netherlands led the ranking in the study period. This behavior expands the dependence of the agro-system on external inputs. The Netherlands is home to one of the main greenhouse production models in the EU. Spain and Italy, despite having a physical area of greenhouse crops, have low energy consumption. Greenhouse agriculture takes place in the southeast of Spain, where the benevolent climate reduces the dependence on

Table 5
Normalized indicators identified by the stepwise linear regression model.

	En.20[a]	E.5	En.11	S5	S.1	En.8	En.12	En.19[a]	S.12[a]	En.15
Austria	0.83	0.13	0.97	0.08	0.28	0.96	0.38	0.84	0.19	0.00
Belgium	0.88	0.17	0.08	0.76	0.04	0.38	0.59	0.30	0.47	0.73
Bulgaria	0.76	0.02	0.02	0.05	0.11	0.05	0.72	0.59	0.81	0.00
Croatia	0.65	0.03	0.05	0.03	0.10	0.14	0.45	0.68	0.71	0.00
Cyprus	0.14	0.00	0.04	0.07	0.01	0.01	0.68	0.65	0.65	0.00
Czechia	0.75	0.07	0.06	0.30	0.16	0.68	0.84	0.24	0.44	0.02
Denmark	0.78	0.08	0.09	0.16	0.04	0.26	0.98	0.43	0.33	0.68
Estonia	0.89	0.01	0.69	0.11	0.05	0.61	0.66	0.88	0.65	0.79
Finland	0.84	0.05	0.96	0.07	0.20	0.37	0.89	0.66	0.54	0.00
France	0.75	0.94	0.04	0.47	0.74	0.20	0.64	0.53	0.31	0.00
Germany	0.75	0.96	0.06	0.20	0.53	0.28	0.80	0.34	0.39	0.01
Greece	0.84	0.10	0.08	0.03	0.20	0.36	0.20	0.91	0.63	0.00
Hungary	0.64	0.05	0.04	0.04	0.18	0.03	0.83	0.52	0.71	0.50
Ireland	0.61	0.17	0.20	0.07	0.16	0.03	0.07	0.48	0.51	0.00
Italy	0.69	0.60	0.10	0.21	0.60	0.23	0.34	0.82	0.51	0.03
Latvia	0.79	0.01	0.19	0.04	0.08	0.71	0.59	0.86	0.69	0.26
Lithuania	0.70	0.03	0.00	0.03	0.09	0.25	0.78	0.71	0.71	0.10
Luxembourg	0.91	n.a.	0.11	0.14	0.01	0.10	0.43	0.28	0.33	0.00
Malta	0.88	0.00	0.03	0.02	0.00	0.01	0.00	0.76	0.96	0.00
Netherlands	0.94	0.33	0.00	0.36	0.04	0.10	0.43	0.07	0.17	0.00
Poland	0.57	0.28	0.08	0.03	0.42	0.09	0.60	0.55	0.76	0.00
Portugal	0.83	0.08	0.33	0.15	0.24	0.10	0.11	0.96	0.67	0.03
Romania	0.82	0.18	0.05	0.00	0.48	0.01	0.46	0.96	0.80	0.00
Slovakia	0.80	0.02	0.15	0.16	0.08	0.39	0.78	0.63	0.66	0.48
Slovenia	0.66	0.01	0.52	0.04	0.05	0.43	0.21	0.70	0.54	0.00
Spain	0.68	0.52	0.13	0.22	0.43	0.08	0.47	0.84	0.68	0.01
Sweden	0.86	0.10	0.07	0.09	0.12	0.60	0.62	0.65	0.59	0.00

Note: the representation is based on the average value of the normalized index of each indicator in the period 2015–2019. n.a.: not available. En.20: Consumption of phosphate fertilizers per unit area; E.5: Weight of food industry in GDP; En.11: Agricultural area subsidized to improve its water efficiency; S.5: Market measures, CAP; S.1: Total investment in CAP; En.8: Heads of organic livestock; En.12: Agricultural area undergoing crop diversification; En.19: Consumption of nitrogen fertilizers per unit area; S.12: Imbalance between overall poverty rate and overall poverty rate; En.15: Forestry area subsidized to improve soil fertility.

[a] Expresses a negative effect on the system.

heating (Rabobank, 2017; Valera-Martínez et al., 2017; Vanthoor et al., 2012). On the other hand, the downturn in energy supply in European countries may increase production costs, especially for those agricultural systems with a high energy footprint. The situation may jeopardize food security in the EU, especially for people with low economic resources. Although the EU has a positive trade balance, it has an external dependence on certain products, such as proteins for animal feed, sunflower oil, and seafood. The current geopolitical situation may force the EU to turn to other markets to purchase these products (European Commission, 2022b).

Spain, Italy and Cyprus consumed the highest number of antimicrobials to develop their livestock production. These products are excreted through manure and are a major source of contamination for the environment, animals, and humans. Zoo-sanitary products can be transported along the food chain, and their main source is intensive animal husbandry systems (Rodríguez et al., 2022; Tacconelli et al., 2018; WHO, 2015). The agricultural systems of Spain, Italy, France, and Germany led on the use of pesticides.

The Czech Republic, Denmark, Germany, Luxembourg, and the Netherlands agricultural models led on GHG emissions per farm, both in terms of ammonia emissions and carbon dioxide equivalent. The latter is perhaps due to the greater importance of livestock production, where enteric fermentation can contribute up to 43.3 % of GHG emissions from livestock production and fertilizer consumption (Froldi et al., 2022; Taylor et al., 2022). In addition, the significant energy demand experienced in Northern European countries to maintain adequate microclimatic conditions inside farms can increase greenhouse gas emissions (Vanthoor et al., 2012). The agri-food industry in Poland and Ireland headed the emission of carbon monoxide per company into the environment. The implementation of eco-innovations can help to reduce the environmental footprint of the activity. Adherence depends on the magnitude of process, organization, and marketing within the corporate values framework. Innovation can mediate social responsibility variables and corporate exports (García-Granero et al., 2020; Martos-Pedrero et al., 2022).

The EU is making a substantial investment to modernize and expand the sustainability of its production system to mitigate the effects caused by climate change. The benefits of techniques, such as sensor technology, big data, artificial intelligence, and cloud computing, can help reduce the demand for inputs and increase the productivity of food production and processing, thereby reducing its environmental footprint (MAPA and Cajamar, 2022).

Farms in Spain and Austria are the most significant contributors to the water footprint. In some cases, water may come from subway sources that are overexploited or at risk of salinization. Therefore, it is necessary to improve water-use efficiency to reduce the water footprint of farms and to introduce new alternative water sources, such as desalinated or reclaimed water. In addition, desalinated water can significantly increase crop production (Aznar-Sánchez et al., 2021; López-Serrano et al., 2022; MAPA and Cajamar, 2022). Using these alternative water resources is of particular importance because climate change is modifying the hydrological cycle, which will affect the availability of water for agricultural use (Zapata Sierra et al., 2022).

4. Discussion

This work aimed to evaluate the triple aspect of the sustainability of food production and processing in the EU Member States. A composite indicator was designed based on a system of indicators. This has made it possible to identify the current state of sustainability of the European agri-food system by representing a complex problem in simple fashion. This fact facilitates assistance in decision-making and in the creation of public or private strategies adapted to the needs of each food production and processing model in order to increase the commitment of the interested parties. In addition, the pillars on which such action plans should be based have been identified.

The results of this research suggest the existence of moderate sustainability of the agr-ifood system of the EU Member States, although the economic, social, and environmental subcomponents behave differently (Figs. 5, 6, 7, and 8).

The expansion of the economic sustainability of this work may have been influenced by the existence of highly productive intensive farming systems (Valera-Martínez et al., 2014; Vanthoor et al., 2012), the presence of crops and their associated processing industry that can obtain high added value from agri-food products (e.g., wine industry, etc.) (OIV, 2021), the high availability of farms and agri-food industries (MAPA, 2022) or the nature and/or strategic position that some countries may have in commercial exchange (ICEX, 2020). As a result, countries such as France, Italy, the Netherlands, Spain, and Germany have topped the economic ranking. The subsectors that can provide the greatest economic benefit are greenhouse crops, olive groves, grapevines, tropical and subtropical fruit trees, and farms of white pigs, Iberian pigs, meat and milk cattle, and meat and milk sheep/goats, among others (MAPA, 2018; Maudos and Salamanca, 2022a; Reisman, 2022). In addition, the availability of differentiated quality seals in some of these subsectors can increase the selling price of these products. Thus, the expansion of this type of certification, as well as organic certification, should be encouraged. This type of certification acts as a differentiating element for agri-food products. Customers are willing to pay more when products have distinctive seals to differentiate quality. About 75 % of Italian consumers would be willing to pay more when products are certified organic (Castellini et al., 2022). The price increase for these products can vary from 31 % to 50 % (Etuah et al., 2022).

A partial relationship between the economic and the social sustainability of the European agri-food system was observed (Figs. 5 and 6). The countries that topped the economic ranking also occupied high positions in the social ranking. However, some Member States that did not have a highly profitable agri-food system occupied relevant positions in the social ranking. Primary production and the associated agri-food industry have generated various Local Production Systems (LPS) that enrich the territorial balance of the demarcations, mainly of rural environments, where economic activity may depend on the livelihood offered by both food production and food processing. Small farms can be very important (Guiomar et al., 2018; Honoré et al., 2019; Ofosu et al., 2020). In turn, SPLs usually generate business clusters formed by their auxiliary industry (e.g., agrotech, biotech, etc.), which supplies products and services to the operations. Therefore, the agri-food system usually generates more jobs and wealth in rural environments both directly and indirectly (Godoy-Durán et al., 2017; Simboli et al., 2015; Valera-Martínez et al., 2014). Also, family-based intensive food production systems have developed over the last fifty years. Such a trend has been reinforced during periods of financial crises (Honoré et al., 2019; Valera-Martínez et al., 2014). Therefore, it is of interest that the economic development of the agri-food system is associated with the generation of SPL, since it may improve the sustainability of the system while at the same time fixing the population to the territory and reducing the system's dependence on external factors.

The environmental component showed an inverse relationship with the economic development of the European agri-food sector (Figs. 5, 6 and 7). The Member States with a leading economic position achieved a lower quality of environmental indicators, due perhaps to a higher demand for inputs and energy to produce and transform food (Escribano et al., 2015; Vanthoor et al., 2012). Highly intensive food production and processing models will have a stronger economic impact on the expense account of their production units as a result of applying the environmental policy and having to adapt their current production techniques to the new needs. However, this is also an opportunity for such systems. Previous research has reported how implementing eco-innovations can improve the agri-food profitability of these production models (Castillo-Díaz et al., 2023; Honoré et al., 2019; Martos-Pedrero et al., 2022). However, the green transition must be gradual to avoid excluding SPLs of high interest for the socioeconomic development of various European regions, as the disappearance of SPLs can have a devastating effect on them and encourage their depopulation.

Therefore, it is necessary to apply a policy at different speeds adapted to the intrinsic needs of each territory and agri-food subsector, as shown by the results of the cluster analysis carried out in this study. The EU should break down its general agri-food policy into various action plans focused on the subsectors of the European agri-food system to maintain its socioeconomic prosperity and improve environmental sustainability. EU Member States should be able to adapt these action plans to their respective territories and thus comply with the EU's wishes to implement its new policy. The documents should indicate the minimum actions per subsector that need to be carried out.

It is also necessary to emphasize that the agri-food sector stakeholders must be offered real alternatives to the techniques that need to be replaced. Therefore, innovation and the correct transfer of knowledge must be an articulating axis of this green transition (Aznar-Sánchez et al., 2021; Castillo-Díaz et al., 2022a, 2022b). All this is not to reduce the productivity of European agrosystems and not to jeopardize the EU's food sovereignty and security.

This articulating axis must include incentives to help producers and entrepreneurs use the best available techniques. These techniques should be selected by activity and subsector, and the granting of aid should depend on the full application of the package of techniques, thus creating “green architectures” (Castillo-Díaz et al., 2023).

The green architectures of the European agricultural policy could be centered on ten pillars, whose themes should be related to the most relevant indicators selected by the stepwise linear multiple regression of this work, although adapted to the needs of each territory. Some of these pillars are already included in the Farm to Table Strategy, the Biodiversity Strategy, or in the Common Agricultural Policy (e.g., reduction of nitrogen and phosphorus consumption, measures to favor biodiversity, water management measures, etc.) (European Comission, 2020a, 2020b; European Council, 2021), but their expansion should be promoted based on specific plans depending on the subsector to increase the commitment of stakeholders.

In terms of business management, the system of indicators, the composite indicator developed in this study, and the methodology applied can be used by companies to establish their sustainability strategies and objectives, allowing them to identify which points may be of greatest importance when applying corrective measures to expand their socioeconomic or environmental development.

Although this study analyzes the sustainability of the European agri-food system, it is not without limitations. The availability of updated and evaluated information for several consecutive years has complicated the selection of indicators, which may have limited the scope of the study. The official databases should be updated periodically to facilitate the identification of the state of sustainability on a short-term scale and then take corrective measures. In addition, updating the official repositories may out-date the limits of the proposed model. The Administration should increase the number of indicators available in its databases, which would increase the accuracy of the calculations. It should also implement specific indicators on the circular economy in the agri-food sector.

5. Conclusions

The results of this research show the existence of a moderate level of sustainability in the food production and processing of the EU Member States. In this sense, none of the European territories reached the highest theoretical sustainability of the composite indicator formed from a system of indicators selected by the PSR protocol. France's food production and processing had the highest overall sustainability (0.46), followed by Austria (0.44), Italy (0.43), Estonia (0.43), Germany (0.42), Belgium (0.40), Finland (0.40), Denmark (0.40), Spain (0.40), Latvia (0.39), Czech Republic (0.39), Sweden (0.38), Greece (0.38), Netherlands (0.38) and Slovakia (0.38), all of them above the EU-27 average. Thus, the results suggest the existence of an inverse relationship between socioeconomic and environmental aspects.

The cluster analysis made it possible to classify the 27 countries into the six proposed groups, resulting from the binomial coefficient given by the three subcomponents of sustainability. The expansion of the economic aspect was associated with a more significant social contribution along with a lower quality of environmental indicators. Therefore, the initiatives promoted by each territory must be adapted to their specific characteristics to meet the common objectives and make further progress in the most deficient areas. In general, the promotion of policies that favor the reduction of the environmental footprint of the agri-food system to address climate change (i.e., reducing the demand for water, agrochemicals, antimicrobials, energy) should be encouraged. The inclusion of production techniques based on the circular economy can help to maintain productivity and, therefore, the economic benefit of agricultural systems while expanding their environmental sustainability.

Future research should quantitatively determine the economic, social, and environmental sustainability of the subsectors of the agri-food system in the different regions of each Member State of the EU to increase the precision of quantification and expand knowledge on this subject. Likewise, it should be quantitatively determined the influence of initiatives based on the framework of the circular economy on the sustainability of the European agri-food system, as well as the state of implementation of these initiatives (e.g., the degree of reuse of byproducts generated in agriculture, livestock farming, and the agri-food industry).

Declaration of competing interest

The authors declare to have no conflict of interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2023.07.010.

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