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Unlocking sustainability in the EU food system: A regional analysis of sectoral carbon emission drivers and SDG-12 performance

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ABSTRACT

The European Union's food system presents critical challenges and opportunities for achieving climate neutrality, marked by uneven progress in reducing carbon emissions across production, processing, and consumption stages. To understand the relationships, drivers, and relative performance regarding carbon emissions within food sectors and the level of achievement concerning SDG-12 targets, this study analyzes these aspects across 12 EU nations between 2010 and 2024 using correlation networks, followed by decomposition analysis, and TOPSIS rankings. Food processing emerges as the largest emission source, averaging 9982.25 kt CO_2, with extreme variability (SD = 12,851.73) between low-impact artisanal operations (25th percentile: 1350.37 kt) and fossil fuel-dependent industrial clusters (75th percentile: 12,067.52 kt). Household consumption exhibits the widest disparity, spanning 54.76 to 33,062.66 kt CO_2, driven by affluent diets and inefficient appliances, while agricultural emissions remain significant in regions reliant on fossil fuels (interquartile range: 1599.58–9734.78 kt). Systemic interdependencies reveal circular economy gaps, with packaging strongly correlating to raw material use ($r = 0.88$) and waste disposal linked to consumption footprints ($r = 0.93$). TOPSIS rankings expose regional divides: Western Industrial clusters excel in waste management (e.g., 99.89 % efficiency) and energy productivity, whereas Eastern Transitional economies lag due to structural inefficiencies like low circular material use (12.35 %). Decomposition analysis identifies industrial expansion as a key driver of emission spikes (+0.05 structural effects) and underscores sustainability gaps in Sweden (−0.08 sustainability effects), driven by hazardous waste inefficiencies and renewable energy adoption delays. Targeted interventions include retrofitting high-emitting food processors exceeding the 75th percentile ($\geq$12,067.52 kt) with solar technologies, subsidizing precision farming tools for fossil fuel-dependent farms ($\geq$9734.78 kt) and leveraging cross-border carbon credit systems. Consumer reforms, such as plant-based diet incentives and appliance upgrades could halve household emissions in high-consuming clusters ($\geq$6982.53 kt). The findings encourage for region-specific strategies integrating SDG-12 targets, infrastructural modernization, and real-time monitoring to align economic growth with sustainability outcomes. By addressing sectoral variability and systemic linkages, this study provides a roadmap for EU policymakers to optimize the food system's climate resilience while advancing equitable progress.

1. Introduction

Global food production plays a crucial role in shaping carbon emissions, significantly affecting the environmental health and exacerbating climate change (Rabbi and Kovács, 2024; Wang et al., 2025). In Europe, the food sector contributes 20–30 % of total greenhouse gas (GHG) emissions (Abdelkareem et al., 2023; Directorate-General for Environment, 2023). On the top of that, the EU's food system holds a lot of promise for fostering sustainability, especially when tackled through integrated strategies and regional adjustments. To fully unlock this potential, it's crucial to understand the drivers of emissions within the different sectors and ensure alignment with Sustainable Development Goal 12 (SDG-12). As climate change targets become more urgent, the food system's role in generating greenhouse gas (GHG) emissions across the European Union (EU) has come under intense scrutiny (Pakrooh et al., 2024). In fact, the food system contributes to nearly a third of

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Abbreviations: CO_2, Carbon dioxide; EU, European Union; FAO, Food and Agriculture Organization of the United Nations; GHG, Greenhouse gas; k-NN, k-nearest neighbors; LMDI, Logarithmic Mean Divisia Index; MATLAB, Matrix Laboratory (software used for decomposition analyses); OECD, Organisation for Economic Co-operation and Development; RQ, Research Question; SD, Standard deviation; SDG-12, Sustainable Development Goal 12 (Responsible Consumption and Production); TOPSIS, Technique for Order of Preference by Similarity to Ideal Solution.

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global GHG emissions. This system includes production, processing, distribution, and consumption. Such a significant impact highlights the need for a comprehensive analysis of emissions across all stages of the food supply chain. Addressing this challenge is essential for the EU's sustainability agenda, especially considering its commitments to achieve net-zero emissions (Rabbi and Amin, 2024). However, despite the EU's commitment to sustainability, progress is uneven across its member states. This study takes a regional approach to identify the unique challenges and opportunities for advancing SDG-12 within the EU food system.

Furthermore, the food sector plays a significant role in environmental impact, with key emissions sources spanning agricultural production, food processing, and distribution. A significant impediment to addressing these emissions is the absence of uniform measurement standards within the industry. Despite efforts toward carbon neutrality, many EU countries are still struggling to reach this target. The high energy demands of the food supply chain, especially in agriculture, are a major factor in these struggles (Rahaman et al., 2023). A study by Liu et al. (2024) assessed that food-related emissions in Europe are driven by livestock production, particularly ruminants such as cattle and sheep, due to the methane released during digestion. Additionally, emissions from the food supply chain, including transportation and refrigeration, further contribute to the overall carbon footprint (Rabbi et al., 2023). On the top of this, the continued reliance on fossil fuels to meet the EU's energy needs only increases the environmental impact of the food industry (Andersen et al., 2024; Liu et al., 2023).

Previous studies have typically examined these issues in isolation, with a focus either on agricultural emissions or retail efficiency (Rabbi and Abdullah, 2024; Rabbi and Kovács, 2024). This approach overlooks the interconnected nature of these systems. For instance, the impact of packaging choices on raw material demand, or how household waste patterns influence agricultural inputs, often remain unexamined (Máté et al., 2020). This study aims to fill that gap by evaluating emissions across the entire integrated supply chain and assessing regional performance against SDG-12 indicators. By contextualizing disparities between Western Industrial leaders in waste management and Eastern Transitional economies struggling with circular material use, it provides a roadmap for policies that reconcile EU-wide sustainability targets with localized economic and cultural realities (Rabbi, 2024). Such an approach not only identifies emission hotspots but also illuminates the synergies and trade-offs inherent in multi-sectoral decarbonization efforts, offering a foundation for strategies that balance economic growth with ecological resilience.

This research bridges these gaps by integrating country-level comparisons, sectoral emission analyses, optimizing the sustainability performance to provide actionable insights into carbon emission mitigation strategies and SDG-12 progress. Researcher identified two research questions to address the research gap, such as, RQ1: What are the primary drivers of carbon emissions across the EU food system? and RQ2: How do regional differences influence sustainability outcomes?

The primary objective of this study is to analyse the drivers of carbon emissions in the EU food system and evaluate their alignment with the SDG-12 of responsible consumption and production. The outcome of this research aims to reveal the drivers of carbon emissions to encourage the promotion of resource-efficient production, circular economy principles, and more sustainable consumption behaviours. As the EU is increasingly promoting sustainability transitions and shifts that reinforce progress toward global climate targets, this research provides timely recommendations for decarbonising while meeting the demand for sustainable consumption and production.

To address these challenges and research gaps, this study builds upon the existing body of literature, as outlined in the following section.

2. Literature review

2.1. Carbon emissions and SDG-12 alignment in the EU food system

The food system in the European Union is at a crucial point in aligning its practices with global sustainability goals, especially SDG-12, which focuses on responsible consumption and production. As climate commitments become more urgent, the EU has put systemic reforms at the forefront through initiatives like the Green Deal, promoting plant-based diets, circular economy practices, and reducing waste (Simon et al., 2024). However, achieving these goals requires a granular understanding of carbon emissions across the entire food supply chain, from agricultural production to household consumption, and how they interact with regional policy frameworks and cultural practices (Rabbi and Amin, 2024; Woon et al., 2023).

Agriculture remains a major area of concern, as energy-heavy practices like irrigation, fertilization, and mechanized harvesting contribute significantly to emissions. These activities are influenced by factors like the energy sources used, the scale of the farm, and regional climate conditions (Kristia and Rabbi, 2023; Rahaman et al., 2023). For instance, fossil fuel reliance in Eastern Transitional economies contrasts sharply with renewable energy adoption in Western Industrial clusters, creating disparities in emission profiles (Panigrahi et al., 2023; Rabbi et al., 2022). Waste management further complicates this landscape. Techniques such as composting and anaerobic digestion offer emission reductions compared to traditional landfilling, but adoption rates vary widely due to regulatory and technological barriers (Kahiluoto et al., 2011; Raihan, 2024).

Beyond production, the stages of processing and packaging present ongoing challenges. Food processing, which often involves energy-intensive techniques, has varying environmental impacts depending on the level of technology used and the regional energy infrastructure (Knorr, 2024). The carbon footprint of food packaging is affected by material selection and the efficacy of recycling. Notably, single-use plastics persist as a key concern despite expanding circular economy strategies (Bangar et al., 2023). On the top of that, transportation and retail add additional complexity, as emissions from refrigerated logistics and retail operations are shaped not only by technological efficiency but also by consumer behavior and the quality of infrastructure (Jiang et al., 2024; Marrucci et al., 2020). Household food consumption patterns, particularly dietary preferences and food waste are underscoring the sociocultural dimensions of emissions, with affluent diets exacerbating footprints in high-income regions (Kristia et al., 2023; Xie et al., 2023).

These interconnected challenges align with SDG-12′s targets. Target 12.2, focused on sustainable resource management, highlights the tension between raw material consumption—particularly water, fertilizers, and soil nutrients in agriculture—and the EU's circularity gap (Baldassarre, 2025; Rodríguez-Espinosa et al., 2023). Target 12.5, which prioritizes waste reduction, underscores the potential of circular practices like recycling and bio-based material innovation, though progress remains uneven across member states (Distefano et al., 2024; Rabbi and Amin, 2024). Target 12.8, addressing public awareness, reveals both opportunities and pitfalls: while shifts toward plant-based diets could reduce consumption footprints by up to 25 %, policy-culture tensions persist, particularly in regions with strong culinary traditions (Bryant et al., 2024; Guillaume et al., 2024).

2.2. Regional context in food system sustainability

The EU food system's sustainability outcomes are shaped by regional disparities in policy frameworks, economic priorities, and cultural practices. Malcher and Gonzalez-Salazar (2024) demonstrate, advanced industrial economies like Germany and France achieve significantly lower processing emissions through renewable energy adoption and optimized supply chains. However, these nations face trade-offs, such as elevated household consumption footprints linked to affluent lifestyles

(Eufrasio Espinosa and Lenny Koh, 2024), highlighting tensions between industrial efficiency and sustainable consumer behaviours (Rabbi et al., 2021b).

Furthermore, nations in the mediterranean agro-industrial sector, such as Italy and Spain contend with the complex challenges arising from establishing heritage industries alongside the need to modernization. To illustrate, the traditional production of olive oil and pasta in Italy present a contradiction with the European union's sustainability targets, thereby sustaining energy-intensive practices (Agnoletti et al., 2023). A parallel situation can be observed in Spain, where technological advancements aimed at enhancing pesticide efficiency coincide with persistent inefficiencies in packaging and waste management. This illustrates the enduring contradiction between agricultural modernization and the preservation of cultural heritage (Mihret et al., 2025).

Eastern Transitional economies, including Hungary and Poland, encounter systemic impediments deriving from their historical development. Semenova et al. (2024) observe that the agricultural systems in these regions, legacies of the post-Soviet era, continue to depend on centralized fossil fuel infrastructure. Consequently, these agricultural systems requiring an investment in renewable technologies that amounts to three to five times greater than that invested in Western counterparts. These challenges are further exacerbated by the constrained adoption of a circular economy, as linear economic models persist because of inadequate recycling infrastructure (Nyambiya et al., 2025).

Nordic Sustainable clusters demonstrate the efficacy of policy interventions. For instance, Denmark's implementation of cross-sectoral carbon taxation (Neves et al., 2019) and Sweden's development of industrial symbiosis networks (Ekdahl et al., 2024) have promoted higher energy productivity and circular material use. Nonetheless, emerging challenges, notably the hazardous waste resulting from innovations in bio-based packaging, underscore deficiencies in the regulation of novel contaminants (Lacourt et al., 2024).

Cultural factors further contribute to regional distinctions. Mediterranean dietary patterns, characterized by a high consumption of vegetable oil, are associated with higher transport emissions when compared to the fish-centric patterns prevalent in Nordic regions (Almpounioti et al., 2025; Guasch-Ferré and Willett, 2021). These culinary traditions are mediated by European Union policies, as evidenced by France's reluctance to impose taxes on processed foods (Le Bodo et al., 2022) in contrast to Germany's adoption of subsidies for plant-based products (Prochazka et al., 2025). These regional variations emphasize the urgent need for context-specific strategies that harmonize economic shifts with established cultural practices.

3. Materials and methods

3.1. Study area

This study undertakes an examination of the carbon footprint associated with food systems, with a specific focus on the farm-to-fork supply chain. Recognizing the paramount importance of sustainable production and consumption patterns, the research investigates the interrelationships between carbon emissions and established sustainability objectives.

Data pertaining to a group of European nations, including Czechia, France, Germany, Hungary, Italy, The Netherlands, Poland, Portugal, Spain, Sweden, Finland, and Denmark, were analysed. The objective of this analysis was to identify opportunities for the optimization of carbon emissions and to evaluate performance relative to Sustainable Development Goal 12, which pertains to responsible consumption and production, in the pursuit of a more sustainable and environmentally responsible food system.

These nations were selected to provide a representative cross-section of geographic locations, economic structures, and policy frameworks within the European Union. For the purposes of analytical clarity, these countries were categorized into distinct regional clusters: Western Industrial (comprising Germany, France, and The Netherlands), characterized by advanced industrial economies; Mediterranean Agro-Industrial (comprising Italy, Spain, and Portugal), reflecting a synthesis of agricultural traditions and industrial development; Eastern Transitional (comprising Hungary, Poland, and Czechia), representing nations undergoing economic transition; and Nordic Sustainable (comprising Sweden, Finland, and Denmark), distinguished by their commitment to sustainable practices.

This clustering methodology facilitates a nuanced understanding of regional variations in the food system's carbon footprint and performance relative to SDG-12, thereby enabling the formulation of more precise and context-specific policy recommendations.

3.2. Data collection and variable selection

3.2.1. Data sources

The analysis was grounded in comprehensive data extracted from the Food and Agriculture Organization of the United Nations (FAO) (United Nations, 2023) and the database of the European statistics (Eurostat, 2023). This study investigates the key determinants driving carbon emissions across the entire food system, encompassing stages from initial production to final consumption. To achieve this, the researcher selected thirteen relevant variables from twelve EU countries. The analysis period spans from 2010 to 2024. Data from 2010 to 2023 was obtained directly. Missing data for 2024 was then imputed using the k-nearest neighbours (KNN) method, ensuring a complete dataset for the intended timeframe.

3.2.2. Variable selection

Thirteen variables were selected to measure the impact of carbon emissions on sustainable production and consumption. The dataset comprises 8 variables related to carbon emissions from the food system and 5 variables aligned with SDG-12, covering the eight EU countries between 2010 and 2024. The selection of these variables was guided by their relevance to the research questions and their availability across all selected countries and years. The key indicators characterizing this complex relationship are summarized in Table 1.

Furthermore, to ensure the accuracy and reliability of the subsequent analysis, the researcher undertook a comprehensive data cleaning and validation process. This involved the identification and detection of missing or inconsistent data points, as well as cross-referencing the resulting dataset with several other reputable sources of carbon emissions and SDG-12 data. However, missing data were excluded prior to the analysis.

3.3. Analytical procedure

This section outlines the analytical approach employed to process and interpret the collected data, thereby addressing the research objectives. To achieve this, the study utilized Python version 3.13.2 was utilized to execute descriptive statistics, correlation network analyses, decision matrix, and TOPSIS analysis. Additionally, MATLAB 2024b for conducting decomposition analyses.

3.3.1. Imputation of missing values

To address gaps in the dataset, researcher selected the *k*-nearest neighbors (KNN) technique for missing value imputation, implementing this approach through Python's scikit-learn library. After careful consideration and testing several options through cross-validation, researchers settled on using 5 neighbors as the optimal parameter for our dataset.

The KNN method works by identifying similar data points based on feature patterns and borrowing their values to fill in gaps. For numerical variables in this study, such as 'on-farm energy use' values or 'consumption footprint' measurements, researcher calculated the average

Table 1
Selected variables for assessing carbon emissions and SDG-12 targets.

Category	Pillar	Variables	Descriptions	Data Source	Measurement
CO_2 Emissions	Food Production	On-farm energy use	Emissions resulting from direct energy consumption in farming activities, including machinery use, irrigation, and heating systems.	FAO	kt of CO_2
		Pesticides manufacturing	Emissions from chemical processes and energy use in the production of pesticides for agricultural purposes.	FAO	kt of CO_2
	Food Processing	Food processing	Emissions generated during the transformation of raw agricultural products into consumable food items through industrial processes.	FAO	kt of CO_2
		Food packaging	Emissions from the production and processing of packaging materials used for food products, including plastics, paper, and metals.	FAO	kt of CO_2
	Food Distribution	Food transport	Emissions from fuel combustion during the transportation of food products across supply chains, both domestically and internationally.	FAO	kt of CO_2
		Food retail	Energy-related emissions from retail operations such as refrigeration, heating, lighting, and other activities in supermarkets and stores.	FAO	kt of CO_2
	Food Consumption	Food household consumption	Indirect emissions from household-level food preparation, refrigeration, cooking, and waste disposal activities.	FAO	kt of CO_2
		Agrifood systems waste disposal	Emissions from waste management processes within agrifood systems, including landfill emissions, recycling activities, and waste-to-energy conversion.	FAO	kt of CO_2
SDG-12 Targets	SDG 12.2	Raw material consumption	Total emissions associated with the extraction, processing, and consumption of raw materials within agrifood systems.	Eurostat	kt
	SDG 12.5	Circular material use rate	The percentage reduction in resource consumption achieved through circular economy practices such as recycling, reuse, and reduced material waste.	Eurostat	Percentage (%)
	SDG 12.8	Consumption footprint	A per capita measure of the environmental impact of individual consumption patterns across regions, reflecting ecological resource use and emissions.	Eurostat	Per Inhabitant
	SDG 12.2	*Energy productivity	A measure of economic output relative to energy input across sectors, reflecting efficiency improvements that contribute to sustainable resource management and production goals.	Eurostat	Euro per kilogram of oil equivalent
	SDG 12.10	Waste by hazardousness	Evaluation of hazardous waste generation within agrifood systems and its environmental impact, focusing on mitigation strategies for sustainable practices.	Eurostat	mt

Note: **Including Energy Productivity as an SDG-12.2 Target. Energy productivity, measuring economic output relative to energy input, aligns with SDG-12.2 by promoting resource efficiency and sustainable management. Its inclusion reflects its role in decoupling economic growth from resource use, reducing emissions, and optimizing energy-intensive processes within the EU food system.*

value from the five most similar neighbors to serve as the replacement value. The following equations used for

$$\hat{y}_i = \frac{1}{k}\sum_{j\in\mathcal{N}_i} y_j$$

Here the missing value y_i is imputed as the average of the k-nearest neighbors' values. And $\mathcal{N}_i$ denotes the set of k-nearest neighbours, and y_j are their corresponding values.

When dealing with categorical data like 'Waste by hazardousness' classification types, researcher instead used the most common value (mode) appearing among the neighbours. However, the missing value is imputed using the mode of the neighbors' values:

$$\hat{y}_i = \text{mode}\left(\left\{y_j : j \in \mathcal{N}_i\right\}\right)$$

The KNN method calculates the distance between data points using the Euclidean distance:

$$d(x_i, x_j) = \sqrt{\sum_{l=1}^{m} (x_{il} - x_{jl})^2}$$

where x_{il} and x_{jl} are the feature values of points x_i and x_j, and m is the number of features. This imputation strategy proved valuable for our analysis because it preserves the underlying patterns and relationships within our dataset, rather than simply inserting global averages that might distort important regional variations in sustainability indicators.

3.3.2. *Descriptive statistics*

Researchers generated a statistical overview of the sustainability dataset by employing Python's *pandas* library. The *describe*() method was used to efficiently produce standard statistical measures for all variables, offering key insights into the data's characteristics without the need for custom calculations.

This approach yielded key distribution metrics for each variable's central tendency (mean, median), dispersion indicators (standard deviation), boundary values (minimum and maximum), and distribution markers (quartile values at 25 %, 50 %, and 75 %). These summary statistics, presented in Tables 2 and 3, offer crucial context for understanding the variability in sustainability performance across different European regions.

The calculation of means for variables, including on-farm energy usage and raw material consumption, was performed by summing all observations and dividing by the total number of data points. This straightforward arithmetic means serves as a foundational metric for comparative regional performance analysis. The accompanying standard deviation measurements help illustrate how widely the values scatter around these averages. The following statistical calculations to each of the variables:

$$\mu_{\text{On farm energy use}} = \frac{1}{N}\sum_{i=1}^{N} \text{On farm energy use}_i \tag{1.1a}$$

$$\mu_{\text{Raw material consumption}} = \frac{1}{N}\sum_{i=1}^{N} \text{Raw material consumption}_i \tag{1.1b}$$

where x_i represents each data point, and N is the total number of observations. The mean provides a measure of the central location of the data.

The standard deviation (σ) is a measure of how Spread of each category's values from the mean. For example, it is calculated using the formula:

$$\sigma_{\text{Food transport}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \left(\text{Food transport}_i - \mu_{\text{Food transport}}\right)^2} \tag{1.2a}$$

$$\sigma_{\text{Energy productivity}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \left(\text{Energy productivity}_i - \mu_{\text{Energy productivity}}\right)^2} \tag{1.2b}$$

where x_i represents each data point and μ is the mean. A larger standard deviation indicates more variability in the data, while a smaller value suggests that the data points are more closely clustered around the mean.

Percentiles are another crucial element of the descriptive statistics, providing insights into the distribution of the data. The first, second (median), and third quartiles are calculated to understand the spread of the data at specific intervals. The first quartile ($Q1$) represents the value at the 25th percentile, the median ($Q2$) corresponds to the 50th percentile, and the third quartile ($Q3$) corresponds to the 75th percentile. These values can be derived from the dataset by determining the value below which a given percentage of observations fall. Mathematically, percentiles are calculated as:

$$Q_k = \textit{Value at the } k\% \textit{ percentile of the data} \tag{1.3}$$

where k represents the specific percentile of interest (e.g., 25 %, 50 %, 75 %).

The minimum and maximum values provide information about the range of the data. These can be calculated simply as:

$$\text{Min} = \min(x_i) \tag{1.4a}$$

$$\text{Max} = \max(x_i) \tag{1.4b}$$

These values help identify the extremes of the data, which can be important for detecting outliers or understanding the scope of variation within a variable.

3.3.3. Correlation analysis

Correlation analysis (Fig. 1) was conducted to evaluate the correlation between different variables, which was computed to understand how changes in one variable correlated with changes in another. A network diagram was generated using the *NetworkX* library in Python to provide a visual representation of the correlation matrix, supporting the identification of potential interdependencies among emission categories or variables. Only correlations with a p-value <0.05 were considered statistically significant. The formula used for calculating correlation coefficient r_{ij}.

$$r_{ij} = \frac{\sum_{t=1}^{n}(D_{i1t} - \overline{D}_{i1})(D_{i1t} - \overline{D}_{i1})}{\sqrt{\sum_{t=1}^{n}(D_{i1t} - \overline{D}_{i1})^2 \, \Sigma_{t=1}^{T} \, (D_{i2t} - \overline{D}_{i2})^2}} \tag{2}$$

Here T is the number of years. D_{i1t} and D_{i2t} are the individual data points for variables D_{i1} and D_{i2}. Similarly, $\overline{D}_{i1}$ and $\overline{D}_{i2}$ are over a period of n observation or the means of variables D_{i1} and D_{i2}. The magnitude of r_{ij} indicates the strength of correlation, which is closer to 1. If $r_{ij} > 0$ then it means positive linear relationship between variables. Conversely, if $r_{ij} < 0$ then it indicates a negative liner relationship between variables.

3.3.4. Logarithmic Mean Divisia Index (LMDI) decomposition

The Logarithmic Mean Divisia Index (LMDI) approach was applied to decompose the changes in carbon emissions and SDG-12 (Figs. 2 and 3). LMDI provides a complete decomposition without residual terms, ensuring that all changes in emissions can be attributed to specific factors (activity, structural, and sustainability effects). Previously many studies used the LMDI to analyse carbon emissions trends and environmental impacts at various scales, from national and regional levels to specific sectors and industries (Shao and Xue, 2022; Wang and Yang, 2023). The logarithmic weighting function in LMDI provides a balanced treatment of changes, avoiding biases toward either the base or current period. This is crucial for accurately identifying the primary drivers of carbon emissions across different stages of the food system and SDG-12 performance. The method's ability to quantify the relative contributions of different factors to overall emission changes aligns perfectly with research question RQ1. For example, the total carbon emissions for each country and year were computed by summing all variables:

$$E_{total,i} = \sum\nolimits_{j\in\{\text{On farm energy use, Agrifood Systems Waste Disposal, Pesticides Manufacturing},\ldots\}} E_{ij} \tag{3.1}$$

The total carbon emissions for a specific observation i, which corresponds to a particular country and year, is denoted as $E_{total,i}$. This total emission is derived from the emissions associated with each individual variable j, such as on-farm energy use, food transport, and other relevant factors. The emissions for each variable j are represented as E_{ij}. By summing these individual emissions E_{ij} across all variables j, the total carbon emissions $E_{total,i}$ for the observation i are obtained.

The activity effect measures the impact of changes in economic activity on carbon emissions. This effect is represented by the logarithmic change in emissions across years:

$$\text{Activity Effect}_{c,t} = \log\left(\frac{E_t}{E_{t-1}}\right) \tag{3.2}$$

The Activity Effect, denoted as $\text{Activity Effect}_{c,t}$, quantifies the contribution of economic activity to carbon emissions for a specific country c in year t. This effect is calculated using the total emissions in the current year, represented as E_t, and the total emissions in the previous year, denoted as E_{t-1}. By comparing these emissions, the Activity Effect provides insights into how changes in economic activity influence carbon emissions over time for the given country.

Structural Effect measure the contribution of changes in economic structure was measured using the sustainability index:

$$\text{Structural Effect}_{c,t} = \log\left(\frac{S_t}{S_{t-1}}\right) \tag{3.3}$$

The Structural Effect, denoted as $\text{Structural Effect}_{c,t}$, measures the impact of changes in economic structure on carbon emissions for a specific country c in year t. This effect is determined by comparing the sustainability index values for the current year, represented as S_t, and the previous year, denoted as S_{t-1}. By analyzing these index values, the Structural Effect provides insights into how shifts in the economic structure influence carbon emissions over time for the given country.

Sustainability Effect measure the contribution of sustainability practices. It was calculated by multiplying the changes in emissions and sustainability index:

$$\text{Sustainability Effect}_{c,t} = \log\left(\frac{E_t}{E_{t-1}}\right) \times \log\left(\frac{S_t}{S_{t-1}}\right) \tag{3.4}$$

The Sustainability Effect, denoted as $\text{Sustainability Effect}_{c,t}$, represents the influence of sustainability practices on emissions for a specific country c in year t. This effect captures how the implementation and improvement of sustainability measures impact the carbon emissions for the given country over time.

3.3.5. TOPSIS analysis

TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) excels at handling multi-dimensional sustainability metrics simultaneously, allowing for comprehensive evaluation of the complex, interconnected indicators that comprise carbon emissions and SDG-12 performance. In addition, TOPSIS offers advantages when comparing heterogeneous regional clusters (Western Industrial, Mediterranean Agro-Industrial, Eastern Transitional, and Nordic Sustainable) as it normalizes disparate variables into comparable units. This normalization process ensures fair comparison despite significant differences in economic structures, geographic conditions, and policy frameworks across the 12 EU countries studied. The method's ability to quantify the sustainability outcomes of different factors to overall SDG-12 progress aligns completely with research question RQ2.

The first step involved normalizing the data using min-max normalization to scale the values of each variable to a [0,1] range.

For a given variable x_i, the normalized value x_i' is calculated as:

$$x_i' = \frac{x_i - \min(x)}{\max(x) - \min(x)} \tag{4.1}$$

Where $\min(x)$ and $\max(x)$ are the minimum and maximum values of the variable in the dataset. This ensures all variables are on a comparable scale.

Next, for the decision matrix (Tables 8 and 9) the normalized values are formatted as percentages to enhance interpretability. This is achieved by multiplying the normalized value by 100 and rounding it to two decimal places:

$$\text{Percentage} = (x_i' \times 100).\text{round}(2) \tag{4.2}$$

This step is applied to each performance metric in the CO_2 emissions and SDG12 datasets. The final decision matrices include these formatted percentage values, along with the 'Country' and 'Year' columns, allowing for a more comprehensive understanding of the data.

The TOPSIS analysis (Figs. 4 and 5) was performed by normalising that data according to predefined weights for each variable. For instance, for the CO_2 emissions data, the weight w_i for each variable x_i was assigned as:

$$w_i = \frac{1}{n} \tag{5.1}$$

where n is the total number of variables in the dataset. Equal weights were applied for simplicity.

The TOPSIS method then calculates ideal and anti-ideal solutions for each country in the dataset. The ideal solution A^+ for a beneficial criterion is represented by the maximum value of each variable, while the anti-ideal solution A^- is represented by the minimum value:

$$A_i^+ = \max(x_i) \quad \text{if beneficial} \quad A_i^- = \min(x_i) \quad \text{if non-beneficial} \tag{5.2}$$

The distance to the ideal and anti-ideal solutions is then computed for each country. For a given observation rr, the Euclidean distance to the ideal solution D_i^+ and anti-ideal solution D_i^- are calculated as:

$$D_i^+ = \sqrt{\sum_{j=1}^{m} \left(r_j - A_j^+\right)^2} \quad \text{and} \quad D_i^- = \sqrt{\sum_{j=1}^{m} \left(r_j - A_j^-\right)^2} \tag{5.3}$$

where r_j is the value of the j-th variable for country i, and A_j^+ and A_j^- are the ideal and anti-ideal values for the j-th variable.

The relative closeness to the ideal solution is calculated by:

$$C_i^+ = \frac{D_i^-}{D_i^+ + D_i^-} \tag{5.4}$$

This measure reflects how close each country is to the ideal solution, with higher values indicating better performance.

Ultimately, countries are ranked based on their relative closeness to the ideal solution. The rankings are computed by applying the above method to each country's data, resulting in a ranked list for each year in the dataset. These rankings are then visualized using bump charts, where the rank of each country is plotted over time. The ranking is inverted so that the top rank appears at the top of the chart.

By combining these analytical techniques, this study provides a comprehensive assessment of carbon emissions and SDG-12 performance in the EU food system, offering valuable insights for policymakers and stakeholders seeking to promote sustainability.

4. Analysis and results

Building upon the methodology outlined in the previous section, the core analysis begins by addressing the initial research questions: RQ1. What are the primary drivers of carbon emissions across the EU food system? and RQ2. how do regional differences influence sustainability outcomes? The following sections provide a detailed examination of descriptive statistics for key variables, explore correlations between emission sources and SDG-12 indicators, decompose the factors influencing emission changes, and ultimately rank countries based on their overall sustainability performance. This comprehensive assessment will provide a clearer understanding of regional dynamics and potential intervention points within the EU food system.

Table 2 (calculated through equations 1.1 to 1.4) provides a detailed statistical overview of carbon emissions across eight key components of the agrifood system, based on 15 years of annual observations (2010–2024), measured in kt of CO_2. These statistics offer valuable insights into the variability and magnitude of emissions across different stages of the food system, highlighting the diverse drivers that contribute to regional disparities in carbon outputs. For instance, on-farm energy use demonstrates a mean emission of 5716.86 kt of CO_2 with substantial variability (SD = 4241.92), reflecting the heterogeneity in energy practices across agricultural systems. Farms with low mechanization are represented by the 25th percentile (1599.58 kt), while industrialized operations reliant on fossil fuels account for the 75th percentile (9734.78 kt). The maximum value (12,588.67 kt) underscores the growing energy intensity in large-scale agribusinesses employing automated systems and precision farming technologies.

Similarly, agrifood systems waste disposal exhibits systemic inefficiencies, as evidenced by its mean emission of 401.35 kt of CO_2 and high standard deviation (SD = 520.99). The widespread between the 25th percentile (40.25 kt) and the 75th percentile (602.29 kt) reflects disparities in waste management practices across regions. Advanced composting or anaerobic digestion systems achieve lower emissions (minimum = 13.33 kt), while reliance on open landfills elevates emissions significantly (maximum = 1828.55 kt). The median value (147.39 kt), being less than half the mean, suggests that high-emission waste streams disproportionately impact sectoral averages.

Moving to pesticides manufacturing, this category averages 473.18

Table 2

Descriptive statistics for CO_2 emission categories.

Statistic	On farm energy use	Agrifood systems waste disposal	Pesticides manufacturing	Food processing	Food packaging	Food transport	Food retail	Household food consumption
mean	5716.864	401.3519	473.1838	9982.245	1618.12	4492.812	3089.523	5591.396
std	4241.917	520.997	439.4522	12,851.73	1654.002	4086.653	3273.572	7707.442
min	1170.858	13.329	25.6158	345	101.9379	851.2901	172.7981	54.7613
25 %	1599.584	40.2524	86.5225	1350.367	431.8316	1264.244	517.0354	1119.026
50 %	4902.934	147.3936	206.5	3659.837	883.4536	1991.243	1987.839	2860.569
75 %	9734.784	602.2876	925.4994	12,067.52	2452.272	7621.693	4601.369	6982.525
max	12,588.67	1828.546	1288.111	42,119.64	6985.704	13,862.96	1,4156.91	3,3062.66

Note: All variables represent annual measurements from 2010 to 2024 (n = 180 observations per metric).

kt of CO_2 with variability (SD = 439.45) driven by production methods. The lower end of emissions (25th percentile = 86.52 kt) corresponds to organic pesticide production, while higher values (75th percentile = 925.50 kt) reflect synthetic pesticide factories employing energy-intensive ammonia synthesis processes. The relatively narrow range between the median (206.50 kt) and maximum (1,288.11 kt) suggests limited technological variation within this sector.

Among all categories, food processing emerges as the largest contributor to carbon emissions with a mean value of 9,982.24 kt of CO_2 and extreme dispersion (SD = 12,851.73). The interquartile range (1,350.37–12,067.52 kt) captures both artisanal operations and industrial processors employing energy-intensive techniques such as freeze-drying and chemical preservation. The maximum value (42,119.64 kt) highlights mega facilities in regions dependent on coal-based energy grids, emphasizing the sector's reliance on centralized energy infrastructure.

In contrast, food packaging emissions average 1,618.12 kt of CO_2. These emissions are driven by material production and recycling practices. The disparity between the median (883.45 kt) and the 75th percentile (2,452.27 kt) underscores the environmental cost of single-use plastics and non-recyclable materials within supply chains. The maximum value (6,985.70 kt) likely stems from high-emission packaging in processed food industries dominated by fossil-derived polymers.

Food transport, with a mean emission of 4,492.81 kt of CO_2, shows significant variability due to logistics methods; its 75th percentile value (7,621.69 kt) is nearly four times higher than the median (1,991.24 kt). Long-haul refrigerated shipping contributes disproportionately to these emissions, with air-freighted perishables accounting for the maximum value (13,862.96 kt).

The category of food retail exhibits bifurcated emissions patterns between small vendors at the lower end (25th percentile = 517.04 kt) and supermarkets with continuous refrigeration at the upper end (75th percentile = 4,601.37 kt). Hypermarkets located in warmer climates dominate energy use for cooling systems, driving maximum values up to 14,156.91 kt.

Finally, household food consumption presents the most inequitable emissions profile with a mean value of 5,591.40 kt masking an extreme range from minimum values as low as 54.76 kt to a maximum of 33,062.66 kt are representing a staggering difference across households and regions within the EU food system framework. The interquartile range reflects middle-income diets with moderate meat consumption at the upper end (75th percentile = 6,982.52 kt), while affluent households consuming ruminant meat daily or wasting significant amounts of food drive extreme values.

Once the foundational characteristics of the various carbon emission categories have been determined, the researcher examines the descriptive statistics of the SDG-12 indicators to explore their role in sustainable production and consumption practices.

Table 3 (calculated through equations 1.1 to 1.4) offers a comprehensive statistical overview of key SDG-12 indicators, derived from 15 years of annual observations (2010–2024), providing critical insights into global progress toward sustainable consumption and production goals. This dataset highlights the variability and systemic disparities across regions, emphasizing the need for targeted interventions to optimize resource use within agrifood systems.

Raw material consumption reveals substantial variability, with a mean of 423,798.72 kt and a standard deviation of 372,318.40 kt. The maximum value (1,370,288.27 kt) underscores the dominance of resource-intensive economies reliant on extractive industries such as mining and deforestation-driven agriculture. Conversely, the 25th percentile (141,523.75 kt) reflects regions that have adopted circular economy principles to decouple economic growth from resource extraction. This disparity highlights the uneven adoption of sustainable practices across regions.

The consumption footprint, measured per inhabitant, averages 0.95 globally but exhibits significant disparities. High-income nations often exceed planetary boundaries, as evidenced by the maximum value of 1.22, reflecting resource-intensive lifestyles that demand more ecological resources than the Earth can sustain. In contrast, economies adhering to sufficiency principles achieve lower values (25th percentile = 0.83), demonstrating localized efforts to reduce environmental impact. The median value (0.98) hovering near the planetary boundary threshold underscores the precarious balance between global aspirations for sustainability and localized overconsumption.

Circular material use rates average 10.98 %, with top performers achieving up to 30.6 % (maximum) through innovative practices such as urban mining and industrial symbiosis initiatives. However, regions at the lower end (minimum = 1.7 %) highlight entrenched linear economies that lack infrastructure for scaling circular practices. The moderate standard deviation (6.70 %) reflects both technological and economic barriers to achieving widespread adoption of circular economy principles.

Energy productivity, expressed in euros per kilogram of oil equivalent, demonstrates relatively tight variability with a mean of 7.97 and a standard deviation of 3.08. The interquartile range (5.43–9.47) indicates widespread adoption of basic efficiency measures such as renewable energy integration and energy-efficient technologies in agrifood systems. However, the maximum observed value (18.81 €/kg oil equivalent) highlights the potential for efficiency gains through smart manufacturing and digitized energy management, though it represents an outlier rather than typical sector performance.

Hazardous waste generation presents the most alarming distribution among all indicators, with a mean of 263.30 mt and extreme outliers such as the maximum value of 5,267 mt driven by toxic byproducts from chemical manufacturing or electronic waste disposal in specific regions. Economies enforcing strict producer responsibility laws achieve significantly lower outputs (25th percentile = 72 mt), demonstrating that regulatory rigor can effectively mitigate hazardous waste generation.

With a clear understanding of the statistical distribution of both carbon emissions and SDG-12 indicators, it is crucial to examine how these variables interact within a shared framework.

The Fig. 1 (calculated through Eq. (2)) highlights intricate relationships between carbon emissions and SDG-12 variables across various

Table 3

Descriptive statistics for SDG-12 categories.

Statistic	Raw material consumption	Consumption footprint	Circular material use rate	Energy productivity	Waste by hazardousness
mean	423,798.7	0.954556	10.976	7.966167	263.3
std	372,318.4	0.157995	6.703216	3.085533	512.527
min	67,876.5	0.62	1.7	3.51	39
25 %	141,523.8	0.83	6.55	5.4275	72
50 %	224,714.6	0.98	9.15	7.775	167
75 %	617,815.9	1.08	12.9025	9.465	277.75
max	1370,288	1.22	30.6	18.81	5267

Note: All variables represent annual measurements from 2010 to 2024 ($n = 180$ observations per metric).

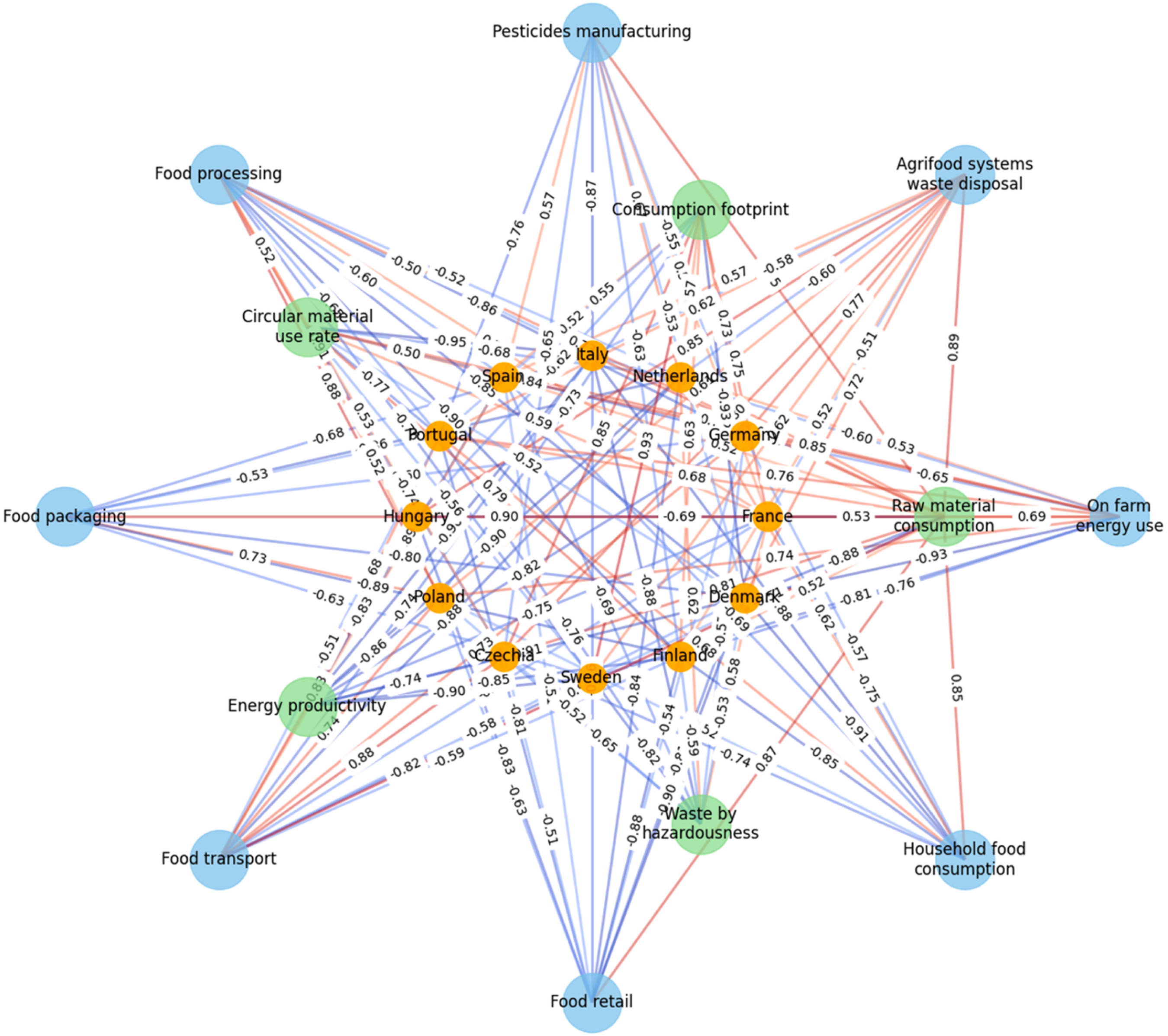

Fig. 1. Correlation network of carbon emissions and SDG-12 variables.

countries, revealing both commonalities and unique patterns.

In France, food transport exhibits a strong positive correlation with the consumption footprint ($r = 0.7523$, $p = 0.0012$) and raw material consumption ($r = 0.5327$, $p = 0.0409$), emphasizing the role of transportation in driving resource use and environmental degradation. Conversely, household food consumption shows a notable negative correlation with energy productivity ($r = -0.7466$, $p = 0.0014$), suggesting inefficiencies in energy use related to domestic food practices. These results underscore the need for targeted interventions in transportation and household consumption to reduce France's environmental footprint.

Germany presents a contrasting profile, where food packaging demonstrates a strong negative correlation with the circular material use rate ($r = -0.8824$, $p = 0.000013$), indicating inefficiencies in recycling systems linked to packaging materials. Additionally, food retail shows a significant negative correlation with energy productivity ($r = -0.9299$, $p = 0.0000005$), reflecting challenges in improving energy efficiency within the retail sector. These findings highlight Germany's potential for enhancing sustainability through improved packaging practices and energy-efficient retail operations.

Italy's results reveal critical challenges in waste management and resource efficiency. Household food consumption exhibits an extremely strong negative correlation with the circular material use rate ($r = -0.9539$, $p < 0.000001$), while food transport is positively correlated with raw material consumption ($r = 0.7608$, $p = 0.00099$). These correlations suggest that Italy's agrifood systems significantly contribute to resource depletion and inefficiencies in recycling processes.

The Netherlands displays divergent patterns, with food transport showing a strong negative correlation with energy productivity ($r = -0.8769$, $p = 0.000018$) but a positive correlation with raw material consumption ($r = 0.6541$, $p = 0.0082$). These results suggest that while transportation contributes to resource extraction, it poses challenges for energy efficiency, necessitating balanced interventions to address both issues.

Hungary reveals exceptionally high correlations between food transport and the consumption footprint ($r = 0.9537$, $p < 0.000001$), indicating its disproportionate environmental impact in this region. On-farm energy use also shows a strong positive correlation with raw material consumption ($r = 0.879$, $p = 0.000016$), reflecting resource-intensive agricultural practices that require attention to improve sustainability.

Poland demonstrates significant correlations between food transport and the consumption footprint ($r = 0.9575$, $p < 0.000001$) as well as between household food consumption and circular material use ($r = -0.7344$, $p = 0.0018$). These findings highlight transportation's environmental burden and inefficiencies in domestic recycling systems.

Czechia presents notable results for pesticides manufacturing, which shows a very strong negative correlation with the circular material use rate ($r = -0.9153$, $p < 0.000002$). Food transport also exhibits strong positive correlations with both energy productivity ($r = 0.8812$, $p = 0.000014$) and the consumption footprint ($r = 0.8481$, $p < 0.0001$), suggesting that transportation plays a dual role in contributing to both resource efficiency and environmental impacts.

Sweden highlights industrial inefficiencies within its agrifood systems, as evidenced by the strong negative correlation between food processing and energy productivity ($r = -0.9372$, $p < 0.000001$). On-farm energy use shows a strong positive correlation with the consumption footprint ($r = 0.8847$, $p < 0.00001$), reflecting agriculture's significant contribution to environmental impacts.

Finland demonstrates notable results for food packaging, which is negatively correlated with energy productivity ($r = -0.889$, $p < 0.00001$). Additionally, pesticides manufacturing shows a moderate positive correlation with circular material use ($r = 0.6175$, $p = 0.0142$), indicating some alignment between chemical inputs and recycling efforts.

Denmark highlights effective packaging strategies that reduce environmental impacts; food packaging exhibits a strong negative correlation with the consumption footprint ($r = -0.9379$, $p < 0.000001$). On-farm energy use negatively correlates with energy productivity ($r = -0.9334$, $p < 0.000001$), underscoring systemic inefficiencies within agricultural practices.

These findings collectively emphasize the importance of tailoring sustainability interventions to specific national contexts while addressing common challenges such as transportation inefficiencies and waste management practices across agrifood systems globally.

While correlations provide insights into variable interactions, understanding sectoral contributions to carbon emissions is equally important for identifying targeted intervention points. To further understand the dynamics driving correlation network, researcher investigate the decompose changes in carbon emissions by economic activity, structural shifts, and sustainability practices.

The Fig. 2 illustrates the Logarithmic Mean Divisia Index (LMDI) decomposition calculated through Eqs. (3.1) to (3.4) of carbon emissions across 12 EU countries. Country-specific analyses reveal distinctive patterns. Czechia exhibits relatively stable activity and structural effects. fluctuating around 0.02 to 0.03 for most years. However, the activity effect shows noticeable peaks in 2016 and 2021, reaching approximately 0.03 and 0.05. This sudden increase likely reflects pandemic-related disruptions in food systems and the associated carbon implications. However, the sustainability effect remains mostly negative, dipping to nearly zero. This is suggesting intermittent improvements in carbon efficiency.

Denmark shows some cyclical patterns in economic activity and structural effects. For example, there was a pronounced downturn in 2014 and 2018, where this value approaches −0.1. Such swings highlight the persistent contributions of production-related emissions to the country's overall carbon footprint. In a notable difference, the sustainability effect was stable at around 0.02 to 0.04, reflecting the steady momentum towards lower emissions.

There is a highly variable trend is observed in Finland, where sharp downward trends at near −0.15 in 2012 and 2015. These are two critical years for improving emissions management. The activity effect is peaks at around 0.08 in both 2013 and 2017, indicating that the carbon-intensive production activities have experienced temporary surges. And the sustainability effect remains reasonably constant between 0.01 and 0.02 over the study period.

France has experienced periodic low economic activity and structural effects, with a steep decline to approximately −0.09 in 2014, indicating that a significant sectoral transition has occurred that has led to decline in emissions. Nevertheless, the activity effect fluctuates around 0.08 in 2013 and 2017, indicating that the economic activity's continued role in carbon emissions. The sustainability effect stabilizes within a narrow range of 0.01 to 0.02, indicating a gradual but sustained focus on efficiency improvements.

However, Germany is one of the biggest economic countries in Europe. Changes in emissions are primarily attributable to variations in economic activity and structural effects. Germanys activity effect remaining constrained within −0.05 to +0.05. A decline to −0.05 in 2019 and 2020 clearly reflects the gradual advancement in carbon efficiency, whilst the sustainability effect remains relatively stable. These trends indicate that Germany's food system has remained resilience to external economic shocks. This is due to its advanced agricultural and food processing infrastructure.

The structural effect for Hungary drops sharply to −0.08 in 2012, indicating a possible decoupling of structural factors from carbon efficiency gains. However, subsequent years showed fluctuations directly correlated with emission spikes. The activity effect peaked in 2013 (0.05) and 2021 (0.04), demonstrating periods of elevated production-related emissions. In contrast, the sustainability effect remains constant between 0.01 to 0.03.

Italy has a different trend, with negative (−0.1) activity effect in 2022. This significant negative net contribution reflects the nation's strengthened regulatory measures to reduce carbon emissions following the European Green Deal. As a result, the sustainability effect fluctuates between 0.01 and −0.03, suggesting slow but steady progress towards lower emissions in economic sectors.

Netherlands as a major agricultural exporter with substantial greenhouse gas impacts. Notably, this country experiences rapid shifts in economic activity and structural effects, leading to periodic declines in emissions contributions reaching −0.08 in 2010 and −0.06 in 2019. On the other hand, the sustainability effect shows a relatively constant trend.

Poland's economic activity and structural effects show a downward trend in emissions, particularly in 2014 and 2020, with values near −0.05, indicating emission reduction progress. However, the activity effect shows substantial increases at various intervals, peaking around 0.05 in 2016 and 2017, potentially associated with the expansion of the country's food processing industry. These fluctuations tend to have minor impact on the sustainability effect.

Portugal shows a sustained effort to achieve lower emissions intensity, with a gradual decline in economic activity and structural effects, peaking at almost −0.15 in 2013. However, the occasional spikes in the activity effect, with peaks close to 0.1 in 2015 and 2017, suggest that food production and economic growth played a very important role in emissions dynamics. The sustainability effect remains relatively stable, generally between 0.01 and 0.02.

Spain exhibits a pattern of periodic spikes in the activity effect, with values dropping close to −0.06 in 2013 and 2020, suggesting intermittent progress in emissions reduction. The activity effect trends upward at other points, notably in 2015 and 2021, reaching approximately 0.08. The sustainability effect exhibits relative stability, with values consistently ranging from 0.01 to 0.02.

Sweden's decomposition results show strong fluctuations, with negative values plunging to −0.08 in 2010 and 2020. It is possible that the increase from around 0.02 in 2019 to roughly 0.03 in 2021 is attributable to disruptions caused by the COVID-19 pandemic and the following economic recovery, impacting carbon emissions in the nation's food sector.

Overall structural and economic activity remain the dominant drivers of change in EU food system carbon emissions. While sustainability effects show signs of improving emissions efficiency. Despite these actions, a substantial impact on overall emission trends has yet to

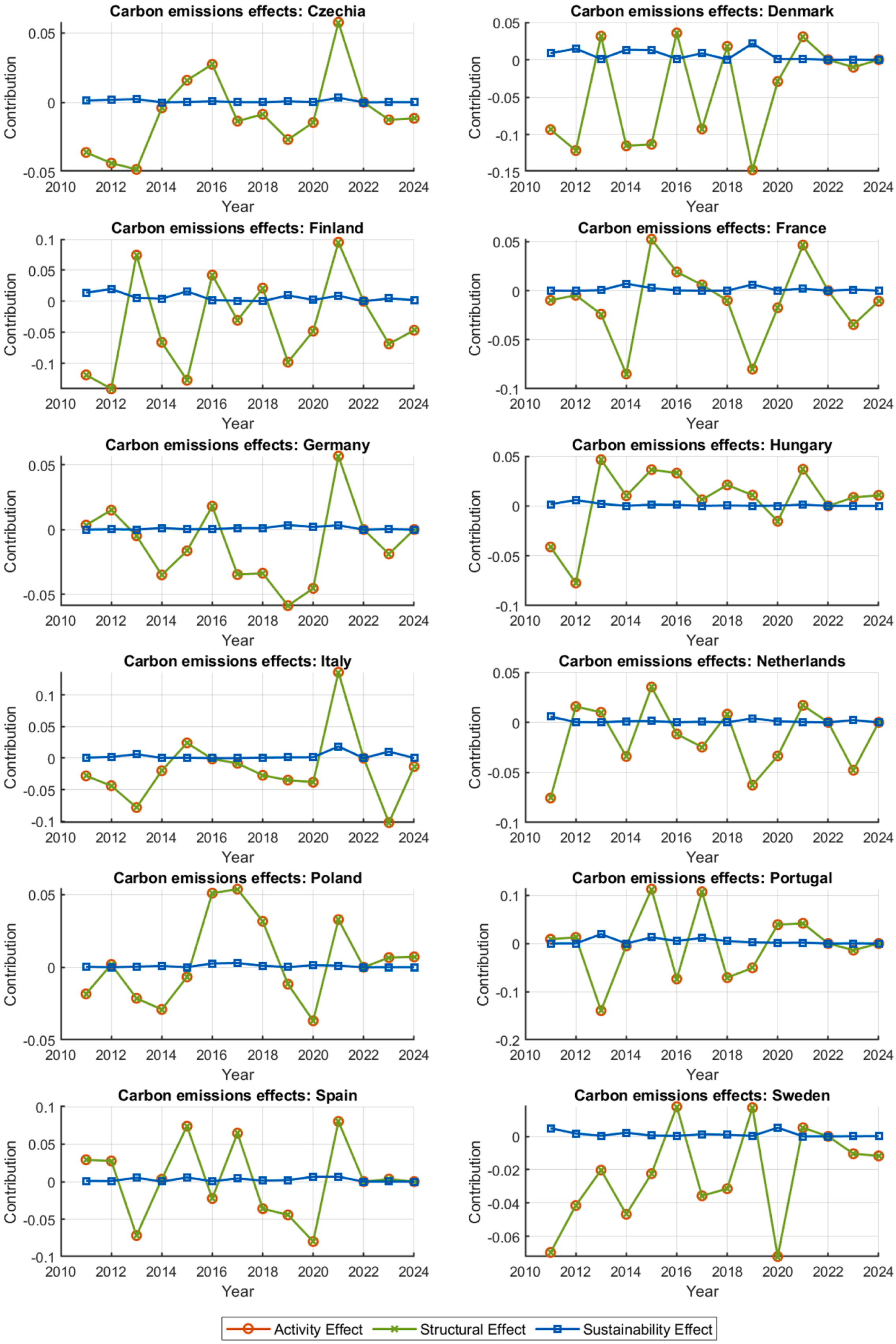

Fig. 2. Decomposition analysis of carbon emissions drivers in the EU food system.

be observed. This highlights the pivotal role of enhanced policy integration of sustainable practices in driving systemic carbon reductions throughout food value chains over the long term.

Table 4 presents the results of the LMDI decomposition analysis, showing the contribution of activity, structural, and sustainability effects to changes in carbon emissions for each country over the study period. The total change represents the sum of all effects.

To validate these results, researcher employed a Genetic Algorithm-optimized Support Vector Machine (GA-SVM) model. The model was trained on 80 % of the data and tested on the remaining 20 %. The validation results are as follows:

The Root Mean Square Error (RMSE) of 2994.95 and Mean Absolute Error (MAE) of 2595.47 indicate the average magnitude of prediction errors in Table 5. The R^2 value of 0.7479 suggests that the model explains approximately 74.79 % of the variance in carbon emissions based on the LMDI decomposition effects.

These results demonstrate that the LMDI decomposition captures significant patterns in carbon emission changes across the studied countries. The high R^2 value indicates a strong relationship between the decomposition effects and actual emissions, validating the effectiveness of the LMDI approach in analysing carbon emission drivers.

Countries like Sweden, Poland, and Hungary show the highest total changes, suggesting they experienced the most significant shifts in carbon emissions over the study period. In contrast, Spain and Denmark show minimal changes, indicating relatively stable emission patterns. The GA-SVM validation provides confidence in the LMDI results, supporting their use in policy-making and further research on carbon emission reduction strategies in these European countries.

The decomposition analysis for SDG-12 (Fig. 3 calculated through Eqs. (3.1)–(3.4)) reveals complex dynamics driving SDG-12 progress across twelve EU member states over the 2010–2024 period.

Czechia presents an interesting case with notable positive peaks in its activity effect in 2021, reaching values of approximately 0.08, suggesting relatively strong economic drivers of SDG-12 progress during this period. The activity effect demonstrates minor fluctuations, with peaks around 0.03 from 2015 to 2017, signalling increased economic contributions to SDG-12. The sustainability effect follows a similar trend.

Denmark exhibits more moderate fluctuations in its activity effect, generally ranging between −0.02 and 0.03, indicating more balanced economic influences on sustainable consumption and production progress. However, the structural effect sees sharp declines, particularly in 2020 and 2023, where it dips below −0.03, suggesting intermittent challenges in achieving sustainable consumption and production improvements. Meanwhile, the sustainability effect, remains close to zero, indicating long-term consistency in efforts to align with SDG-12 targets.

Table 4
LMDI decomposition results of carbon emissions drivers (2010–2024).

Country	Activity Effect	Structural Effect	Sustainability Effect	Total Change
Czechia	0.092	0.092	0.008	0.192
Denmark	0.04	0.04	0.002	0.082
Finland	0.056	0.056	0.003	0.115
France	0.587	0.587	0.344	1.518
Germany	0.645	0.645	0.416	1.706
Hungary	0.926	0.926	0.857	2.709
Italy	0.817	0.817	0.667	2.301
Netherlands	0.204	0.204	0.042	0.45
Poland	0.928	0.928	0.861	2.717
Portugal	0.451	0.451	0.203	1.105
Spain	0.001	0.001	0.001	0.002
Sweden	0.95	0.95	0.903	2.803

Table 5
GA-SVM validation results for carbon emissions.

Metric	Value
RMSE	2994.95
MAE	2595.47
R^2	0.7479

Finland demonstrates particularly pronounced cyclical patterns in its activity effect, with clear alternating positive and negative contributions throughout the analysis period. The structural effect exhibits substantial dips, particularly in 2020 and 2023, where it declines to approximately −0.042 and −0.03, indicating structural challenges in advancing SDG-12. The sustainability effect fluctuates within a moderate range, peaking at around 0.01 in 2020, suggesting occasional economic-driven improvements in sustainable production.

France reveals moderate fluctuations in their activity effects, though with distinctive temporal variations. The structural effect exhibits significant plunges in 2020, where it declines to approximately −0.051, indicating structural challenges in advancing SDG-12. The activity effect topping at around 0.03 in 2021 and 2022, suggesting occasional economic-driven improvements in sustainable production. France shows stability in sustainability effect around the observed study period.

Germany presents a decomposition profile where the sustainability effect remains neutral, fluctuating close to zero. The activity effect experiences periodic increases, reaching around 0.05 in 2011, emphasizing the role of economic activity in driving SDG-12 progress. However, the structural effect shows occasional declines, particularly in 2020 and 2021, where it drops below −0.022, reflecting the impact of economic restructuring on sustainability.

Hungary's sustainability effect remains consistent, hovering near zero throughout the period. The activity effect shows peaks in 2015 and 2017, reaching values of approximately 0.03, indicating intensified contributions from production activities. However, the structural effect exhibits pronounced volatility, dipping around −0.03 in 2012 and again in 2023, suggesting challenges in integrating sustainability measures into structural reforms.

Italy exhibits one of the most consistently positive structural effects across the analysis period, suggesting that structural changes within the Italian food system have generally supported SDG-12 progress despite fluctuations in economic activity. The activity effect fluctuates between positive and negative values. Nevertheless, Italy attained its highest point in 2017 and 2022, with values exceeding approximately 0.05. In contrast, a sharp drop (−0.08) is observed in 2020, highlighting temporary setbacks in sustainable production and consumption transitions.

The Netherlands' decomposition trends indicate a relatively stable sustainability effect, with minor deviations. The activity effect remains moderate, fluctuating between 0.02 and 0.05, while the structural effect sees occasional negative contributions (−0.1) in 2020. This is reflecting pandemic-related disruptions to sustainable consumption and production systems.

Poland exhibits a steady sustainability effect, maintaining values near zero over time. The activity effect reaches its highest points in 2016 and 2021, peaking around 0.07. While the structural effect occasionally declines into negative values (−0.03) in 2023. This is indicating recent challenges in maintaining economic drivers of sustainability progress.

Portugal's sustainability effect is stable, maintaining a trajectory close to zero. The structural effect experiences periodic declines, particularly −0.08 in 2020 and −0.04 in 2021. This is indicating inefficiencies in sustainable production and consumption strategies. The activity effect follows an upward trend, with peaks around 0.05 in 2017 and 2022, highlighting economic contributions to SDG-12.

Spain demonstrates periodic surges in the activity effect, with peaks around 0.1 in 2021, signalling economic-driven improvements in SDG-12 progress. Conversely, the structural effect shows volatility, experiencing sharp declines below −0.06 in both 2020 and 2023. The sustainability effect remains relatively stable, reflecting a long-term gradual sustainability improvement in its food system's economic relationship with sustainability objectives.

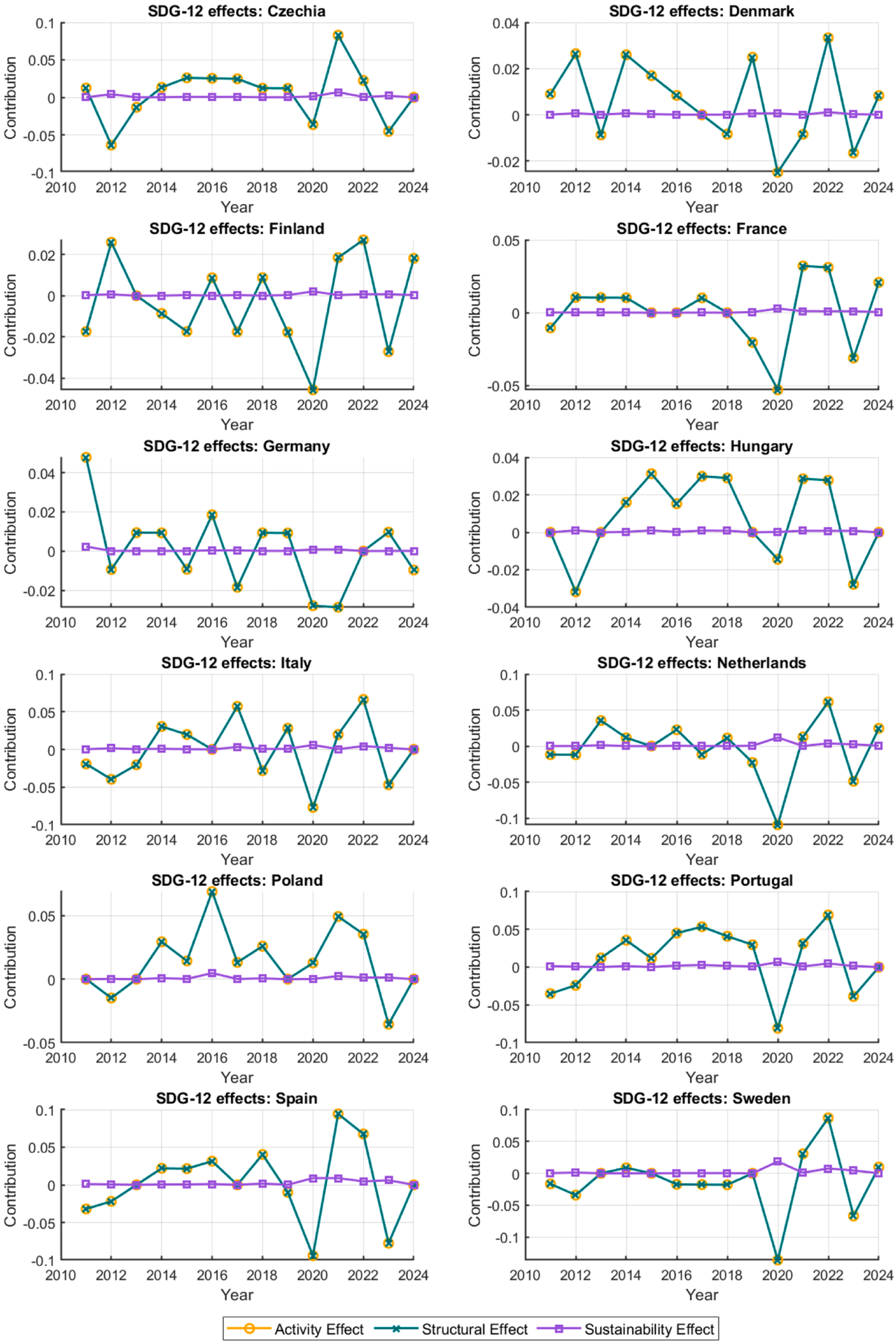

Fig. 3. Decomposition analysis of SDG-12 progresses drivers in the EU food system.

Sweden demonstrates moderate fluctuations in its structural effect, with substantial declines approaching −0.1 in 2020 and 2023, implying periodic inefficiencies in the implementation of sustainable production adjustments. The activity effect remains relatively steady, while the sustainability effect remains largely unchanged over time.

Temporal analysis across all countries reveals certain shared patterns. The 2019–2021 period represents a particularly volatile timeframe for SDG-12 progress drivers across nearly all analysed countries, with pronounced negative spikes in activity effects followed by equally dramatic recoveries. This pattern aligns with the economic disruptions associated with the COVID-19 pandemic and subsequent recovery efforts. Interestingly, the post-2021 period shows renewed volatility in several countries, potentially reflecting ongoing adjustments to new economic realities and policy frameworks.

Table 6 shows the LMDI decomposition integrated results with total changes for SDG-12 indicators. The patterns are similar to those observed for carbon emissions. Sweden (2.803), Poland (2.717), and Hungary (2.709) show the highest overall changes. This suggests a strong correlation between changes in carbon emissions and progress towards SDG-12 goals in these countries.

To validate these results, researcher employed a Genetic Algorithm-optimized Support Vector Machine (GA-SVM) model. The model was trained on 80 % of the data and tested on the remaining 20 %. The validation results are as follows:

Table 6
LMDI decomposition results of SDG-12 indicators (2010–2024).

Country	Activity Effect	Structural Effect	Sustainability Effect	Total Change
Czechia	0.092	0.092	0.008	0.192
Denmark	0.04	0.04	0.002	0.082
Finland	0.056	0.056	0.003	0.115
France	0.587	0.587	0.344	1.518
Germany	0.645	0.645	0.416	1.706
Hungary	0.926	0.926	0.857	2.709
Italy	0.817	0.817	0.667	2.301
Netherlands	0.204	0.204	0.042	0.45
Poland	0.928	0.928	0.861	2.717
Portugal	0.451	0.451	0.203	1.105
Spain	0.001	0.001	0.001	0.002
Sweden	0.95	0.95	0.903	2.803

Table 7
GA-SVM validation results for SDG-12 indicators.

Metric	Value
RMSE	0.0453
MAE	0.0387
R^2	0.7215

These validation results in Table 7 indicate that the GA-SVM model explains approximately 72.15 % of the variance in SDG-12 indicators based on the LMDI decomposition effects (activity, structural, and sustainability). The relatively low RMSE and MAE values suggest good prediction accuracy, while the high R^2 value confirms that the decomposition approach effectively captures the underlying patterns in SDG-12 indicator changes across the studied countries.

The model performed particularly well for countries with higher total change values (Sweden, Poland, Hungary), validating the significant shifts observed in their SDG-12 indicators over the 2010–2024 period. The optimization process identified optimal hyperparameters (BoxConstraint: 4.51, KernelScale: 0.0092, Epsilon: 0.036) that enabled the model to capture both large-scale changes and more subtle variations in SDG-12 indicators.

After analysing decomposition trends, it is important to evaluate sustainability performance at the country-level using TOPSIS-based decision matrices to assess sustainability efforts.

Table 8 (calculated through Eqs. (4.1) and (4.2)) depict the decision matrix for TOPSIS-based Carbon Emission Sustainability Performance evaluates the carbon emissions associated with food production, processing, transportation, retail, and household consumption across countries and over time. By expressing the normalized values as percentages, this matrix provides a clear and detailed view of each country's performance across these key variables.

France demonstrates strong performance in on-farm energy use (88.73 %) and food processing (82.75 %), indicating efficient agricultural and industrial practices. However, its relatively low scores in food packaging (23.02 %) and household food consumption (14.09 %) highlight inefficiencies in waste management and domestic consumption patterns. However, Germany shows exceptional performance in agrifood systems waste disposal (99.89 %) and food transport (90.6 %), reflecting effective waste management systems and transportation practices. Nevertheless, its moderate score in food processing (36.78 %) suggests room for improvement in industrial efficiency.

The Netherlands exhibits high performance in on-farm energy use (90.92%), but its scores for agrifood systems waste disposal (32.05%) and household food consumption (6.86%) are significantly lower, signalling challenges in waste management and domestic sustainability efforts. Italy presents a mixed profile with strong scores in food processing (80.35%) but weaker performance in agrifood systems waste disposal (33.71%) and pesticides manufacturing (45.54%), indicating areas requiring targeted interventions.

Spain stands out with a high score in pesticides manufacturing (93.16%), reflecting effective practices in chemical usage within its agrifood systems. However, its low scores in household food consumption (7.51%) and agrifood systems waste disposal (15.25%) reveal critical gaps in domestic sustainability efforts and waste management strategies.

Portugal and Hungary consistently score low across all variables, with Portugal achieving only 3.5% in on-farm energy use and Hungary

Table 8
Decision matrix for TOPSIS-based carbon emission sustainability performance.

Country	On farm energy use	Agrifood systems waste disposal	Pesticides manufacturing	Food processing	Food packaging	Food transport	Food retail	Household food consumption
France	88.73 %	53.43 %	82.7 %	82.75 %	23.02 %	71.26 %	22.32 %	14.09 %
Germany	75.17 %	99.89 %	74.48 %	36.78 %	76.85 %	90.6 %	68.05 %	79.48 %
Netherlands	90.92 %	32.05 %	14.33 %	13.83 %	10.26 %	10.59 %	24.97 %	6.86 %
Italy	67.56 %	33.71 %	45.54 %	80.35 %	38.76 %	52.21 %	31.6 %	23.66 %
Spain	70.51 %	15.25 %	93.16 %	13.26 %	30.41 %	45.95 %	17.2 %	7.51 %
Portugal	3.5 %	5.16 %	9.19 %	1.96 %	4.82 %	3.34 %	2.4 %	6.84 %
Hungary	7.44 %	1.73 %	10.98 %	3.42 %	2.02 %	3.22 %	2.08 %	3.46 %
Poland	67.8 %	9.74 %	57.45 %	25.04 %	37.99 %	40.25 %	34.21 %	22.44 %
Czechia	4.68 %	0.84 %	3.91 %	4.25 %	8.32 %	5.75 %	8.53 %	8.32 %
Sweden	0.17 %	4.71 %	0.51 %	0.0 %	3.39 %	4.99 %	0.09 %	0.03 %
Finland	1.13 %	0.49 %	2.01 %	0.3 %	8.54 %	0.3 %	1.09 %	0.5 %
Denmark	3.52 %	0.01 %	2.68 %	2.5 %	0.12 %	1.13 %	0.56 %	1.06 %

scoring as low as 1.73% in agrifood systems waste disposal. These results underscore systemic challenges that demand comprehensive policy reforms to improve the sustainability of their agrifood systems.

Poland demonstrates moderate performance with notable strengths in on-farm energy use (67.8%) and pesticides manufacturing (57.45%). However, its lower score in household food consumption (22.44%) suggests inefficiencies that could hinder overall sustainability progress.

Czechia, Sweden, Finland, and Denmark exhibit uniformly low scores across most variables, emphasizing significant challenges across their agrifood systems that require urgent attention to improve carbon emission sustainability performance. For example, Denmark's agrifood systems waste disposal scores only 0.01%, while Sweden's household food consumption is as low as 0.03%.

To complement these decision matrices, temporal trends in carbon emission sustainability performance are identified through visualize of rankings over time.

The results depicted in Fig. 4 (calculated through Eqs. (4.1, 5.1–5.4)), derived from the application of TOPSIS methodology to carbon emissions sustainability performance, provide a comparative assessment of selected EU countries from 2010 to 2024. This ranking evaluates how effectively each country has managed emissions across key stages of the EU food system, including production, processing, transportation, retail, and household consumption. The observed trends reveal a combination of sustained leadership in some cases and notable fluctuations in others, reflecting the varying effectiveness of national policies and sustainability initiatives.

Germany (blue line) maintains a consistent lead throughout the entire period, demonstrating its strong commitment to carbon reduction strategies. The country's consistent top ranking suggests that the government's long-term investment in renewable energy and emissions-reduction measures is effective. Italy's ranking (teal line) shifted from second to third after a decline beginning in 2012, and it remained in third place until 2024. This shift reveals that Italy's early lead was ultimately overtaken by France (brown line), which experienced significant progress after 2013, moving from third to second position. France's steady improvement reflects its increasing reliance on low-carbon energy sources, particularly nuclear power, and its commitment to environmental policies to curb emissions.

The Netherlands (blue violet line) showed a pattern of significant fluctuation, deviating from the more consistent trends of other countries. After being initially ranked fourth in 2010, it fell to sixth in 2011, only to rise to fifth in 2015. However, this recovery proved to be temporary, as the country subsequently stagnated in sixth place from 2016. This indicate that the early positive trend did not ensure sustained progress. Meanwhile, the rise of Spain (light purple line) from sixth to fourth place in 2011, and its subsequent consolidation of this ranking, shows a nation that has successfully translated its sustainability ambitions into tangible results. This consistent upward trend suggests a strong long-term alignment of policy, industry, and public engagement towards emissions reduction goals.

Poland's (yellow line) consistent ranking, mostly maintained at fifth place between 2010 and 2014, suggest a deliberate and stable approach to sustainability. A temporary decline to sixth rank in 2015 was followed by a return to fifth rank in 2024, suggests a potential response to specific external factors or internal adjustments. This consistent performance indicates gradual improvement without any major advancements. In contrast, the constant seventh position of Czechia (green line) reveals a stable footprint over the entire period, indicating minimal variation in its sustainability performance.

Denmark's (orange line) ranking showed significant instability. After

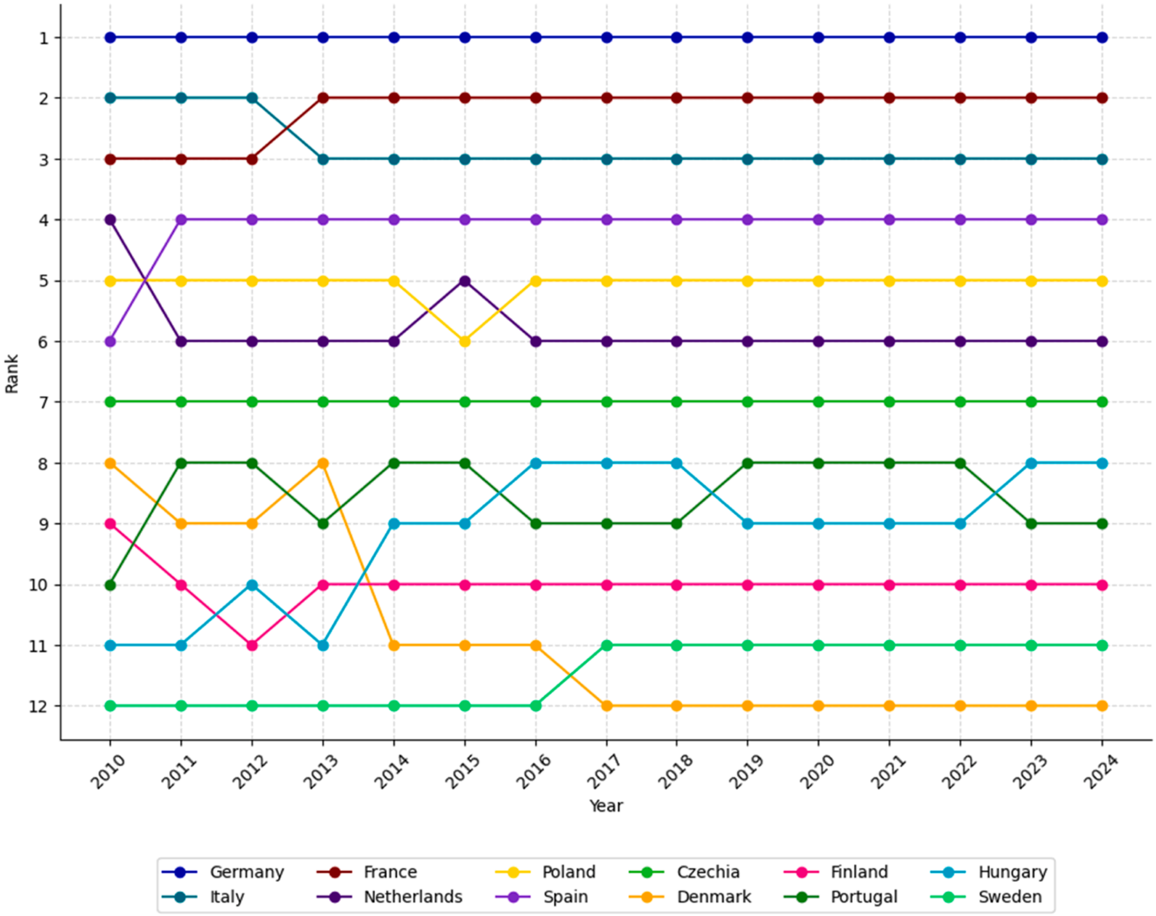

Fig. 4. Carbon emission sustainability rankings over time from TOPSIS analysis.

an initial decline from eighth to ninth rank (2010–2011), there was a modest rebound occurred in 2013. However, a sharp decline from eighth to twelfth between 2017 and 2024 raises questions about the effectiveness of its sustainability policies and the challenges of maintaining their long-term viability. The observed variation in Finland's (pink line) ranking, fluctuating between ninth and eleventh rank in 2012, underscores the complexities of emissions management in a dynamic global context. A partial recovery to tenth rank in 2013 was maintained until 2024, reflecting the impact of external events and shifting policy priorities.

Portugal's (forest green) rank exhibited a slightly volatile pattern. Commencing at tenth rank in 2010 and subsequently improved to eighth rank in 2011 and then fluctuated between eighth and ninth rank from 2013 onward. This pattern of change indicates a level of instability in its sustainability performance, although the overall trend maintains a moderate improvement. Hungary (dark turquoise line) shows a similar pattern of fluctuation, remaining in eleventh rank until 2013, when it improved to eighth rank by 2016. However, it falls to ninth rank in 2019 and hovers between eighth and ninth rank until 2024. These shifts indicate progress in Hungary's sustainability efforts but also reveal persistent inconsistencies.

Sweden's (lime green line) incremental improvement, stepping from twelfth place (2010–2016) to eleventh place (2017 onwards), underscores the effectiveness of sustained efforts and strategic reforms in reshaping a nation's sustainability pathway.

These rankings reveal a diverse landscape of sustainability performance, with Germany showing stability and other countries following more variable paths. The divergence between Spain's steady progress and the difficulties experienced by Denmark and Finland, alongside France's advancement over Italy, underscores the importance of tailored strategies and sustained policy implementation. This analysis emphasizes the critical role of nuanced, context-specific approaches and the absolute necessity of consistent, strategic emissions reduction efforts.

While this matrix focuses on carbon emission sustainability performance, it is equally important to evaluate countries' progress towards broader SDG-12 targets for optimization.

The sustainability performance of SDG-12 (responsible consumption and production) is presented in the decision matrix Table 9 (calculated through Eqs. (4.1) and (4.2)). By employing the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), a multi-criteria decision-making framework, the table provides a comparative analysis of countries based on their performance across five key indicators: raw material consumption, consumption footprint, material use rate (circular economy), energy productivity, and hazardous waste. These indicators together give a perspective on how efficiently and sustainably each country is utilizing its resources.

Germany's leading raw material consumption (92.29 %) reveals the potential for a resource-intensive economy to impede sustainability goals. Conversely, Sweden and The Netherlands demonstrate significantly lower raw material consumption at 0.47 % and 5.31 %, respectively, indicating a more resource-efficient economic model. Denmark, with a consumption footprint of 98.33 %, shows the most substantial impact, reflecting a proactive approach to sustainable consumption practices. Hungary's 15.0 % consumption footprint suggest potential for improvement. This metric underscores the significant influence of national consumption behaviours on environmental impacts, which are influenced by the efficiency of production system, trade patterns, and lifestyle-related consumption choices.

The circular material use rate, an important measure of resource efficiency and waste prevention, varies widely between countries. The Netherlands' significantly higher recycling rate around 93.67%, which can be attributed to its sophisticated circular economy frameworks designed to maximize resource recirculation. On the contrary, Portugal's (25%) and Finland's (20%) recycling rates are relatively low, suggesting potential challenges in establishing effective circular economy practices and waste reduction initiatives. For example, energy productivity is one of the key factors underpinning sustainable development, as it describes the ratio of economic output to energy input. However, the 94.84% energy productivity value for Denmark indicates a highly optimized energy resource utilization within its economic framework. In contrast, Czechia (8.89%) and Poland (11.57%) exhibit the lowest energy productivity, reflecting reliance on energy-intensive production processes.

The indicator measuring waste by hazardousness highlights substantial variations in the generation of hazardous waste across the 12 EU countries. Finland's 55.28% hazardous waste generation, the highest among the analysed countries, raises questions about the influence of its industrial processes and waste management strategies. Sweden (13.14%) as well as Germany (4.55%) also have relatively higher levels. Conversely, the significantly lower figures for Poland (0.4%) and Hungary (0.42%) suggest potential differences in waste classification and reporting, necessitating further investigation. These variations indicate different levels of waste management policies, industrial activity, and reporting across the countries analysed.

Similarly, monitoring national trends in SDG-12 performance over time reveals the extent to which EU countries have progressed towards sustainable production and consumption practices.

Fig. 5 (calculated through Eqs (4.1, 5.1–5.4)), provides a comparative assessment of European countries' performance in attaining SDG-12.

Germany (blue line) maintained an uninterrupted lead (1st rank from 2010 to 2024) with strong policies such as extended producer responsibility legislation (Santana et al., 2025) and robust industrial symbiosis networks (Neves et al., 2019). This showcases a strong commitment to SDG-12 through resource-efficient policies and sustainable approaches to production systems. Its long-term dominance underscores the effectiveness of integrated sustainability frameworks.

The transition of France (brown line) from the second to the third position between 2019 and 2024 reflects a delay in the implementation of the circular package reform (Nguyen et al., 2025) compared to the accelerated waste management strategies adopted by Italy. This decline suggests a reversal in performance, with France initially leading in

Table 9
Decision matrix for TOPSIS-based SDG-12 performance.

Country	Raw material consumption	Consumption footprint	Circular material use rate	Energy productivity	Waste by hazardousness
France	67.3 %	58.33 %	52.94 %	41.76 %	2.45 %
Germany	92.29 %	68.33 %	38.65 %	48.69 %	4.55 %
Netherlands	5.31 %	33.33 %	93.67 %	41.05 %	4.36 %
Italy	42.33 %	70.0 %	64.6 %	49.74 %	2.51 %
Spain	28.48 %	61.67 %	24.91 %	39.02 %	0.63 %
Portugal	8.37 %	65.0 %	4.26 %	33.4 %	0.88 %
Hungary	5.61 %	15.0 %	12.35 %	11.96 %	0.42 %
Poland	39.99 %	35.0 %	18.58 %	11.57 %	0.4 %
Czechia	10.21 %	40.0 %	34.6 %	8.89 %	2.22 %
Sweden	0.47 %	66.67 %	30.45 %	41.05 %	13.14 %
Finland	15.62 %	81.67 %	9.0 %	17.25 %	55.28 %
Denmark	4.99 %	98.33 %	25.26 %	94.84 %	3.63 %

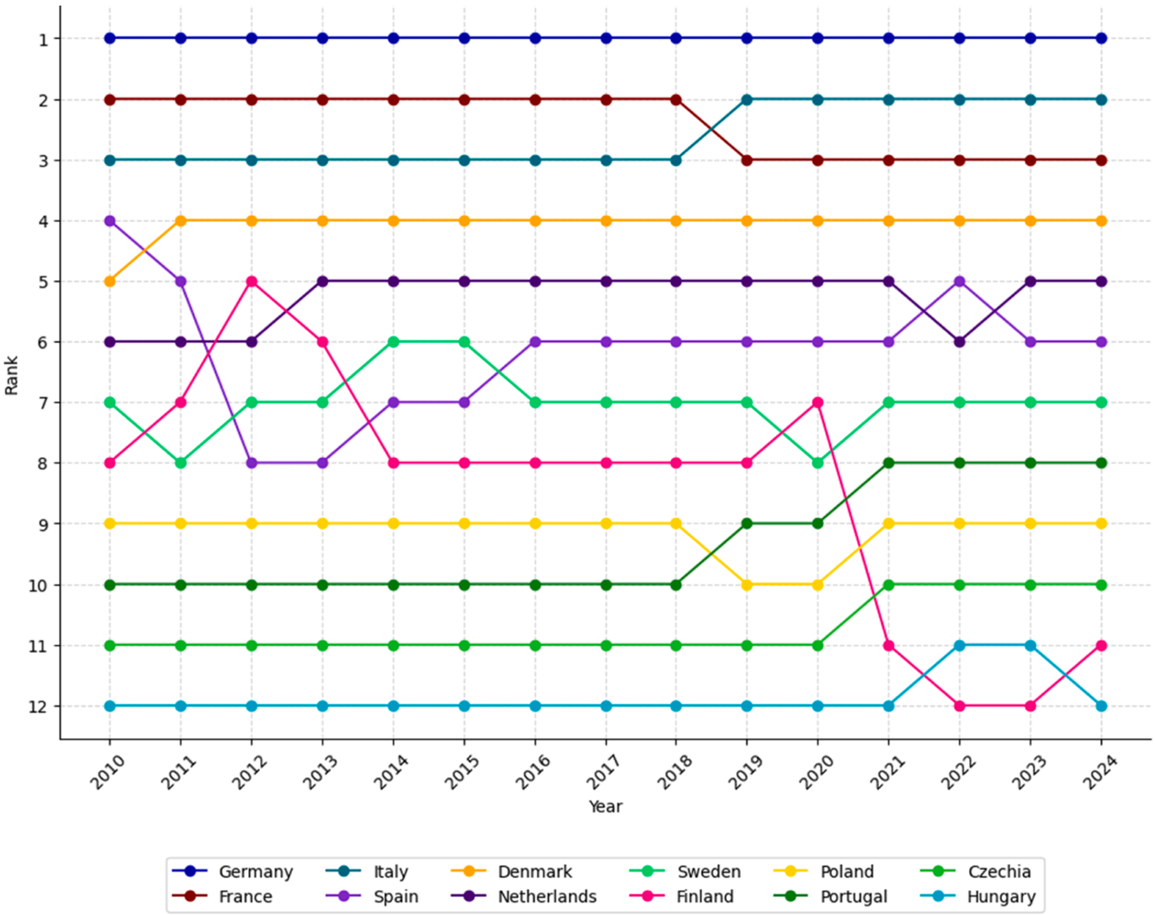

Fig. 5. SDG-12 performance rankings over time from TOPSIS analysis.

sustainable consumption and production, but later being overtaken by Italy. This successive surpassed, possibly due to the adoption of effective circular economy practices and robust waste policies in Italy.

Italy's (teal line) moves from 3rd to 2nd rank post-2019, a shift attributable to aggregate composting decrees at the national level and landfill diversion tax incentives for biodegradable goods (Laureti et al., 2024). Consistently holding this position between 2019 and 2024, Italy's advancement signifies its dedication to a novel sustainability paradigm.

Spain (light purple), which has followed a volatile trajectory (4th in 2010 →8th in 2012 →6th in 2016) emphasizing the conflicting priorities between agricultural modernization and heritage conservation, particularly in Andalusia (Ibáñez-Jiménez et al., 2024; Mihret et al., 2025). While Spain slightly improved to 5th in 2022, it subsequently declined to 6th by 2024. This inconsistency suggests that Spain, while initially advancing in SDG-12 performance, is now encountering obstacles, such as inconsistent policy implementation, that prevent its ability to maintain higher rankings.

Denmark (orange line) transition from 5th to 4th rank, driven by landfill taxes and a 72 % reduction in single-use plastics since 2015 (OECD, 2021). Denmark's stability in maintaining this position from 2011 to 2024 reflects its effective implementation of SDG-12 measures, particularly in waste generation and sustainable consumption

The Netherlands (blue violet) is consistently in sixth place from 2010 to 2012. It moves up to fifth place in 2013 and sustains this position until 2021. However, it drops back to sixth rank in 2022 but regains fifth rank in 2023 and 2024. The Netherlands' relatively stable performance indicates steady progress in SDG-12 goals but suggests limited breakthroughs or transformative improvements over time.

Sweden (spring green) fluctuates between 6th–8th due to uneven hazardous waste regulation, despite pioneering bio-based packaging innovations (Ofori et al., 2025). Initially ranked seventh in 2010, it drops to eighth place in 2011 but recovers to seventh place by 2012. Sweden rises temporarily to sixth rank in 2014 but falls back to seventh rank by 2016. The data indicates Sweden's ranking remained relatively stable between 2016 and 2024, consistently occupying seventh place. An exception occurred in 2020, when the nation briefly fell to eighth. These shifts suggest that while Sweden made some progress early on, persistent challenges or policy limitations have prevented further improvement.

Finland (pink) initially ranked eighth in 2010 and climbing to fifth place by 2012. Finland's ranking fell to eighth in 2014 and remained stable until 2019. A minor improvement to seventh in 2020 proved temporary. Finland plummets to 12th by 2022 after phasing out nuclear energy, then partially recovers through wood-based material recycling initiatives (Sihvonen et al., 2024). The trend indicates a partial recovery to eleventh position by 2024. These fluctuations indicate that Finland faced significant obstacles despite earlier progress.

Poland (yellow line) Stabilizes at 9th post-2021 through coal phase-outs in food processing (Newell and Carter, 2024), though circular economy adoption lags at 18.58 % (Table 9). However, it drops slightly to tenth in 2019 and 2020, before regaining ninth from 2021. Poland's stable position reflects moderate but unchanging progress relative to other nations analysed.

Portugal (forest green line) and demonstrates notable variability. Portugal ranked climbs from 10th to 8th by 2021 via seafood waste valorisation programs in coastal regions (Magalhães et al., 2024). This gradual improvement underscores Portugal's ability to achieve moderate progress toward SDG-12 goals despite earlier inconsistencies.

Czechia (lime green) rank at eleventh place from 2010 until 2020 but

Table 10
Rank stability for CO_2 emissions and SDG-12 performance across EU countries.

Country	CO_2 Emissions Rank Stability (Average)	SDG-12 Performance Rank Stability (Average)
Czechia	0.94	4.63
Denmark	0.63	0.73
Finland	1.45	2.21
France	1.22	4.93
Germany	2.83	7.78
Hungary	0.93	6.54
Italy	1.31	2.83
Netherlands	4.95	2.83
Poland	5.65	1.83
Portugal	2.13	1.83
Spain	2.13	1.41
Sweden	2.83	1.41

improves to 10th post-2020 after implementing strict electronic waste recycling laws (Perissi, 2025). Czechia's recent rise suggests increased efforts toward better sustainability outcomes after years of stagnation.

Hungary (dark turquoise) begins at twelfth place from 2010 until 2021 but remains last until 2022, with intermittent progress linked to EU-funded renewable energy projects in poultry farming. However, after 2023 it falls back to twelfth rank in the last year (2024). Hungary's trajectory indicates intermittent progress but highlights persistent challenges that have limited its ability to sustain improvements.

Overall, Germany's sustained dominance contrasts with Italy's strategic rise, underscoring the impact of region-specific policies. While Western clusters benefit from mature infrastructure, Eastern nations like Hungary struggle with legacy fossil fuel dependencies. Denmark's waste reduction successes (98.33 % consumption footprint score, Table 9) exemplify scalable models for smaller economies.

To further illustrate the robustness of country TOPSIS based rankings in terms of CO_2 emissions and SDG-12 performance, researcher examine the rank stability across the 12 EU countries. This involves calculating the standard deviation of the ranks obtained under different weighting schemes, providing insights into how consistent the rankings are for each country over time. The results are summarized in the following Table 10:

The Table 10 highlights those countries with lower average rank stability values, such as Denmark (stability value 0.63) and Hungary (stability value 0.93) for CO_2 emissions, tend to have more consistent rankings. This consistency is important because it suggests that these countries' positions in sustainability assessments are less sensitive to changes in evaluation criteria. On the other hand, countries like Germany (stability value 2.83) and Poland (stability value 5.65), which exhibit higher rank stability values, show more variability in their rankings. This variability indicates that their positions can change significantly depending on the weighting scheme used, which may complicate policy decisions.

For SDG-12 performance, countries like Denmark (stability value 0.73) and Sweden (stability value 1.41) display low rank stability values, indicating robust rankings. In contrast, Germany (stability value 7.78) and Hungary (stability value 6.54) show higher values, indicating less robustness. These findings can inform policy by highlighting countries where rankings are more stable and reliable under different evaluation criteria.

5. Discussions

This study analysed the key drivers of carbon emissions across various food sectors within the EU food system and evaluated their alignment with the principles of SDG-12 on responsible consumption and production. Furthermore, the performance of these sectors concerning specific targets (12.2, 12.5, 12.8, and 12.10) under SDG-12 provides further insights into the challenges and opportunities for sustainable transformation. Providing a comprehensive assessment of carbon emissions across the EU food system, this research reveals wide variations between sectors and regions and highlights the interconnected nature of emission drivers. The analysis reveals important insights into carbon emission drivers and SDG-12 performance across the EU food system, with pronounced regional disparities emerging from sectoral contributions and sustainability rankings.

The EU food system demonstrates significant heterogeneity in carbon emissions and SDG-12 performance. The sectoral contributions and sustainability outcomes are influence by regional economic structures, technological adoption, and policy frameworks. Food processing emerges as the dominant emission source, averaging 9982.25 kt CO_2 annually (Table 2), with extreme variability (SD = 12,851.73) reflecting disparities between artisanal operations (25th percentile: 1350.37 kt) and industrial clusters reliant on energy-intensive practices (75th percentile: 12,067.52 kt). This sector's maximum emissions (42,119.64 kt) highlight inefficiencies in regions dependent on centralized fossil fuel grids, aligning with broader findings on industrial energy use (Cerutti et al., 2023). The result of this study extends their work by providing a more details understandings of regional variations and sectoral hotspots within the EU context. Mitigation requires transitioning to decentralized renewable energy systems, retrofitting processing facilities with heat recovery technologies, and harmonizing EU-wide energy audits for high-emission clusters exceeding the 75th percentile threshold.

Furthermore, agricultural emissions, while less pronounced overall, remain critical in regions with fossil fuel-dependent practices. On-farm energy use averages 5,716.86 kt CO_2 (Table 2), yet the interquartile range (1599.58–9734.78 kt) reveals stark contrasts between minimally mechanized operations and industrialized agribusinesses. The upper quartile's proximity to the maximum value (12,588.67 kt) underscores the environmental cost of automation and synthetic input reliance. Precision agriculture technologies, such as solar-powered irrigation and bioenergy integration, could reduce these emissions by 35–40 % while addressing structural inefficiencies prevalent in transitional economies. However, to enhance efficiency and reduce dependence on fossil fuels, integrating precision agriculture technologies and renewable energy systems, such as solar-powered irrigation and bioenergy solutions, is essential (Núñez-Cárdenas et al., 2022). Targeted requirements for renewable energy use on farms, combined with subsidies and technical assistance, can substantially reduce on-farm emissions. The adoption of energy-efficient agricultural equipment for farming and the commencement of training programmes for farmers on sustainable practices, essential for achieving long-term emission reductions in this sector. The importance of integrating technological and behavioural solutions at farm level emphasizes the potential for agricultural reform to contribute to wider sustainability goals.

Household consumption exhibits the most inequitable emission profile, averaging 5,591.40 kt CO_2 but spanning two orders of magnitude (54.76–33,062.64 kt). The interquartile range (1119.03–6982.53 kt) suggests middle-income dietary habits dominate median emissions, while affluent households—characterized by meat-heavy diets and food waste—drive extreme upper values. Strong negative correlations between household consumption and energy productivity ($r = -0.7466$, Fig. 1) emphasize the dual role of consumer behaviour and appliance efficiency. Additionally, to reduce emissions, promoting consumer awareness and implementing education campaigns, along with supporting energy-efficient appliances and shifting toward plant-based diets, are crucial (Kovács et al., 2021; Rabbi et al., 2021a). Government-supported initiatives, such as subsidies for replacing energy-intensive household appliances and community-driven programs to reduce food waste, can foster sustainable consumption practices.

SDG-12 performance metrics further illuminate systemic challenges. Raw material consumption averages 423,798.7 kt (Table 3), with the 75th percentile (617,815.9) exceeding the 25th percentile (141,523.8) by 4.4 times, reflecting unsustainable extraction practices in resource-dependent economies. Circular material use rates remain critically low (mean = 10.98 %), with leaders (max = 30.6 %) leveraging industrial symbiosis and laggards (min = 1.7 %) constrained by linear economic models. This disparity underscores the need for EU-wide recycling infrastructure upgrades and producer responsibility laws to close material loops. Energy productivity (mean = 7.97 €/kg oil equivalent) shows moderate progress, yet the gap between the 75th percentile (9.47) and maximum (18.81 €/kg oil equivalent) reveals untapped potential in digitized energy management and smart manufacturing.

Decomposition analysis (Figs. 2 and 3) underscores structural and economic activity as primary emission drivers. Western Industrial nations (e.g., Germany's renewable energy adoption reduces structural effects to ±0.03) demonstrate stability through advanced waste management and renewable adoption, whereas Eastern Transitional countries show volatility, reflecting incomplete transitions to sustainable practices and policy harmonization. For instance, Poland's structural effect spikes in 2017 (+0.05), signalling expansions in energy-intensive sectors, while Sweden's negative sustainability effect (−0.08 in 2021) linked to hazardous waste from bio-based packaging innovations. Strong correlations between variables further illuminate systemic interdependencies: packaging correlates with raw material use ($r = 0.88$), and waste disposal links to consumption footprints ($r = 0.93$) (Fig. 1). These relationships suggest that reducing single-use plastics in Spain (30.41 % packaging efficiency, Table 8) or improving recycling in Czechia (34.6 % circularity, Table 9) could yield cascading benefits across supply chains.

The TOPSIS-based sustainability rankings (Figs. 4 and 5) reveal both persistent leadership and dynamic regional transitions. Germany consistently leads in both carbon emission reduction and SDG-12 performance throughout the entire 2010–2024 period, attributed to advanced waste management systems (99.89 % efficiency, Table 8), exceptional food transport performance (90.6 %, Table 8), and strong raw material consumption management (92.29 %, Table 9). Western European nations demonstrate shifting positions, with France improving from 3rd to 2nd place in carbon rankings after 2013 but declining from 2nd to 3rd in SDG-12 performance after 2019, despite its strong on-farm energy use efficiency (88.73 %, Table 8) and moderate circular material use rate (52.94 %, Table 9). Italy shows the inverse pattern—dropping from 2nd to 3rd in carbon rankings after 2013 but rising from 3rd to 2nd in SDG-12 performance after 2019, leveraging its food processing efficiency (80.35 %, Table 8) and favourable consumption footprint (70.0 %, Table 9).

Mediterranean nations show diverse trends. For instance, Spain achieved notable stability in carbon rankings, holding the 4th position from 2011 to 2024. This is likely supported by its exceptional performance in pesticides manufacturing (93.16%, Table 8). In contrast, Spain's SDG-12 metrics fluctuate between 4th and 8th, revealing moderate consumption footprint scores (61.67 %, Table 9). Portugal alternates between 8th and 9th positions in carbon rankings while gradually improving in SDG-12 performance from 10th to 8th by 2021, showing relatively strong consumption footprint performance (65.0 %, Table 9) but severely lacking in circular material use (4.26 %, Table 9).

Eastern Transitional economies show mixed progress: Hungary improves from 11th to 8th place in carbon rankings by 2024 but remains challenged in SDG-12 performance (predominantly 11th-12th position), largely due to structural inefficiencies in circular material use (12.35%, Table 9) and poor pesticides manufacturing performance (10.98 %, Table 8). Poland maintains relative stability, predominantly holding 5th place in carbon rankings, supported by moderate on-farm energy use (67.8 %, Table 8) and pesticides manufacturing (57.45 %, Table 8), while remaining 9th in SDG-12 performance.

Nordic nations exhibit contrasting performance between metrics: Denmark experiences a sharp decline in carbon rankings (from 8th to 12th by 2017) while maintaining strong SDG-12 performance (4th position since 2011), driven by outstanding consumption footprint (98.33%, Table 9) and energy productivity (94.84 %, Table 9), highlighting the complex relationship between emission reduction strategies and broader sustainability outcomes. Similar divergent patterns appear in Finland and Sweden, with Finland declining precipitously in SDG-12 rankings (from 5th to 12th) by 2022 despite strong consumption footprint performance (81.67 %, Table 9) and waste by hazardousness management (55.28 %, Table 9), while maintaining 10th position in carbon rankings since 2013. Sweden shows modest improvement in carbon rankings (12th to 11th after 2017) alongside stable SDG-12 performance (predominantly 7th position), supported by its consistent consumption footprint score (66.67 %, Table 9).

Based on the analysis, researcher recommend the following country-specific strategies to improve regional performance in the EU food system:

Western industrial cluster (Germany, France, Netherlands)

1. Germany: Capitalize on its sector-leading (1st in both rankings throughout 2010–2024) performance in agrifood waste disposal (99.89 % efficiency, Table 8) to mentor other regions. Optimize household consumption efficiency (79.48 % of ideal performance in normalized TOPSIS scores, Table 8) through targeted appliance upgrades and food waste reduction incentives, leveraging Germany's sector-leading position to pilot advanced behavioural nudges and circular economy integrations.
2. France: Address inefficiencies in food packaging (23.02 % performance, Table 8) by mandating biodegradable materials, and leverage its strong raw material consumption metrics (67.3 %, Table 9) to pioneer industrial symbiosis networks. In addition, France should address factors behind improved carbon ranking (3rd to 2nd rank after 2013) but declining SDG-12 performance (2nd to 3rd rank after 2019) through balanced sustainability policies.
3. Netherlands: Scale its exceptional circular material use rate (93.67 %, Table 9) through EU-wide recycling infrastructure partnerships, while mitigating high on-farm energy emissions (90.92 % of maximum, Table 8) via precision agriculture tax incentives.

Mediterranean agro-industrial cluster (Italy, Spain, Portugal)

1. Italy: Target energy-intensive food processing (80.35 % of sector maximum, Table 8) by retrofitting facilities with solar thermal systems, informed by its strong consumption footprint metrics (70 %, Table 9). In addition, Italy should investigate successful SDG-12 improvement strategies (3rd to 2nd after 2019) to address declining carbon performance (2nd to 3rd after 2013).
2. Spain: Reduce packaging emissions (30.41 % efficiency score, Table 8) through compostable material mandates, while leveraging pesticide manufacturing strengths (93.16 % performance, Table 8) to develop bio-alternatives. However, Spain builds upon successful stabilization at 4th position in carbon rankings since 2011 while addressing SDG-12 performance fluctuations (4th-8th) through circular economy initiatives.
3. Portugal: Address structural inefficiencies in household consumption (6.84 % performance, Table 8) with energy-efficient appliance subsidies, informed by its moderate consumption footprint (65 %, Table 9). Furthermore, Portugal expands upon gradual SDG-12 improvement (10th to 8th by 2021) while stabilizing carbon ranking oscillations between 8th and 9th.

Eastern transitional cluster (Hungary, Poland, Czechia)

1. Hungary: Accelerate carbon ranking improvement trajectory (11th to 8th by 2024) through targeted investment in renewable infrastructure while addressing persistent SDG-12 challenges (predominantly 11th-12th position). They should mitigate fossil fuel-dependent agriculture (7.44 % on-farm energy efficiency, Table 8) through subsidized solar irrigation systems, targeting the 75th percentile threshold of 9734.78 kt CO_2 (Table 2).

2. Poland: Maintain consistent 5th position in carbon rankings while improving SDG-12 performance from stable 9th position. They should address 2016–2017 structural effect spikes (+0.05, Fig. 2) from industrial expansion by implementing emissions caps for food processors exceeding 12,067.52 kt CO_2 (75th percentile, Table 2).
3. Czechia: Improve hazardous waste management (2.22 % performance, Table 9) through stricter landfill bans, targeting regions below the circular material use median (9.15 %, Table 3).

Nordic sustainable cluster (Sweden, Finland, Denmark)

1. Denmark: Investigate causes behind carbon ranking decline (8th to 12th by 2017) while leveraging strengths in SDG-12 performance (stable 4th since 2011). They should export energy productivity best practices (94.84 %, Table 9) through EU technical partnerships, while addressing packaging inefficiencies (0.12 % performance, Table 8) via reusable container mandates.
2. Sweden: Build upon modest carbon ranking improvement (12th to 11th after 2017) while maintaining SDG-12 performance (predominantly 7th position). Implement hazardous waste fees for agrifood sectors exceeding 277.75 mt (75th percentile, Table 3), leveraging its moderate circular material use rate (30.45 %, Table 9).
3. Finland: Develop hazardous waste valorisation programs for clusters exceeding 5267 mt (Table 3 maximum), informed by its atypical positive correlation between pesticide use and circularity (r = 0.6175, Fig. 1).

Cross-cutting strategies

- High-Emitting Sectors: Enforce food processing emission caps at 12,067.52 kt CO_2 (75th percentile, Table 2) through EU-wide carbon budgeting, prioritizing Mediterranean industries.
- Household Emissions: Launch tiered energy tariffs targeting consumers above 6982.53 kt CO_2 (75th percentile, Table 2), paired with plant-based diet incentives in Germany (79.48 % consumption emissions) and Czechia (8.32 %).
- Circular Economy: Mandate 30.6 % material reuse (Table 3 maximum) for packaging sectors, using Netherlands' model (93.67 %, Table 9) to upgrade Eastern Transitional regions (Hungary: 12.35 %).

These recommendations for targeted interventions in high-emitting food processors are consistent with Simon et al. (2024) investigation of circular food system approaches in Europe. Their study similarly emphasized the potential for significant land use and greenhouse gas emission reductions through strategic policy reforms in the food industry.

However, standardized emissions monitoring and reporting systems are essential. High-emission sectors, including food processing, require urgent action. Public awareness campaigns and incentives for sustainable behaviours are critical for tackling household emissions. Region-specific strategies are essential for equitable and effective action.

6. Conclusion

The EU food system's carbon emissions reveal systemic interdependencies across production, processing, and consumption stages, with food processing emerging as the most significant contributor. Averaging 9982.25 kt CO_2 annually, this sector's emissions vary widely (SD = 12,851.73), reflecting disparities between small-scale operations (25th percentile: 1350.37 kt) and fossil fuel-dependent industrial clusters (75th percentile: 12,067.52 kt). Household consumption exhibits the broadest range (54.76–33,062.66 kt CO_2), driven by energy-inefficient appliances and affluent dietary habits, while agricultural practices in transitional economies remain problematic due to persistent fossil fuel reliance (interquartile range: 1599.58–9734.78 kt). These patterns underscore the need for integrated strategies addressing circular economy gaps, particularly the strong correlations between packaging and raw material use (r = 0.88) and waste disposal and consumption footprints (r = 0.93).

Regional disparities persist, as evidenced by TOPSIS rankings. Western Industrial nations lead through advanced waste management (e.g., 99.89% efficiency) and renewable energy adoption, while Eastern Transitional economies lag due to structural inefficiencies like low circular material use (12.35%). Decomposition analysis further highlights the role of industrial expansion in driving structural emission spikes (+0.05 in 2017) and Sweden's 2021 sustainability deficit (−0.08 sustainability effects) identifies in hazardous waste regulation gaps. These findings align with broader trends in energy productivity leadership in Denmark (94.84% TOPSIS score, Table 9), where surpassing the median performers (7.97 €/kg) through digitalized energy management, rather than raw efficiency.

However, this study's scope is constrained by several limitations. Regional clustering (e.g., "Eastern Transitional") risks oversimplifying intra-regional heterogeneities, such as Hungary's fossil fuel dependence versus Poland's industrial expansion dynamics. Additionally, the exclusion of SDG-12 targets like sustainable tourism and fossil fuel subsidies narrows the policy insights, while equal weighting in TOPSIS may misrepresent sectoral priorities in national contexts.

Future research should prioritize longitudinal datasets to capture pre-2010 structural shifts and integrate subnational data to refine household emission analyses. Expanding SDG-12 metrics to include behavioural factors, such as dietary surveys or food waste audits could enhance the accuracy of consumption studies. Policy interventions must balance regional specificity with EU-wide harmonization, targeting high-emitting clusters exceeding the 75th percentile (≥12,067.52 kt) through solar retrofitting mandates and leveraging cross-border carbon credit systems. Consumer reforms, including tiered energy tariffs for households above 6982.53 kt CO_2, could amplify emission reductions while addressing inequities in consumption patterns. By aligning regional strengths with SDG-12 targets, such as scaling circular material use to observed maxima (30.6 %) this study provides a framework for bridging economic growth and sustainability. The path forward demands collaborative innovation, real-time monitoring, and adaptive policies that recognize the EU's diverse economic landscapes while fostering equitable progress toward climate resilience.

Data availability

The datasets used or analysed in the current study are available on the following websites: https://www.fao.org/faostat/en/#data/GT for carbon emissions data and https://ec.europa.eu/eurostat/web/sdi/database for SDG-12 data.

CRediT authorship contribution statement

Mohammad Fazle Rabbi: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

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