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Sustainability of European agri-food supply chain using MRP-PCI multicriteria analysis method

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Abstract

The need for a more sustainable agri-food system is a topic that has attracted growing interest in recent years. Several international and European policies such as Agenda 2030 and the European Green Deal have been defined with the aim of making agri-food systems more sustainable at all stages of the supply chain, from production to consumption. Particularly, the European Union concentrates several policies on it. Therefore, the assessment of the level of sustainability among the states of the European Union is a key aspect to properly address and evaluate the implementation of these policies. The objective of this paper is to measure the sustainability of the global agri-food supply chain (AFSC) of the European Union countries through the application of a multi-criteria analysis. In particular, the method used is the Multiple Reference Point Partially Compensatory Indicator, which allows the creation of composite indicators using different levels of compensation across them. A set of 50 indicators, referred to 2011 and 2019, were built and then divided into the three basic dimensions of sustainability (economic, social and environmental), aggregated into the four main AFSC sectors (agriculture, food industry, distribution, and consumption) in order to obtain an overall sustainability index. Through such an index we provided a sustainability ranking for the EU countries, while the analysis of dimensions of each sector contributed to increase the knowledge about the supply chain that can be used by decision-makers. According to the results, Italy achieved the best level of sustainability of the AFSC with a value of 48.53, followed by Sweden, Austria, Spain, France, Germany, the Czech Republic, Portugal and Slovakia. In relation to the different sectors, the biggest problems were observed in the consumption sector, where most countries did not perform well, especially for the social dimension (e.g. excess of overweight and obese persons). In contrast, the performance of the agricultural sector was good, with few exceptions, showing a fair state of sustainability.

Keywords: Agri-food supply chain, Sustainability, European Green Deal, EU countries, Multicriteria analysis

Introduction

The call for a more sustainable agri-food supply chain (AFSC) is an issue that has reached growing interest in the last decade, especially because of the increased awareness of the effects of food production and consumption on the natural environment and of the living and working conditions of some of the chain actors (Allaoui et al. 2018). AFSC refers to all the activities related to agricultural products handling from the farmers to customers, and it implicates a complex network of stakeholders, directly or indirectly involved, with common objectives (Agnusdei and Coluccia 2022). The various stages comprised can be classified as agricultural production and livestock production, food industry, distribution, and consumption. Each stage, except the consumption, adds a specific value to the final product.

Achieving sustainability involves striking a balance between economic growth, environmental protection, and social conditions. Therefore, it is needed to set a management policy that is framed in the context of sustainable development. The 2030 Agenda for Sustainable Development includes several Sustainable Development Goals (SDGs) related to the sustainability of agri-food supply chains, such as SDG2 (Zero hunger), SDG7 (Affordable and clean energy), and SDG12 (Responsible consumption and production). The European Green Deal (EGD), one of the six political priorities of the von der Leyen Commission, has its core in the "Farm to Fork" strategy (F2F), aiming at making agri-food systems more sustainable in all the phases of the supply chain, from production to consumption (European Commission 2020; De Castro et al. 2020; Wesseler 2021).

Previous studies devoted to the issues of the sustainable AFSC mainly focused on the improvement of individual firms or processes rather than the design of the entire supply chain (Allaoui et al. 2018). Galli et al. (2015) explored dimensions of sustainability relevant to investigating the performance of the wheat-to-bread supply chain by assessing Italian case studies. The research identifies critical aspects and provides a qualitative assessment of the performance of local and global wheat-to-bread chains. Pancino et al. (2019) in their paper focused on the understanding of the process of designing a multistakeholder partnership in the adoption and diffusion of sustainable innovations in food value chains, promoted and facilitated by private actors, using the Barilla Sustainable Farming initiative as a case study. Considering the sustainability paradigm, the attention of literature is devoted largely to the environmental pillar, compared to the economic and social ones (Agnusdei and Coluccia 2022; Allaoui et al. 2018). In addition, there is a lack of analyses about the ranking of the European Union countries in terms of sustainable food supply chains. Due to the absence of such studies, there is a gap in the assessment of similarities or distances between countries regarding the level of sustainability in the AFSC, which is a key point in order to correctly address and evaluate the F2F application.

To fill this gap and to broaden the knowledge of the current sustainability level and trends of AFSC in the EU countries, this study proposes a multicriteria analysis (MCDA) application. The main objective of the work, therefore, is to measure for the first time the level of sustainability of the AFSC among the different EU countries, by means of MCDA. A framework of 50 indicators has been built, divided according to the Triple Bottom Line paradigm (Environmental, Economic, and Social dimensions)

(Elkington 1998) and considering the four main sectors within AFSC (Agriculture, Food industry, Distribution, and Consumption).

MCDA has been widely used for sustainability assessment in several contexts, proving its feasibility and flexibility (Bond et al. 2012; Cinelli et al. 2014; Diaz-Balteiro et al. 2017; Lombardi Netto et al. 2021). In particular, we propose the development of a composite indicator for each sector of the AFSC as well as a global one, using the method named Multiple Reference Point Partially Compensatory Indicator (MRP-PCI) (Ruiz and Cabello 2021). The use of such a method allows for including reference levels (thresholds, targets, etc.), which is a key point in sustainability studies (Ricciolini et al. 2022). MRP-PCI permits the use of reference levels for each indicator and produces composite indicators with different compensation degrees, along the supply chain. The opportunity of having different levels of compensation is a considerable advantage when different levels of analysis require diversified treatment, allowing considering the effect of compensation in terms of sustainability. For example, total compensation reflects a weak sustainability concept, in which bad performance of some criteria can be 'covered' by the very good performance of others. In contrast, the absence of compensation allows adherence to a strong sustainability idea, in which only cautious solutions are possible. The effects of a non-compensatory approach are more evident the earlier it occurs in the path of hierarchical aggregation on multiple levels. Therefore, the combination of different levels of compensation, null, total or partial, as in the present work, allows for modulation of the level of expression of sustainability.

Given that, the construction of a composite indicator implies several single indicators that may be in conflict with each other, it is natural to treat this problem as a multicriteria one. Many multicriteria making methods have been used to build composite indicators (see El Gibari et al. 2019, and references therein). When decision makers wish to use reference levels as benchmarks for the single indicators, distance-based methods are suitable for this purpose, given that they produce results that can be interpreted, as the position of each unit examined with respect to these benchmarks. On the other hand, the compensation issue is critical when building composite indicators: to a certain extent, poor performance in a given indicator can be compensated by good performance in other ones. The Multiple Reference Point Weak–Strong Composite Indicator methodology (MRP-WSCI) takes these two issues into account: reference levels are incorporated in the process and composite indicators for different compensation degrees can be built. A first version of this methodology, using two reference levels (reservation–aspiration), was proposed in Ruiz et al. (2011), and afterwards generalized to any number of reference levels in Ruiz et al. (2020). In El Gibari et al (2021), the advantages of the joint use of compensatory and non-compensatory schemes are analysed. This methodology has been successfully applied to sustainability assessment problems in several papers, even in agri-food sector (Cabello et al 2014, 2019, 2021; Ricciolini et al. 2022; Boggia et al. 2023). The Multiple Reference Point-based Partially Compensatory Composite Indicator (MRP-PCI), described in Ruiz and Cabello (2021), is an adaptation of the MRP-WSCI to the use of different compensation degrees for the single indicators considered.

The paper is organized as follows: paragraph 2 outlines the method used, i.e. MRP-PCI, while paragraph 3 reports the case study and is divided into several parts (description of the case study, framework of indicators, assumptions made); paragraph 4 reports the results and discussion; the main conclusions close the paper.

Method MRP-PCI (multiple reference point-based partially compensatory composite indicator)

For completeness, the MRP-PCI methodology, as applied in this paper, is summarized next.

Let us assume that we wish to build a composite indicator for J countries, making use of an initial set of I single indicators. The value of indicator i ($i=1, \ldots, I$) for country j ($j=1, \ldots, J$) will be denoted by x_{ij}. In this paper, statistical reference levels will be considered. Namely, the percentiles 25, 50 and 75 of the values of all European countries will be used, apart from the minimum and maximum values. These reference levels for indicator i will be denoted as

$$\left(q_i^{min}, q_i^{25}, q_i^{50}, q_i^{75}, q_i^{max}\right).$$

Besides, for each indicator i ($i=1, \ldots, I$), two more parameters are considered:

- A weight $\mu_i \geq 0$, measuring the relative importance of indicator i in the overall assessment;
- A compensation index $\lambda_i \in [0, 1]$, measuring to which extent a bad performance in indicator i can be compensated by better performances in other indicators, where 0 means no compensation and all and 1 means total compensation.

Given these elements, the following steps are taken to construct a partially compensatory composite indicator.

Step 1. All the indicators are bought down to a common scale, by means of the so-called achievement function. In our case, this function takes the following form (for an indicator of the-more-the better type):

$$s_{ij} = \begin{cases} \frac{25}{q_i^{25}-q_i^{\min}}\left(x_{ij} - q_i^{\min}\right) & \text{if} q_i^{\min} \leq x_{ij} \leq q_i^{25} \\ 25 + \frac{25}{q_i^{50}-q_i^{25}}\left(x_{ij} - q_i^{25}\right) & \text{if} q_i^{25} \leq x_{ij} \leq q_i^{50} \\ 50 + \frac{25}{q_i^{75}-q_i^{50}}\left(x_{ij} - q_i^{50}\right) & \text{if} q_i^{50} \leq x_{ij} \leq q_i^{75} \\ 75 + \frac{25}{q_i^{\max}-q_i^{75}}\left(x_{ij} - q_i^{75}\right) & \text{if} q_i^{75} \leq x_{ij} \leq q_i^{\max} \end{cases}$$

With these settings, s_{ij} takes a value between 0 and 25 if the country performs between the minimum value and percentile 25, a value between 25 and 50 if the country performs between percentiles 25 and 50, a value between 50 and 75 if the country performs between percentiles 50 and 75, and a value between 75 and 100 if the country performs between percentile 75 and the maximum value, for indicator i. Therefore, the achievement function s_i of indicator i is a piece-wise linear function (Ruiz and Cabello 2021).

Step 2. For each indicator i, and each country j, we build the so-called fully compensated value. If I_{ij} denotes the subset of indicators whose corresponding achievement functions take a value better or equal to indicator i for unit j, we define.

$$a_{ij} = \frac{\sum_{k \in I_{ij}} \mu_k s_{kj}}{\sum_{k \in I_{ij}} \mu_k}.$$

a_{ij} is the weighted average of s_{ij} and the rest of achievement function values that are at least as good as s_{ij}.

Step 3. For each indicator i and each country j, we build the so-called partially compensated achievement function:

$s_{ij}^{c} = s_{ij} + \left(a_{ij} - s_{ij}\right)\lambda_i$.

In the extreme cases, if no compensation is allowed for indicator i ($\lambda_i = 0$), then $s_{ij}^{c} = s_{ij}$, and if full compensation is allowed for indicator i ($\lambda_i = 1$), then $s_{ij}^{c} = a_{ij}$.

Step 4. For each country j, the partially compensatory composite indicator takes the following value:

$PCI_j = \min_{i=1,\ldots,I} \left\{ s_{ij}^{c} \right\}$.

As seen, the use of the partially compensatory approach (PCI) allows us to introduce different compensation degrees for different indicators or at different stages of the process. In general, the composite indicators obtained are less extreme than those obtained using a fully compensatory or a non-compensatory scheme and, besides, the range of variation of the composite indicator is usually greater, thus allowing better comparisons between the different countries (Ruiz and Cabello 2021). The problem is that this adds new subjective elements to the model and therefore, a greater cognitive burden for the experts. Just like it happens with the weights, other possibilities could of course be considered. Therefore, the results obtained in this study should be regarded as a proof of concept in terms of the application of the methodology suggested, where the subjective elements are clearly identified, so that different experts or decision makers could carry out the study based on their own preferences.

Usually, the indicators to be aggregated do not form a single group, but a system of indicators is designed, with a classification in dimensions, levels, etc. This is the case of the present paper, where the indicators are grouped in dimensions, and dimensions are grouped in sectors (Fig. 1). Thus, three successive aggregations need to be performed. The first aggregation consists in creating a partially compensatory composite indicator for each dimension of sustainability. Given that, the MRP-SCI takes values in the same scale as the achievement functions, the MRP-SCI values of the dimensions play the role of the achievement function in the next aggregation (which here is made for each sector of the AFSC). Given weights and compensation indexes for the three dimensions of a

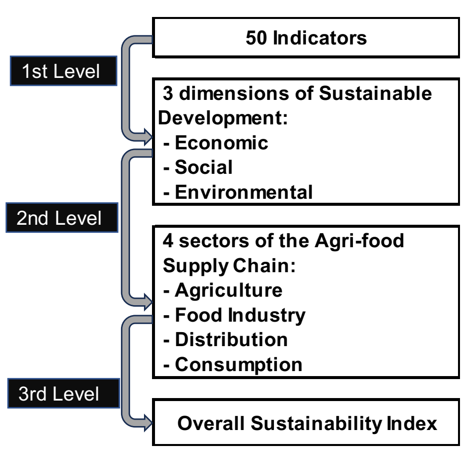

Fig. 1 Aggregation levels

given level, the procedure described above can be followed to build the MRP-SCI of that level, and so on.

Case study

The MRP-PCI method was applied to assess the sustainability of AFSC of 25-member states present within the EU, considering two different years, 2011 and 2019. The countries surveyed are: Austria, Belgium, Bulgaria, Cyprus, Croatia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Czech Republic, Romania, Slovakia, Slovenia, Spain, and Sweden. Luxembourg and Malta have been excluded because insufficient data were available. Therefore, they were removed to avoid stripping too many key indicators for the study. On the other hand, we included the United Kingdom due to its strategic relevance in the European AFSC. Thus, the analysis involved 26 countries in total.

Indicators

To assess the sustainability of European agri-food supply chains, 50 indicators were identified, categorized according to the four sectors that make up the supply chain: Agriculture and livestock farming, Food industry, Distribution and Consumption. Each indicator was then categorized according to the three dimensions of sustainable development (environmental, economic and social) that it allows to be monitored. The source of the data is the Eurostat database. The selection of the indicators has been guided by some criteria. First of all, the relevance of each indicator to describe one dimension of sustainable development within a certain sector was considered. Then, we considered the possibility to measure such indicator at the scale and time horizon chosen by this study, which is subject to the availability of data, not abundant in comparison with the needs.

The indicators chosen can measure both a state or a change, because the topics treated in the analysis are very different among each other, representing different trends or phenomena. For this reason, we chose to capture both kinds of dynamics, also because multicriteria analysis allows treating different kinds of indicators together.

Tables 1, 2, 3 and 4 report indicators for the sector of Agriculture and livestock farming (Table 1, 19 indicators), Food industry (Table 2, 10 indicators), Distribution (Table 3, 14 indicators), and Consumption (Table 4, 7 indicators).

Aggregation and weighting

One of the main advantages of the MRP-PCI methodology lies in the possibility to aggregate a plurality of indicators. Combining a set of indicators makes possible to obtain a single result (composite indicator) that holds a set of information in a single matrix, easy to read and interpret. In this paper, three different aggregations were made (Fig. 2):

(1) The first level of aggregation includes all 50 indicators, grouped into three composite indicators covering the three dimensions of sustainable development (economic, social and environmental) for each of the four sectors of the AFS identified;
(2) The second level joins the three dimensions within each sector;

Table 1 Indicators of the Agricultural dimension divided into the three dimensions of sustainable development with the measurement unit (in bracket)

Agriculture		
Economic indicators	**Social indicators**	**Environmental indicators**
1.1.1 Standard economic output of Agriculture per hectare (€/ha)	1.2.1 Index of the real income of factors in agricultural per annual work unit (%)	1.3.1—Organic UAA as a percentage of total UAA (%)
1.1.2—Standard economic output of Farming per holding (€)	1.2.2—Number of hours worked per week in agriculture (average hours per week)	1.3.2—Kg of Pesticides sold per hectare (kg/ha)
1.1.3—Standard economic output of Arable crops per hectare (€/ha)	1.2.3—Number of hectares managed by owners less than 40 years old (%)	1.3.3—Nitrogen balance per hectare (nitrogen/ha)
1.1.4—Standard economic output of horticultural crops per hectare (€/ha)	1.2.4—Percentage of holdings with owner with full education (%)	1.3.4—Phosphorus balance per hectare (phosphorus/ha)
1.1.5 Standard economic output of perennial crops per hectare (€/ha)	1.2.5—Number of persons employed/number of farms (employees/farms)	1.3.5—Tonnes of CO2 produced in agriculture per hectare (ton/ha)
1.1.6—Research and development funds per hectare (€/ha)		1.3.6—Irrigated UAA over total UAA (%)
		1.3.7—Energy consumed in agriculture per hectare (KW/ha)
		1.3.8—Kg of waste produced by agriculture per capita (kg/person)

Table 2 Indicators of the Food industry dimension divided into the three dimensions of sustainable development with the measurement unit (in bracket)

Food industry		
Economic indicators	**Social indicators**	**Environmental Indicators**
2.1.1—Production value in € per food processing company (€)	2.2.1—Social security cost per employee per company (€/person)	2.3.1—Energy consumed per company (€)
2.1.2—Share of labour costs in € per employee (%)	2.2.2—Share of persons employed (%)	2.3.2 Circular material use rate (%)
2.1.3—Investment rate in food processing (%)		2.3.3—Share of renewable energy in gross final energy consumption (%)
2.1.4—Profit in € per person employed (€)		2.3.4—Kg of waste produced by food processing per capita (€/person)

(3) The third and last level defines the final overall sustainability index for the countries, ranging between 0 and 100.

The three aggregations have been repeated for the two reference years (2011 and 2019) for each EU member, applying the MRP-PCI scheme. For each aggregation step, the application of weights, which define the importance of each individual criterion in the final composite measure, was performed.

The weight assessment process was executed with a participatory approach, through the selection of experts in the field to incorporate both the scientific and the political dimension into the evaluation. Eight experts were chosen, based on their field experience and academic backgrounds, particularly within European Union universities.

Table 3 Indicators of the Distribution dimension divided into the three dimensions of sustainable development with the measurement unit (in bracket)

Distribution		
Economic indictors	**Social indicators**	**Environmental indicators**
3.1.1 Production value in € per company (€)	3.2.1—Persons employed per company (people/companies)	3.3.1—Transport performed over distances of less than 500 km (%)
3.1.2—Production value in € per wholesale company (€)	3.2.2—Distribution centre density (inhabitants/centre)	3.3.2 Grams of CO2 produced per TKM (tonne-kilometre)
3.1.3—Production value in € per non-food specialized company (€)	3.2.3—Total wages of persons employed in distribution companies per employee (€)	3.3.3—Kg of waste produced by distribution per person (kg/person)
3.1.4—Production value in € per food specialized company (€)	3.2.4—Security costs per employee per company (€)	
3.1.5—Profit in € of the company per person employed (€)		
3.1.6—Investment rate per company (%)		
3.1.7—Exported food production/imported food production (export/import) (€)		

Table 4 Indicators of the Consumption dimension divided into the three dimensions of sustainable development with the measurement unit (in bracket)

Consumption		
Economic indicators	**Social indicators**	**Environmental indicators**
4.1.1—Food consumption in € per person	4.2.1—Overweight persons	4.3.1—Kg of waste created by consumption per person
4.1.2—Consumption of € in restaurants and hotels out of total consumption	4.2.2—Obese persons	4.3.2—Number of quality labels
4.1.3—Consumption of € in catering out of total consumption		

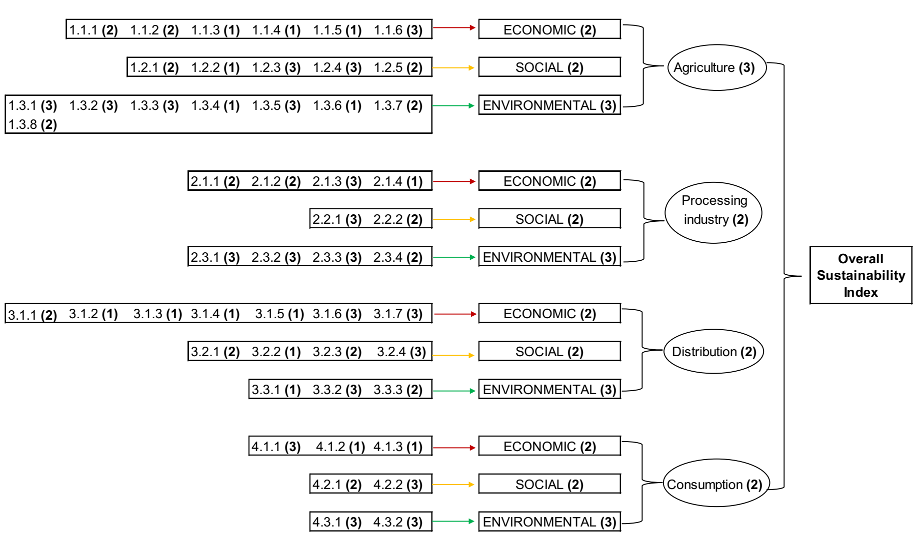

Fig. 2 Aggregation and weighting scheme of composite (the weights are reported in brackets)

Table 5 Weight allocation scale

Value	Rating
Important	1
Very Important	2
Critically Important	3

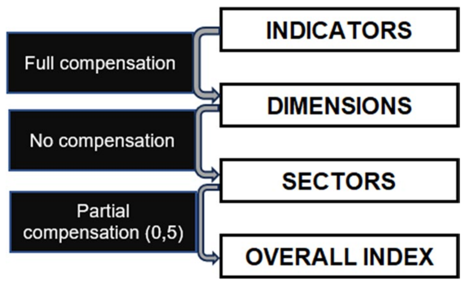

Fig. 3 Compensation Index

Through online focus groups, the experts were asked to assess the importance of each indicator within each sub-dimension and of each sub-dimension within each dimension. They assigned a value on a weight scale ranging from 1 to 3, where a value of one corresponded to a significant assessment, two to a highly important assessment, and three to a critically important assessment (Table 5).

The final consensus weights were therefore obtained after the focus group discussions (assignment reported in Fig. 2).

Compensation index

The possibility of providing a different compensation index λ_i for each indicator is one of the many advantages of the MRP-PCI method, allowing the most realistic possible behaviour of a Decision Maker to be simulated. λ_i is a coefficient, to be set between 0 and 1, indicating to what extent a poor performance of an indicator i can be compensated by better values of other indicators. However, it must also be noted that there is a strong relationship between the weights and the compensation indices; in fact, the greater the weight of an indicator, the more relevant it is and therefore the lower the compensation it is.

In this paper, three different compensation indices (Fig. 3) were assigned for each of the aggregation steps:

- $\lambda_i = 1$, full compensation between indicators (a bad value of indicator i can be fully compensated by better values achieved by other indicators)
- $\lambda_i = 0$, no compensation among dimensions (a bad value of indicator i cannot be compensated by better values achieved by other indicators)
- $\lambda_i = 0.5$, medium compensation between sectors (a bad value of indicator i can be partially compensated by better values achieved by other indicators).

Between indicators of the same dimension, total compensation ($\lambda_i = 1$) was allowed, assuming that indicators with negative values can be compensated by those that perform better if they belong to the same dimension.

The basic idea is to allow for full compensation between indicators of the same dimension, since by dealing with related topics there is no risk of neglecting a fundamentally important aspect, as might be expected if full compensation occurs, for instances, between the different dimensions of sustainability.

Thus, since the compensation happens within dimensions, this does not affect the sustainability, allowing nevertheless to follow a strong approach. Going forward with the aggregations, it is assumed that the decision maker will implement less compensation between the composite indicators obtained, following the strong sustainability theory; this presupposes that 'human capital' and 'natural capital' are complementary, but not interchangeable. Therefore, among the three dimensions of sustainable development, $\lambda_i = 0$ (no compensation) was used. The result obtained reflects the worst value achieved in one of the three dimensions of sustainability, with the environmental one having a higher weight than the other two. This choice was made because strong sustainability argues that certain functions performed by the environment cannot be duplicated by human capital and emphasizes the ecological scale over economic gains.

Finally, for the last aggregation, among the sectors of the agri-food supply chain, partial compensation ($\lambda_i = 0.5$) was used, assuming that a bad value of one sector can be partially (half) compensated by better values achieved in the other sectors, considering the greater weight assigned to the agriculture sector.

Results and discussion

In this section, we present the Overall Sustainability Index (OSI), which represents the global degree of sustainability of the AFSC in each country. Then, we will analyse the four sectors of the AFSC (Agriculture, Food industry, Distribution, and Consumption) and how each dimension of sustainability affected the final performance.

The Overall Sustainability Index (OSI) presents a narrow range of values (Fig. 4). This narrow range is mainly due to the second aggregation step, where no compensation is allowed among the three dimensions (Economic, Environmental, and Social) to respect the principle of Strong Sustainability. Therefore, the resulting value is the worst achieved by each dimension. Moreover, the partial compensation ($\lambda_i = 0.5$) between the four sectors contributes again to narrow the range. As Fig. 4 shows, the indices related to the four sectors have a wider range of values, although with some differences across them. In particular, Food Industry reveals the narrowest range and Consumption the widest one, indicating a different variability between the countries, smaller for Food Industry than for Consumption. This could be probably due to the fact that Food industry, and all the productive sectors, share common rules and compete in the same market, while Consumption is strictly linked to people behaviours.

OSI: Overall sustainability index

As shown in Table 6, the mean and median values are very close for all the indices, especially for Distribution and Food Industry, thus indicating that the different sectors are not significantly different. In addition, for both Consumption and OSI, a greater

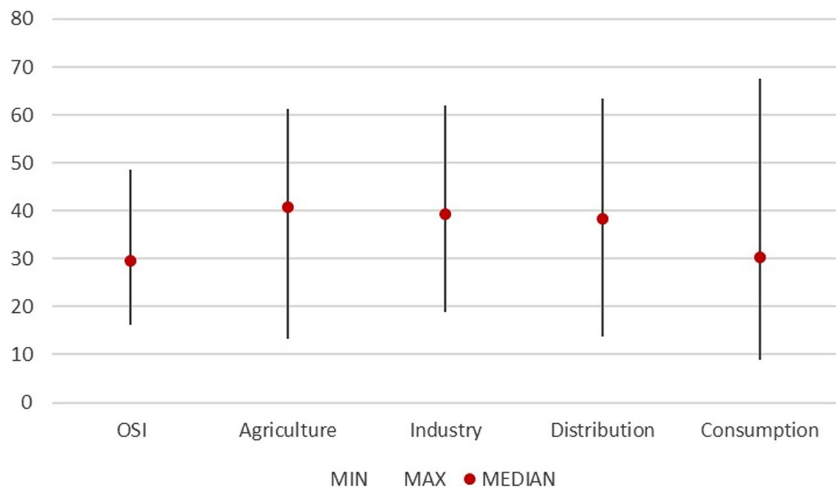

Fig. 4 Range of values and median of dimension indices

Table 6 Delta between Median and Average value of the dimensions

	OSI	Agriculture	Food Industry	Distribution	Consumption
AVERAGE	29.66	40.74	39.25	38.38	30.41
MEDIAN	32.25	37.28	38.80	38.31	33.33
Delta	-2.59	3.46	0.45	0.07	-2.92

variation can be seen, and the mean value is lower than the median value, indicating negative skewness.

The correlation between the composite indices of the 26 EU countries in relation to the four sectors that make up the OSI was also analysed, but no correlation can be considered significant or relevant.

Since the reference levels used are statistical, minimum, percentiles 25, 50, 75 and maximum, a good value indicates that a particular country performs better than the others, while a bad value indicates that it performs worse than the others. Thus, a high value is not necessarily a good result in absolute terms, and a low value can also be a good value in absolute terms. In comparative terms, the best-performing countries are those belonging to the very high class, represented by a value above 75 up to a maximum of 100, while the worst-performing countries are those belonging to the very low class, represented by a value of the composite indicator between 0 and 25.

Considering the OSI value, it can be seen that no country has an overall value above 50 (Fig. 5). From a strong sustainability perspective, therefore, all countries are far from the very high class and need to improve at least their performance in one dimension. The different levels of compensation in different levels of aggregation certainly plays a role in this result. In fact, the second level of aggregation does not allow for any compensation, immediately showing situations of lower sustainability in one of the dimensions considered.

To analyse the results, we identified three groups, dividing the countries in the range between 25 and 50 in two subgroups, given the large number of countries present, using

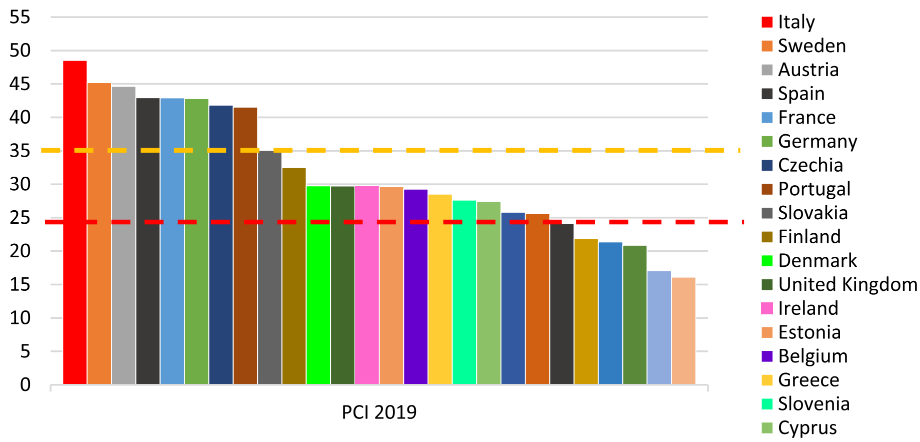

Fig. 5 Overall Sustainability Index: countries distribution (reference year 2019). Red and yellows lines identify the division in three groups

35 as threshold, while keeping the other countries in the very low class together (values < 25). So, it was possible to identify: Group 1 contains the best-performing countries (values above 35), Group 2 comprises the countries with values between 25 and 35, and Group 3 contains the worst-performing countries (below 25).

Group 1: best-performing countries

The countries belonging to this first group (Fig. 5) show values above the median value for the OSI and in most cases also for the four sectors. Only for Distribution, four countries are below the median value (France, Spain, Germany, and Slovakia).

Italy leads the first group, achieving the best level of sustainability of the AFSC with a value of 48.53. It is followed by Sweden, Austria, Spain, France, Germany, the Czech Republic, Portugal and Slovakia (Fig. 5). Italy has good performance for all sectors, achieving the best one for Consumption.

In the Food Industry and Distribution sectors, the highest value for this group is achieved by Austria, and in the Agriculture sector by Sweden (Fig. 6). With reference to the Austrian situation, Hambrusch and Quendler (2009) highlighted that important developments and trends occurred during the years in the Austrian fruit and vegetable retail sector; among other factors, societal developments influenced and increased the demand for fruit and vegetables during the last years, and regional organic producers gained increasing importance. Portugal, on the other hand, has the worst value in Agriculture due to negative results in the economic dimension (Fig. 7a) and also in the Food Industry sector, given the low values in the social dimension (Fig. 7b). In contrast to Austria and Sweden, that experience problems in the environmental dimension of Consumption (Fig. 7d), Portugal has a high value in this sector; in relation to Consumption, it achieves good results in all the three dimensions of sustainability (Fig. 7d).

France manages to have the best value of all countries for Consumption, but at the same time has the worst result for Distribution. This negative value is due to the low value of the environmental dimension, as no compensation is allowed in the aggregation between the dimensions of sustainability; therefore, even if the economic and social dimensions perform well, the country still scores negatively in this sector (Fig. 7c). In

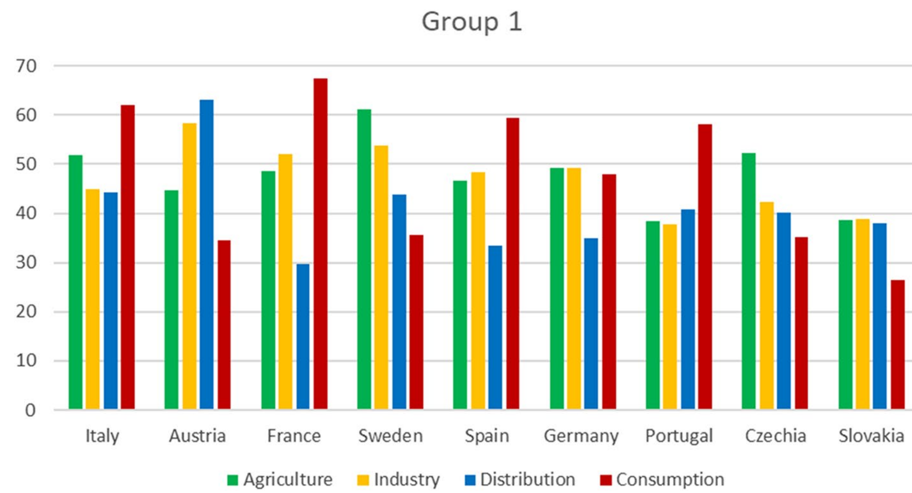

Fig. 6 Four AFSC sectors (Group 1)

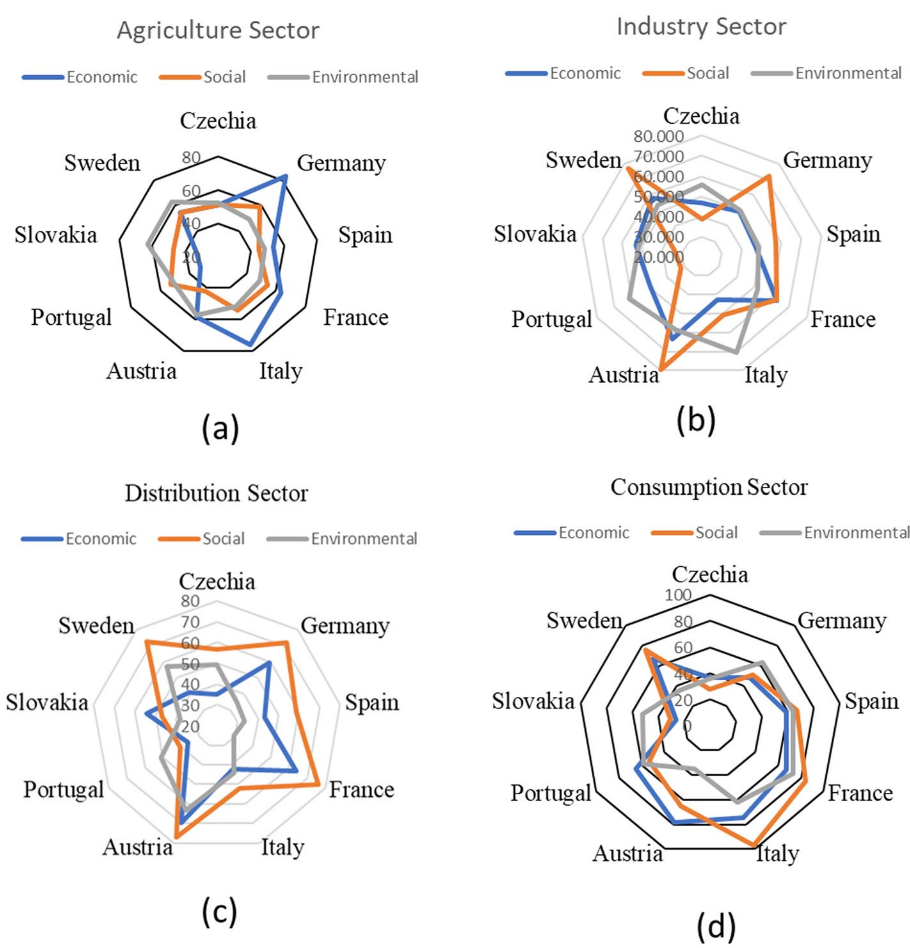

Fig. 7 Sustainability Dimensions in each Sector- Group 1

particular, France shows a low performance for Indicator 3.3.2 (Fig. 8), which refers to the grams of CO_2 that are produced with respect to the kilometres transported. In this context, the work of Hawkins and Dente (2010) found that the total emissions associated with French household consumption were estimated to be 627Mt CO_2eq, or 11t CO_2eq per capita. Of these, 3% were associated with the transportation of goods within France and 10% with transport of goods outside or into France. Road transport contributed the highest share to the transport of all goods (with the exceptions of coal and coke and petroleum).

Thus, generally speaking, in Group 1, a good performance for Distribution is associated with a bad one for Consumption and vice versa: this is particularly true for France, Spain, and Austria. The Czech Republic does not show good values in general but performs well in Agriculture (Fig. 6). Slovakia presents the worst values in the Consumption sector, particularly in the economic and social dimensions (Fig. 7d). In the report by Galli et al. (2018), it is emphasized that regulations aimed at reducing the environmental impacts of food production were not closely linked to how food was consumed. Additionally, the Common Agricultural Policy granted subsidies to "green" production processes, but the majority of these subsidies primarily concerned production actors. This underscores the importance of sustainability policies addressing issues related to consumption as well as production models. Our results seemed to partially support these outcomes.

Group 2: second-best countries

The second group is the largest, including Finland, Denmark, the United Kingdom, Ireland, Estonia, Belgium, Greece, Slovenia, Cyprus, the Netherlands, and Hungary (Fig. 5). In this second group, every country has at least one sector performing under the median level, even severely, although the others have good performance.

Looking at the performance of the singular sectors, Denmark confirms the trend of group 1, having the best performance in the group for Distribution and the worst for Consumption (Fig. 9), which is also the third worst value among all the countries. Such a bad result is due to the low value of the environmental dimension (Fig. 10d). Specifically, it can be noted how poor the results are for Indicator 4.3.2 (number of quality labels) and for Indicator 4.3.1 (kg of waste created by consumption per person) (Fig. 11). Indeed, the generation of municipal waste per capita in Denmark increased from 740 kg per capita in 2006, reaching its peak in 2011 at 862 kg per capita. The trend plateaued after 2011, and from 2012 to 2019, waste generation remained at the same level, fluctuating between 810 and 840 kg per capita per year, before slightly decreasing in 2020 to 814 kg. These values are among the highest in Europe, compared to the 2020 per capita European average of 517 kg (European Environment Agency 2023).

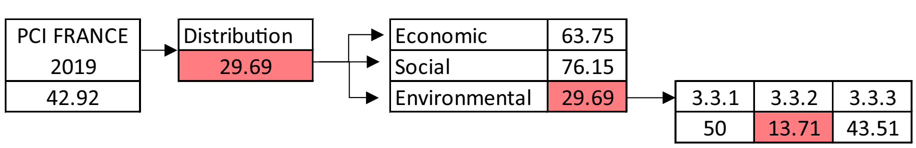

Fig. 8 France PCI graph of distribution 2019

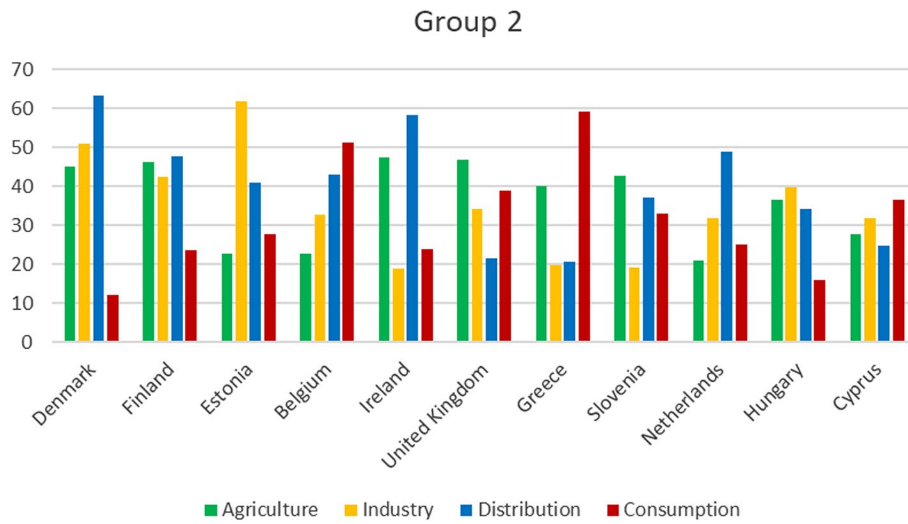

Fig. 9 Four components of the overall PCI of Group 2

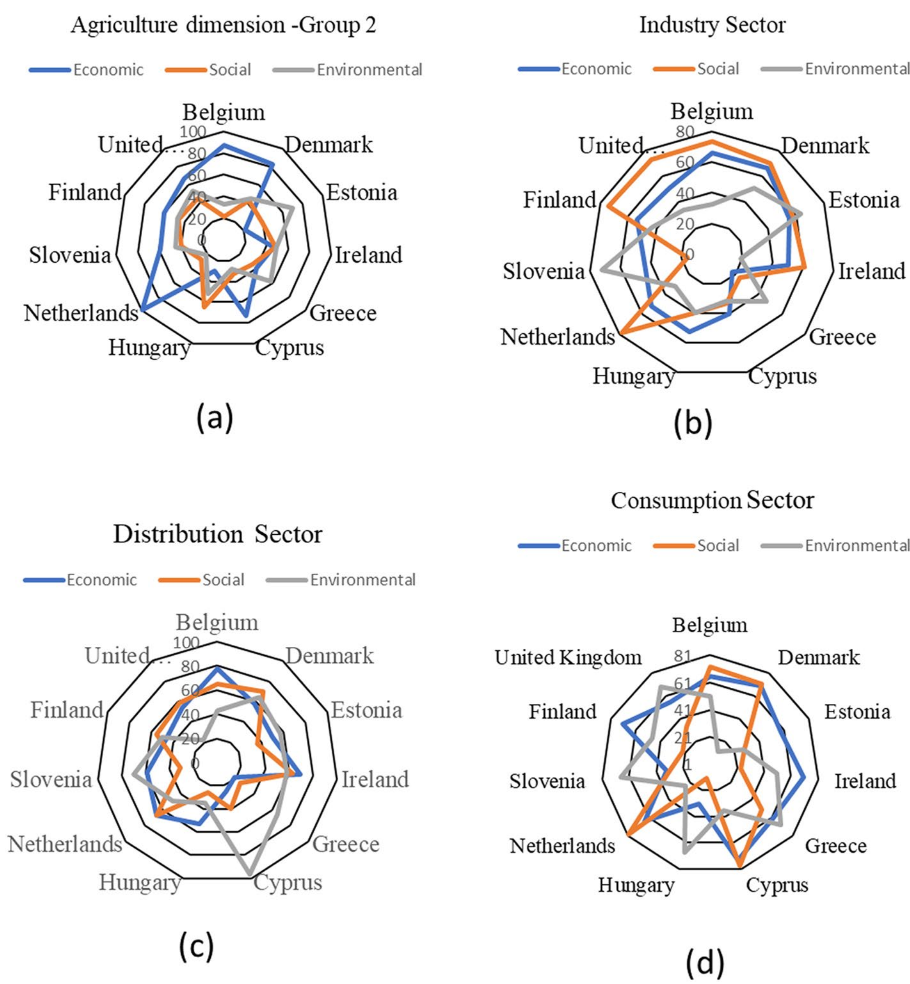

Fig. 10 Sustainability Dimensions in each Sector- Group 2

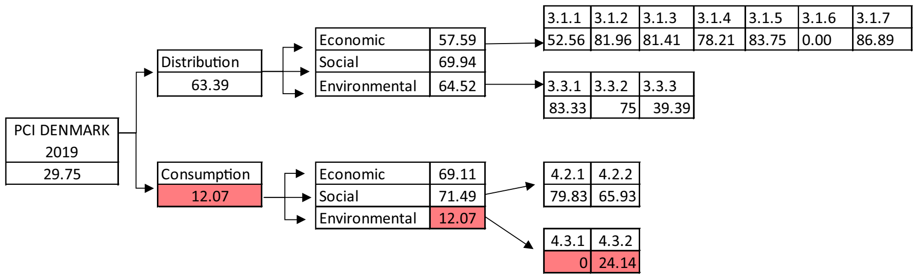

Fig. 11 Denmark PCI graph of distribution and Consumption 2019

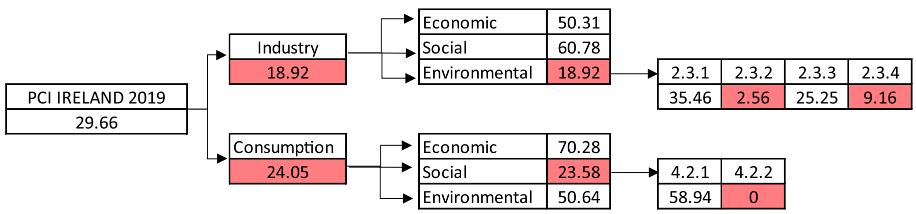

Fig. 12 Ireland PCI graph of Industry and Consumption 2019

A particular trend for Consumption is that the four nations that have their best performance in the environmental dimension also have the worst values in the social dimension. Similarly, all of the nations that have as their best the social dimension also have as their worst the environmental dimension. Moreover, the majority of the countries have the Environmental (5 out of 11) or Social (4 out of 11) dimension as the worst dimension.

Ireland also has a very low value in the Consumption dimension as well as in Food Industry, while it has a good level of sustainability in the Distribution one (Fig. 10b–d). In particular, it has problems in the environmental dimension of Food Industry (Fig. 10b), due to poor performance in the rate of recycled material used (Indicator 2.3.2) and Kg of waste produced by food industries (Indicator 2.3.4) (Fig. 12). In the consumption sector, on the other hand, the negative value concerns the social dimension (Fig. 10d) due to the very high rate of obese people (Indicator 4.2.2) (Fig. 12). Indeed, from the results of the study conducted by Pineda et al. (2018), in which they projected the prevalence of obesity in European regions to assess the feasibility of achieving the WHO's goal to halt the increase in obesity to 2010 levels by 2025, it emerges that Ireland will have the highest prevalence among all the countries, with 43% of the population projected to be obese by 2025.

For Ireland it is worth to note how the score of Consumption does not coincide with the value of its worst dimension, which is the social one, as it happens for Industry, which has the environmental dimension as its worst. This occurs because the environmental dimension has the greatest weight among the three and thus in the case of Consumption influences the sector value by raising it slightly, while in Industry it prevails over the other two.

The Consumption sector has bad performance also for Hungary due to the low performance of Indicators 4.2.1 and 4.2.2 (overweight and obese persons) in the social dimension (Fig. 10d). Belgium, on the other hand, performs the best in Consumption and the worst in Agriculture. To note how this sector has very good economic sustainability,

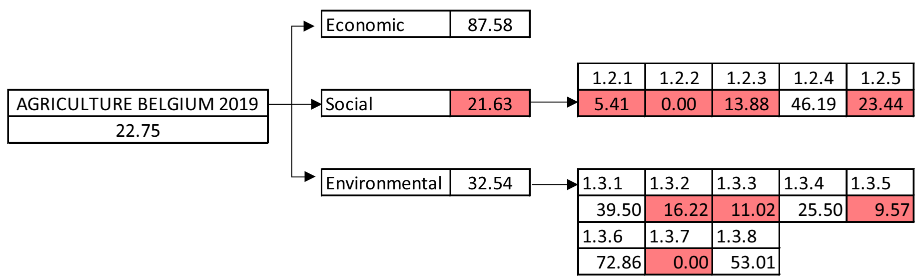

Fig. 13 Belgium PCI graph of agriculture 2019

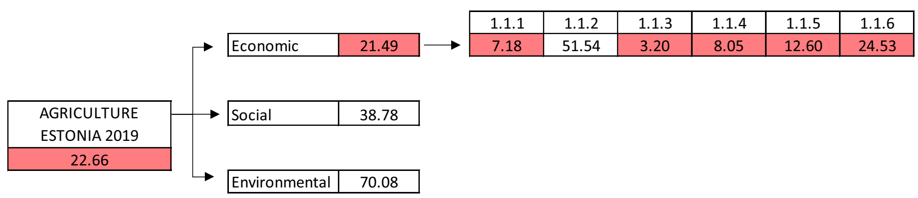

Fig. 14 Estonia PCI graph of agriculture 2019

while the social one is poor (Fig. 10a). For the Social dimension, 4 out of 5 indicators are insufficient, reaching the worst performance for Indicator 1.2.2 (number of hours worked per week in agriculture) (Fig. 13). Some of these outcomes are confirmed by the literature: for instance, Pereira Andrade et al. (2022) found that agriculture sector can be considered a very low risk activity in Belgium, but it is also considered a very low-paid sector. The same is for the environmental dimension of agriculture (Fig. 10a), which shows warning signs for energy consumption per hectare (Indicator 1.3.7) (Fig. 13). As noted by Rokicki et al. (2021) in the period 2005–2018, the agricultural sector in Belgium has a consumption comparable to the France, having a smaller agricultural surface. One of the causes can be the high presence of greenhouse production, such as the strawberries (Mousavi et al. 2023).

The best country in the group for Consumption is Greece, which has good levels of sustainability in all the three dimensions (Fig. 10d). However, it shows bad results for Food Industry and Distribution, in both cases due to the social and economic dimensions, while the environmental one has good values (Fig. 10).

Estonia has the best value for Food Industry in the group thanks to very good values in all three dimensions (Fig. 10b). In the Agriculture sector, however, it has low economic sustainability (Fig. 10a), mainly because of agricultural economic production (Indicator 1.1.1, 1.1.3, 1.1.4, 1.1.5), and limited funds for research and development in this sector (Indicator 1.1.6) (Fig. 14). Estonia can be considered in as one of the EU countries in which the agricultural gross value added has increased less in comparison with the other member states, or even decrease between 2000–2016 (Zsarnóczai and Zéman 2019).

Tail lights countries

Group 3 is the smallest one: we find Lithuania, Poland, Latvia, and Croatia, having values ranging from 20 and 25, and Bulgaria and Romania, with values below 20, presenting the worst overall performances (Fig. 5). In particular, Bulgaria has very low values in all the four sectors, while Romania only performs better in the Distribution dimension (Fig. 15). In general, all the countries in the group perform under the median values in all the sectors, with very few exceptions, like Poland for Agriculture and Food Industry, and Latvia for Food Industry and Distribution. The good results of the Polish Agriculture sector are mainly linked to the social sub-dimension. However, these good results are not evenly distributed across the country: as pointed out by Sroka et al. (2019) socio-economic changes, especially generational turnover, have been significantly sustained in the peri-urban areas of major centres (metropolises), where both exogenous and endogenous factors have led to profound changes. The authors, in particular, emphasize the role played in these areas by the high level of education of entrepreneurs. On the other hand, Poland has low values in the Distribution due to the bad value of the environmental dimension (Fig. 16).

In particular, the Polish Distribution has problems in reducing the transport of raw products to processing and manufacturing companies to distribution centres, carried out over distances of less than 500 km, which indicates the threshold of lower product perishability (Indicator 3.3.1); moreover, there was an increase in the CO_2 grams produced in relation to the kilometres that the distribution sector covers (Indicator 3.3.2) (Fig. 17). The greatest contributors to the GHG emissions in the transport sector in Poland are by far road vehicles with combustion engines (Bebkiewicz et al. 2020). In 2017, they accounted for 96.52% of GHG emissions in this sector, which correspond to 14.78% of the total GHG emissions in the country (Poland's National Inventory Report 2019).

The Agriculture sector of Romania, Bulgaria, Latvia, and Lithuania has very low values (Fig. 15), and, as shown in Fig. 16a, problems mainly concern the economic dimension. For some of those countries, the accumulated lag is such that an alignment with the performance of Western member states cannot be expected even in the long run. For instance, in their study Feher et al. (2022) analysed the historical evolution of the Romanian agriculture sector, finding that Romania cannot reach the average level of the EU until 2040.

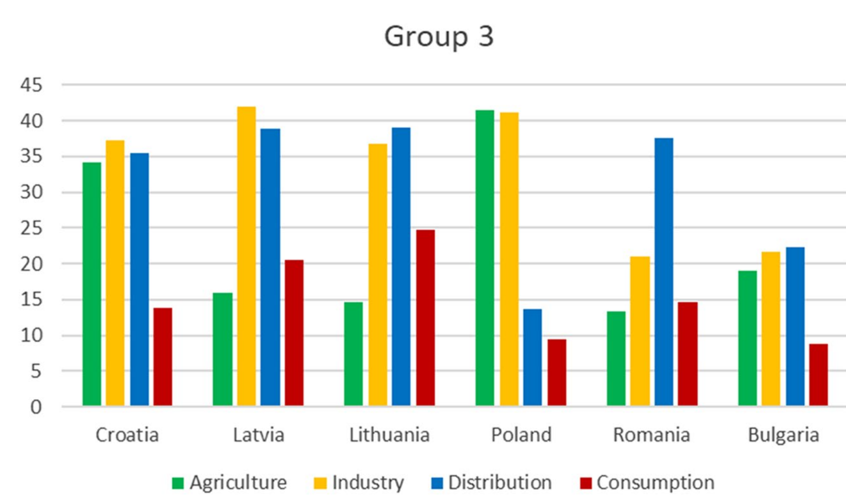

Fig. 15 Four components of the overall PCI of Group 3

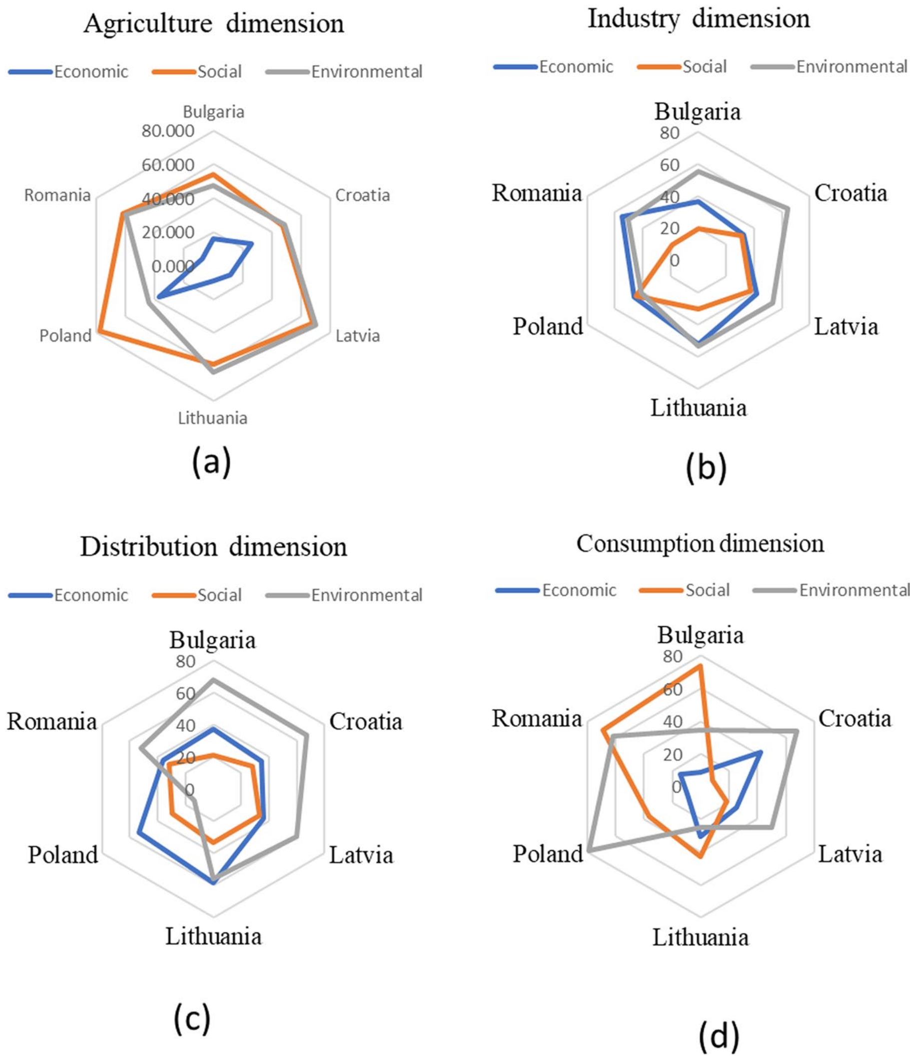

Fig. 16 Sustainability Dimensions in each Sector- Group 3

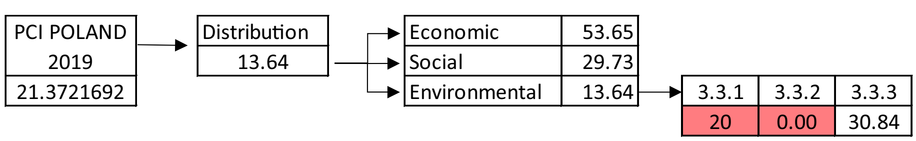

Fig. 17 Poland PCI graph of distribution 2019

In the Food Industry sector, only Romania and Bulgaria have very low values (Fig. 15), finding the greatest issues in the social sub-dimension (Fig. 16b).

In the consumption sphere, on the other hand, all states have poor results (Fig. 15). As shown in Fig. 16c, the values of the environmental dimension are good for all the countries, while some problems can be attributed to the social dimension for Croatia and Latvia and to the economic one for Lithuania, Romania, Bulgaria, and also for Latvia.

Trends over the years

Comparing the results of 2019 with those of 2011 (Fig. 18), it is possible to analyse how the performance of the states changed between the 2 years with respect to the overall ranking. In fact, the reference levels and respective values were calculated for the 2 years separately. Therefore, it is not effectively possible to measure the improvement or worsening of each individual country from an absolute level, but it is possible to analyse the differences within the EU context. That is, we assess the evolution of the performance of each country, as compared to the evolution of the performances of all the countries considered.

In particular, a relative worsening in the performance of five countries (Denmark, Estonia, Austria, Finland and Sweden) can be observed, while the major improvements are registered for Czechia, Spain, France, Cyprus and Slovakia.

The remaining countries made some slight improvements in the relative sustainability performance of their AFSC or remained stable over the years. However, unchanged results cannot be considered a good outcome: Bulgaria and Romania remained at the bottom of the ranking in the two reference years, thus showing a persistent bad situation as compared to the general European context. Moreover, comparing only 2 years does not allow us to assess the speed of change when present. In particular, we cannot tell whether the improvement proceeds at a pace that accelerates or decelerates over time.

Finland in 2011 achieved an OSI value of 39.89, while in 2019 it was 32.48; with a decrease between the 2 years of 18.6%, it represents the greatest deterioration. Considering the singular sector, only Agriculture has improved in 2019 compared to 2011, while all the other sectors have significantly deteriorated (Table 7). The greatest decrease is observed in the Consumption sector, particularly in the social and environmental dimensions. The number of overweight and obese persons (Indicator 4.2.1, 4.2.2) increased significantly, as well as the kg of waste produced per person (Indicator 4.3.1), while the number of quality labels decreased (Indicator 4.3.2). Other alarming signals can be found in the distribution sector. In the economic dimension, there was a reduction in the food products exported compared to that imported from the country (Indicator 3.1.7), and also the investment rate of companies greatly reduced

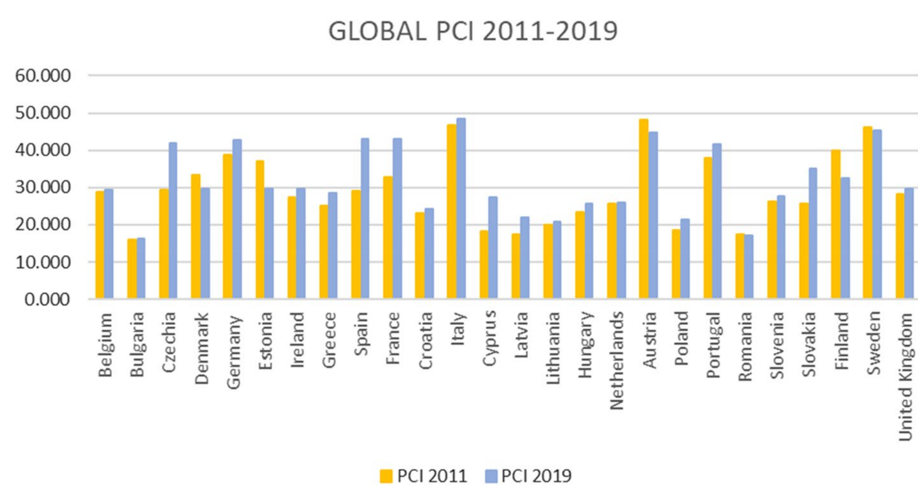

Fig. 18 Overall Sustainability Index: trend between 2011 and 2019

Table 7 Finland OSI and its components 2011 and 2019

	2011	2019	Delta	%
PCI FINLAND	39.89	32.49	− 7.41	− 18.6
Distribution	48.56	47.78	− 0.78	− 1.6
Economic	47.84	46.68	− 1.17	− 2.4
3.1.1 Production value in € per company	85.81	100	14.19	16.5
3.1.2 Production value in € per wholesale company	71.29	64.4	− 6.89	− 9.7
3.1.3 Production value in € per non-food specialized company	74.99	84.7	9.67	12.9
3.1.4 Production value in € per food specialist company	90.89	100	9.11	10.0
3.1.5 Profit in € of the company per person employed	80.41	77.3	− 3.12	− 3.9
3.1.6 Investment rate per company	20.75	11.3	− 9.50	− 45.8
3.1.7 Exported food production/imported food production	7.56	0	− 7.56	− 100.0
Social	63.55	55.40	− 8.15	− 12.8
3.2.1 Persons employed per company	50.41	24.14	− 26.27	− 52.1
3.2.2 Number of inhabitants per distribution centre	6.64	10.98	4.35	65.5
3.2.3 Total wages of persons employed in distribution companies per employee	82.24	76.29	− 5.95	− 7.2
3.2.4 Security costs per employee per company	78.84	*77.13*	− 1.71	− 2.2
Environmental	52.42	49.90	− 2.52	− 4.8
3.3.1 Transport performed over distances of less than 500 km	76.34	50.00	− 26.34	− 34.5
3.3.2 Grams of CO2 produced per TKM (tonne-kilometre)	38.89	67.86	28.97	74.5
3.3.3 kg of waste produced by distribution per person	60.77	22.93	− 37.84	− 62.3
Consumption	39.61	23.76	− 15.84	− 40.0
Economic	67.19	71.99	4.80	7.1
4.1.1 Food consumption in € per person	86.03	94.14	8.11	9.4
4.1.2 Consumption € in restaurants and hotels out of total consumption	27.27	26.85	− 0.42	− 1.5
4.1.3 Consumption € in catering out of total consumption	50.61	50.68	0.08	0.1
Social	34.41	23.14	− 11.27	− 32.7
4.2.1 Overweight persons	40.63	22.14	− 18.49	− 45.5
4.2.2 Obese persons	30.26	23.81	− 6.45	− 21.3
Environmental	61.80	47.79	− 14.02	− 22.7
4.3.1 kg of waste created by consumption per person	78.30	67.01	− 11.29	− 14.4
4.3.2 Number of quality labels	45.31	28.57	− − 16.74	− 36.9
Industry	53.22	42.45	− 10.76	− 20.2
Economic	53.99	53.37	− 0.63	− 1.2
2.1.1 Production value in € per food processing company	76.27	75.98	− 0.29	− 0.4
2.1.2 Share of labour costs in € per employee	65.00	75.32	10.32	15.9
2.1.3 Investment rate in food processors	25.00	17.74	− 7.26	− 29.0
2.1.4 Profit in € per person employed	74.41	71.10	− 3.31	− 4.4
Social	68.13	74.36	6.23	9.1
2.2.1 Safety costs per number of persons employed per company	76.15	75.63	− 0.52	− 0.7
2.2.2 Share of persons employed	56.12	72.47	16.35	29.1
Environmental	53.22	42.45	− 10.76	− 20.2
2.3.1 Energy consumed per company	24.12	21.04	− 3.09	− 12.8
2.3.2 Circular material use rate	79.93	42.44	− 37.49	− 46.9
2.3.3 Change in renewable energy used	79.01	80.61	1.60	2.0
2.3.4 kg of waste produced by food processors per capita	18.10	17.36	− 0.73	− 4.0

(Indicator 3.1.6). Regarding the social dimension, there was a decrease in the number of average employees per company (Indicator 3.2.1), as well as a reduction in the transport of raw products to processing and manufacturing companies to distribution centres, carried out over distances of less than 500 km (Indicator 3.3.1), in the environmental dimension. In addition, the level of circularity in the sector declined over the 2-year period, with an increase in waste generation per capita (Indicator 3.3.3) and a sharp deterioration in the use of recycled material within industrial production processes (Indicator 2.3.2).

Looking at the performance of individual sectors and considering the nations that have worsened (Denmark, Estonia, Finland, Austria and Sweden), we can see that Consumption values have always decreased (Fig. 19). In addition, Denmark's deterioration was also related to distribution; for Estonia the worsening was caused by Agriculture, as well as for Austria in addition to Food industry, which also worsened for Sweden.

The current work presents some limitations. The assessment conducted is relative within the context of the European Union, as the reference levels used were derived from the range of values of the country, using a statistical approach. A good value, therefore, indicates that a particular country performs better than others, while a bad value indicates that it performs worse than others. Thus, a high value can be negative, and a low value can be positive in absolute terms. This issue could be overcome in the future analysis by using absolute levels defined by experts or, for example, by using targets derived from policies.

Since the evaluation is relative, it is challenging to highlight the progress made by some countries on specific issues in an absolute sense. However, it has been possible to analyse them comparatively among EU countries.

Moreover, in this kind of analysis, we chose a set of indicators that do not consider interdependencies among the different countries (e.g. the issue of intra-EU and international trade). However, international trade, in particular within the EU borders, is an interesting aspect to be analysed and it could be examined in further works.

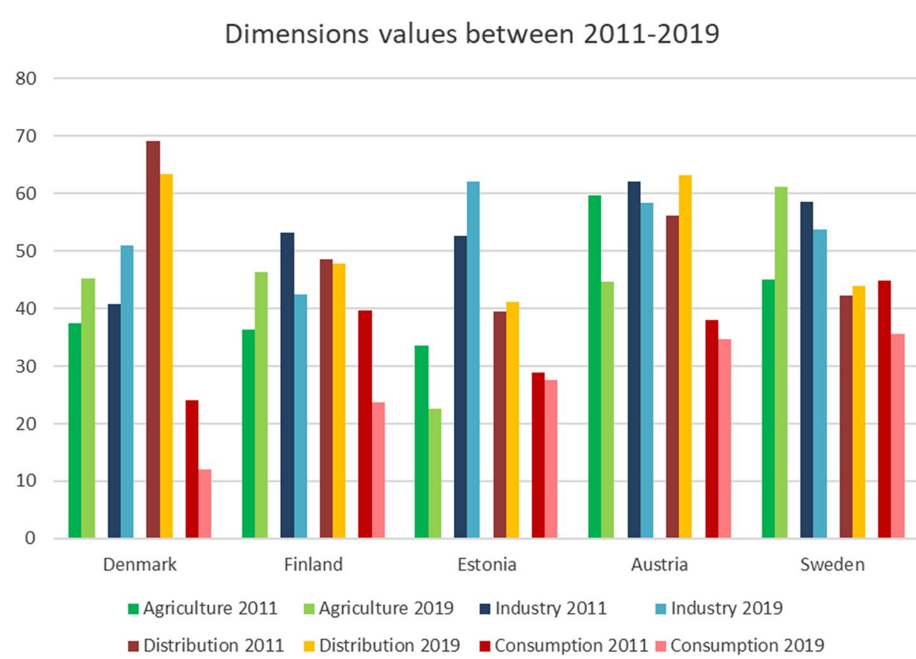

Fig. 19 Comparison of dimensions values between 2011 and 2019

Conclusions

For the next years, the European Union will face numerous strategic challenges to improve its sustainability to achieve both external objectives, such as the Agenda 2030 Sustainable Goals, and internal ones, connected mainly to the Green New Deal. Among the different strategies included in the Green New Deal, a crucial role is covered by the "Farm to Fork" strategy. However, to understand how to achieve a more sustainable agri-food system, it is important to understand at what point, in terms of sustainability, the system is, to try to correctly address the F2F application.

Our paper presented an innovative approach to make a relative evaluation in terms of sustainability of the EU countries, along the supply chain, using multicriteria analysis, in particular a composite index named Overall Sustainability Index (OSI). The innovative characteristics of Multiple Reference Point Partially Compensatory Indicator methodology (MRP-PCI) lay in the fact that reference levels are incorporated into the evaluation process and the final score obtained is not only a number, but also an informative measure of the problem assessed. Furthermore, composite indicators for different compensation degrees can be built. This is a great strength of the methodology, as it accounts for the possibility that a decision-maker considers different compensation degrees at each level, depending on the specific policy context.

According to the OSI, we identified three different groups of countries with very different levels of sustainability in the four sectors identified: Agriculture, Food Industry, Distribution, and Consumption. In the first group identified, all the countries had a good performance, over the median level, while in the second one every nation had at least one sector performing under the median. Generally speaking, good performance in one sector does not guarantee for the performance of the others; the same thing is noticeable for the dimensions, where it was possible to observe opposite results between environmental and social or between environmental and economic dimensions. Looking at the countries, Italy was in the first group, achieving the best level of sustainability of the AFSC with a value of 48.53, and followed by Sweden, Austria, Spain, France, Germany, the Czech Republic, Portugal, and Slovakia. The second group was the largest, including Finland, Denmark, the United Kingdom, Ireland, Estonia, Belgium, Greece, Slovenia, Cyprus, the Netherlands, and Hungary. Lithuania, Poland, Latvia, Croatia, Bulgaria, and Romania were in the third and worst group. Moreover, we analysed the trend between 2011 and 2019, to understand if previous policies have positively hit on the countries' performance.

Considering the direction established by F2F and the results we obtained, we can get some precious indications. Consumption is a sector where there is more need for action. The results indicate that most countries fall below the median values, which means that there is a big group of countries poorly performing in such a sector. Consumption is also the sector where the values range the most, which means a great variability between the different EU Members. Furthermore, looking at the overall trend between 2011 and 2019, we see that the countries that have worsened their performance the most have also reported a reduction in sustainability for the Consumption sector. Therefore, it is required an intense policy effort to counteract such a trend, reaching proper goals for Consumption, so as to halve food waste or to incentivize a healthy lifestyle.

Great attention is given to the Agriculture sector in the F2F, and in particular to the reduction of its environmental impact. In relation to the conditions we applied and the weights given by the experts, our results showed an almost sustainable Agriculture sector, although with some exceptions. However, we did not use absolute thresholds, as the quantitative objectives proposed by the strategy. Therefore, we caught the relative trend and we cannot affirm if in absolute terms the agriculture sector is on the right way to achieving the quantitative objectives of F2F or of the 2030 Agenda.

Due to the cohesion approach, a relative evaluation like the present one allows us to highlight in which countries there is more need for policy action. This work identified a group of EU countries in which a stronger action is requested, highlighting the sector in which it is more urgent. Such an approach should encourage considering the structural differences between the different EU countries, analysing which of them main affect also the results in terms of Agri-food sector. For future studies, it would be interesting to adopt absolute reference levels to assess the sustainability level of EU countries not only in a comparative context but also in absolute terms. Anyway, the authors' experience in this field indicates that it is usually hard for the experts to establish such absolute levels in general, and there is always some underlying comparison.

Additionally, it might be of interest to further divide the individual dimensions into subdimensions to group indicators based on more specific themes. This would allow for a comprehensive compensation among indicators addressing the same specific theme.

Abbreviations

AFSC	Agri-food supply chain
SDGs	Sustainable Development Goals
EGD	European Green Deal
F2F	Farm to Fork
MCDA	Multiple criteria decision analysis
MRP-PCI	Multiple reference point partially composite indicators
MRP-WSCI	Multiple reference point weak–strong composite indicators
OSI	Overall sustainability index

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Author contributions
R contributed to conceptualization, data curation, and writing—original draft preparation. R contributed to conceptualization, data curation, writing—original draft preparation, and reviewing and editing. P contributed to writing—original draft preparation, and reviewing and editing. G contributed to data curation. O contributed to data curation. R contributed to methodology implementation, writing—original draft preparation, and reviewing and editing. B contributed to conceptualization, supervision, and reviewing and editing.

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