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Optimizing carbon emissions and SDG-12 performance in the EU food system

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Abstract

The European Union's aspiration to the sustainable food future hinges on a fundamental question: how to optimize the carbon footprint of our plates? This study evaluates pathways to reduce carbon footprint and enhance SDG-12 performance in eight EU countries from 2010 to 2022. Carbon emissions are analyzed across production, processing, distribution, and consumption stages, providing critical insights for meeting the Green Deal's targets of reducing CO_2 and non-CO_2 emissions. Food processing is identified as the dominant emission source, averaging 30.5% of total emissions and reaching 52% in France and 47.8% in Italy. Household food consumption accounts for 32.2% of emissions in Germany, 28.1% in Czechia, and 26.7% in Portugal, while on-farm energy use contributes 25.2% in Hungary and 19.5% in Portugal. Strong correlations are observed between raw material consumption and both food packaging ($r = 0.88$) and agrifood system waste disposal ($r = 0.93$), indicating systemic inefficiencies. Sustainability Index trends reveal marked regional disparities, with Germany consistently scoring between 0.8 and 1.2, and Hungary and Portugal predominantly in the negative range (-0.4 to -0.8). Principal Component Analysis shows that the first component explains 75.6% of total variance, with key contributions from raw material consumption, household food consumption emissions, and consumption footprint. Decomposition analysis attributes emission changes primarily to structural economic shifts and improvements in sustainability practices, particularly in Italy, Portugal, and Spain. Circular material use rates improved notably after 2013 in France and post-2016 in Spain. The study recommends targeted policies to reduce on-farm emissions, promote renewable energy, and incentivize efficient technologies. Such interventions could reduce emissions by over 20% in food processing and up to 50% in households, highlighting major opportunities for carbon mitigation and progress toward the EU's sustainability and climate goals.

Highlights

- Food processing is the largest emission source in the EU food system, averaging 30.5%, with France (52%) and Italy (47.8%) as the highest contributors.
- Household consumption emissions are significant, particularly in Germany (32.2%), Czechia (28.1%), and Portugal (26.7%), driven by energy-intensive behaviours and dietary preferences.
- On-farm energy use accounts for 25.2% of emissions in Hungary and 19.5% in Portugal, reflecting heavy reliance on fossil fuels in agricultural operations.
- Strong correlations exist between raw material consumption and food packaging ($r = 0.88$) and agrifood systems waste disposal ($r = 0.93$), highlighting systemic inefficiencies and interconnectedness.

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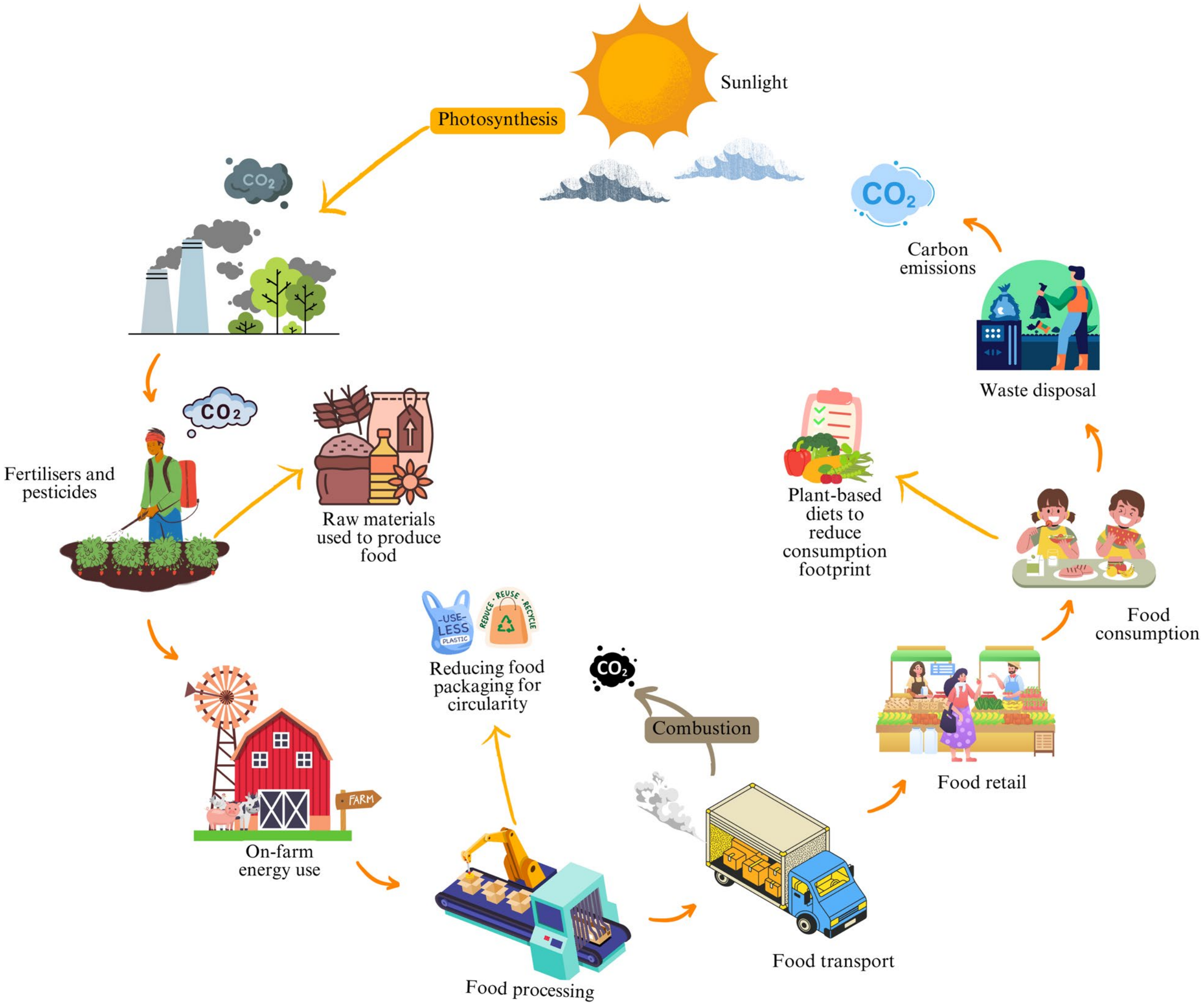
- Sustainability Index trends reveal significant regional disparities, with Germany consistently performing well (index values between 0.8 and 1.2), while Hungary and Portugal face persistent challenges (index values -0.4 to -0.8).
- Circular material use rate trends highlight progress in resource efficiency, with France showing consistent positive contributions post-2013 (+0.02 to + 0.1) and Spain demonstrating robust adoption post-2016 (+0 to + 0.01).

Keywords Carbon footprint, Sustainable food system, Food supply chain impact, Circular food economy, Sustainable production and consumption

Graphical Abstract



1 Introduction

The sustainability transition within the European Union (EU) encounters a considerable impediment in the form of its extensive food system, which is essential to its economic and societal framework. Moreover, achieving the ambitious benchmarks of SDG-12 necessitates a critical evaluation of the EU's food system's carbon performance. The food sector, encompassing production, processing, distribution, and consumption, is responsible for approximately one-third of global greenhouse gas (GHG) emissions (Gautam et al. 2025). In the EU, the building sector contributes between 20% and 30% of total greenhouse gas emissions, highlighting its substantial role in climate change (Directorate-General for Environment 2023; Rabbi MF 2024). Beyond its environmental significance, a sustainable food system represents a key strategic for the EU to effectively meet its overarching target of climate neutrality by 2050 (Raihan et al. 2024).

Agriculture associated with emission-intensive practices (Rahaman et al. 2023), particularly livestock farming, which is notorious for methane emissions stemming from enteric fermentation in ruminants such as cattle and sheep (Liu et al. 2024). Moreover, the production of pesticides has an environmental impact on emissions that depend on the type and quantity of pesticide chemicals used, along with the production methods, and trade practices (Zhang et al. 2024). Methane, being far more potent than carbon dioxide in trapping heat within the atmosphere, amplifies the urgency to address these sources. Beyond livestock, crop production contributes heavily to emissions through energy-intensive processes such as irrigation and fertilization. These activities are further complicated by regional disparities in farming practices, energy policies, and technological adoption, making standardized solutions elusive.

Despite various policy frameworks that aim to decarbonize agriculture and promote sustainability, such as the European Green Deal and its ‘Farm to Fork’ strategy, progress remains uneven (Simon et al. 2024). The Common Agricultural Policy (CAP), while incorporating eco-schemes and other green initiatives, has been criticized for failing to drive substantial environmental transformation (Langlais 2023). For instance, the discretion given to EU member states has frequently resulted in national policies that reinforce conventional agriculture at the expense of more innovative and sustainable methods (Panigrahi et al. 2023). This gap between ambitious policies and their actual implementation highlights the intricate challenges of enacting widespread change within a governance system that lacks strong central coordination.

Energy consumption across the food supply chain presents another critical challenge (Aziz et al. 2025). The reliance on fossil fuels for activities like harvesting and irrigation not only inflates emissions but also reflects inefficiencies that could be mitigated through technological advancements and renewable energy integration (Cerutti et al. 2023; Liu et al. 2023). However, smaller farms often face barriers such as high capital costs for infrastructure improvements or limited access to digital tools that could optimize resource use. Addressing these disparities will require targeted subsidies, training programs, and collaborative approaches that pool resources and knowledge among stakeholders.

Furthermore, the lifecycle of food within the EU also generates substantial emissions through waste (Sund et al. 2025). This issue spans the entire supply chain, from agricultural leftovers to household waste, significantly increasing GHG output. Methane released from landfills demonstrates this issue, while alternative methods such as composting or anaerobic digestion remain underutilized in many regions. The European Green Deal has sought to address this ineffectiveness by promoting circular economy principles that prioritize resource recovery and waste valorization (Raihan 2024; Kristia and Rabbi 2023). SDG-12 serves as a guiding framework for these efforts by advocating for sustainable production patterns that minimize environmental degradation while ensuring economic viability. However, achieving this balance requires a nuanced understanding of carbon emissions across all stages of the food supply chain. For example, monitoring frameworks like the EU Food System Sustainability Model provide valuable insights into emission hotspots but also highlight data gaps that hinder comprehensive analysis (Acs et al. 2025). Bridging these gaps will necessitate robust participatory processes involving policymakers, researchers, farmers, and consumers.

The transition to sustainable food systems also hinges on behavioral changes at both institutional and individual levels (Dagevos and Onwezen 2025). Policies promoting plant-based diets or reducing meat consumption can significantly lower emissions associated with livestock farming. Similarly, consumer education campaigns aimed at reducing food waste or encouraging sustainable purchasing decisions can amplify the impact of systemic reforms (Widayat et al. 2025).

Moreover, post-production activities such as processing, packaging, transportation, and refrigeration exacerbate the food system’s environmental impact. For instance, refrigeration alone accounts for a significant portion of emissions due to its reliance on hydrofluorocarbons (HFCs), which are potent GHGs (Poyntz-Wright et al. 2023). Similarly, food processing is a resource intensive stage that transforms raw agricultural commodities into consumable goods and has often resulted in significant emissions. Variations in CO_2 emissions are associated with differences in the food processing industry, energy and material inputs and outputs of processing, technology, and demand (Knorr 2024). Food packaging, which is essential for protecting and preserving food, also generates emissions influenced by the material used and the efficiency of the packaging process. These interconnected stages highlight the complexity of managing emissions within the food supply chain (Punia Bangar et al. 2023).

Furthermore, transportation and retail activity further amplify the food system’s carbon footprint. Food transport involves fuel consumption for carrying foods and crops from farms to markets, and retail stores to consumers. Consequently, CO_2 emissions from food transport depend on the mode of transport, product delivery distance, infrastructure quality, and the classification of the exhaust gases emitted by the vehicles (Jiang et al. 2024). In addition, food retail, which refers to the food products that are sold to consumers through various outlets, is responsible for significant carbon emissions. However, emissions from retail operations depends on factors such as competition, consumption behavior, and technological advancement (Marrucci et al. 2020). Household's food consumption is the final stage of the food life cycle (Kristia et al. 2023). The energy used in cooking processes, dietary habits, food storage, and waste disposal all contribute to CO_2 emissions. Dietary habits and cultural preferences play a key role in shaping the carbon footprint at the food consumption stage, highlighting the need for targeted interventions that address consumer behavior (Xie et al. 2023).

An additional challenge for the EU's sustainability is the significant environmental impact associated with raw material consumption, the limited use of circular materials, and the growing consumption footprint (Baldassarre 2025; Distefano et al. 2024). Addressing these issues is consistent with the SDG 12, particularly target 12.2 (sustainable management and efficient use of natural resources), target 12.5 (significantly reduce waste generation), and target 12.8 (ensure awareness of sustainable consumption and production). Raw material consumption (target 12.2) and circular material use (target 12.5) emerge as key indicators to measure the sustainability of food systems.

High raw material consumption is often associated with increased emissions, especially when energy-intensive and unsustainable inputs are utilized in the manufacturing process of packaging and fertiliser. However, agricultural activities are solely responsible for over 50% of raw material use in the EU, including water, fertilizers, and soil nutrients (Rodríguez-Espinosa et al. 2023). The unsustainable management of these inputs often leads to resource depletion, biodiversity loss, and soil degradation (Castillo-Díaz et al. 2023). The close correlations between raw material use, packaging emissions, and waste disposal highlight that food supply chains are interconnected. This systemic complexity is a calling for solutions that integrate multiple sectors to maximise emission reductions (Máté et al. 2020). On the other hand, SDG target 12.5 underscores the importance of adopting circular economy principles, such as recycling, reuse, and waste valorisation. Circular material use within the European food system offers a pathway to significantly reduce waste generation and emissions while promoting sustainability (Rabbi and Amin 2024). Greater use of circular materials reflects efficient recycling and reuse practices that help reduce overall emissions. In the EU food sector, these principles translate to innovative strategies for managing by-products, reprocessing food waste, and creating bio-based materials. In addition, SDG target 12.8 emphasizes the need for public awareness and education to promote sustainable consumption patterns (Mensah et al. 2024). The consumption footprint of Europe's food system remains significant, driven by resource-intensive diets, elevated levels of food waste, and a general lack of awareness about sustainable alternatives. The Guillaume et al. (2024) estimated that shifting consumer preferences toward plant-based diets could reduce the consumption footprint of the average European by up to 25%.

Achieving alignment with SDG-12 requires a holistic understanding of carbon emissions across all stages of the food supply chain not merely identifying hotspots but also contextualizing them within broader economic and social frameworks (Raman et al. 2024). Moreover, reduction of emissions and improving sustainability performance requires a multi-dimensional approach that examines the contributions of different sectors to global emissions, as well as cross-country differences in raw material consumption (target 12.2), circular material use (target 12.5), and consumption footprint (target 12.8) (Cifuentes- Faura 2025). Additionally, it will also improve understanding of how food production processes and consumption patterns affect the environment.

Despite existing studies on individual carbon emissions within the EU food system (Corona et al. 2024; Vandermeersch et al. 2014; Bryant et al. 2024; Mensah et al. 2024; Castillo-Díaz et al. 2023; Liu et al. 2024; Directorate-General for Environment 2023), a clear understanding of how to optimize these emissions for improved SDG-12 performance is missing. In addition, measuring the cumulative environmental impact for the integrated carbon emissions from the food production, processing, transport, and consumption stages through the lens of the SDG 12.2, 12.5, and 12.8 indicators in selected eight EU countries remains unexplored.

This research bridges these gaps by integrating country-level comparisons, sectoral emission analyses, optimizing the sustainability performance to provide actionable insights into carbon mitigation strategies. Researchers identified two research questions to address the research gap, such as, RQ1: What are the relative contributions and emission intensities of carbon emission sources across the EU agri-food value chain stages? and RQ2: How do variations in circular material use rates, alongside raw material consumption and consumption footprints, influence the sustainability performance of EU countries?

The primary objectives of this study are twofold: first, to analyze the drivers of carbon emissions within the

EU food system, and second, to assess their alignment with Sustainable Development Goal 12, which promotes responsible consumption and production. By pinpointing the key factors contributing to these emissions, this research aims to inform strategies that encourage resource-efficient production, circular economy practices, and more sustainable consumption behaviors, thereby providing timely recommendations for decarbonizing the food system in line with the EU's Green Deal and Farm to Fork Strategy and meeting the growing demand for sustainable consumption and production.

2 Materials and methods

2.1 Study area

This study analyzes the carbon footprint of the food system, focusing on the entire farm-to-fork supply chain. Recognizing the critical importance of sustainable production and consumption patterns, it examines the links between carbon emissions and the achievement of sustainability goals, particularly within the context of SDG-12. By analyzing data from eight diverse European nations: Czechia, France, Germany, Hungary, Italy, Poland, Portugal, and Spain, this research aims to optimize carbon emission and measure SDG-12 performance in fostering a more sustainable and environmentally responsible food system.

2.2 Data collection and variable selection

Data from the Food and Agriculture Organization of the United Nations (FAO) (United Nations 2023) and the database of the European statistics (Eurostat 2023) provided the foundation for this study. The researcher assessed the impact of carbon emissions on sustainable production and consumption using an eleven-variable dataset. Eight variables track food system carbon emissions, and three correspond to SDG-12 indicators, across eight EU countries from 2010 to 2022.

To accurately model the relationship between carbon emissions and Sustainable Development Goals (SDGs) within EU food systems, a selection of relevant variables and cross-domain indicators was crucial. This approach aims to support global efforts towards achieving the SDGs and the net-zero target. The key indicators selected to characterize this complex relationship are summarized in Table 1.

2.3 Analytical procedure

A structured analytical approach was used to process and interpret the collected data to achieve the research objectives. As a result, the study utilized MATLAB 2024b to perform cross-country comparisons, analyzing sectoral carbon emissions, evaluating the sustainability index, and perform decomposition analyses. In addition, Python version 3.13.2 was utilized to perform correlation network analyses.

To begin with, the country comparisons analysis (Figs. 1 and 2) calculated average carbon emissions and SDG-12 progress for each country, providing insights into the relative contributions of different countries to the overall emission profile. This allowed the researcher to understand the relative contribution of each nation to the total emission landscape. The formula underpinning this analysis is:

$$MeanV_1\left(C_j\right) = \frac{1}{T_i}\sum_{t=1}^{T_i} D_{ij} \tag{1}$$

Here, D_{ij} represents the CO_2 emission value for each variable. However, T_i is the number of years for eleven variables and C_j representing the eight EU country (e.g. Germany, Italy, Hungary).

Following this, correlation analysis (Fig. 3) was conducted to evaluate the relationship between different variables. This step was essential to determine how fluctuations in one variable corresponded with those in others. To facilitate interpretation, a heatmap was generated to visually represent the correlation matrix, aiding the identification of potential interdependencies among emission categories or variables. The formula used for calculating the correlation coefficient r_{ij} is:

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

The magnitude of r_{ij} signifies the strength of the correlation observed. In this context, T represents the number of years included in the analysis. Furthermore, D_{i1t} and D_{i2t} denote the individual data points for variables D_{i1} $\text{SusE}_{c,t} = \log\left(\frac{E_t}{E_{t-1}}\right) \times \log\left(\frac{S_t}{S_{t-1}}\right)$ and D_{i2} respectively, across each of the T years. 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.

Subsequently, the sectoral analysis (Figs. 4 and 5) examined the distribution of total emissions for each variable by summing values across all EU countries. This provided an overview of sectoral contributions, with percentages computed to represent the proportional contribution of each category to the overall emissions profile. The formulas used for this analysis are as follows:

$$TotalEmissionsV_i = \sum_{j=1}^{N} D_{ij} \tag{3}$$

Table 1 Key variables and cross-domain indicators linking carbon emissions to SDG 12 performance in EU food systems

Category	Pillar	Variables	Descriptions (cross-domain impact)	Data source	Measurement
CO_2 Emissions	Food Production	On-farm energy use	Direct CO_2 emissions from energy consumption during farming activities, including machinery operation, irrigation, and climate control, directly contribute to resource-intensive production practices, affecting material and energy efficiency targets under SDG 12	FAO	Kilotons of CO_2
		Pesticides manufacturing	Emissions from the energy-intensive production of pesticides (e.g., raw material extraction, synthesis processes) add to upstream environmental impacts, undermining sustainable production goals in SDG 12	FAO	Kilotons of CO_2
	Food Processing	Food processing	Carbon emissions from energy use and industrial processes in transforming agricultural products into food contribute to production inefficiencies and higher lifecycle emissions, impacting SDG 12 targets on sustainable production and consumption	FAO	Kilotons of CO_2
		Food packaging	Emissions generated during the manufacture of packaging materials (plastics, paper, etc.) increase material throughput and waste, directly challenging SDG 12 objectives on reducing waste generation	FAO	Kilotons of CO_2
	Food Distribution	Food transport	Fossil fuel emissions from transporting food products across supply chains amplify the carbon footprint of food systems, affecting SDG 12 goals related to sustainable supply chain management and resource use	FAO	Kilotons of CO_2
		Food retail	Emissions from energy-intensive retail activities (lighting, refrigeration, heating) reflect inefficiencies in the final stages of food distribution, influencing SDG 12 efforts to improve energy and material efficiency across sectors	FAO	Kilotons of CO_2
	Food Consumption	Household food consumption	Indirect emissions linked to household-level food preparation, storage, and waste disposal contribute to consumption-driven environmental impacts, aligning with SDG 12's call for sustainable consumption patterns	FAO	Kilotons of CO_2
		Agrifood systems waste disposal	Emissions from the management and disposal of agrifood waste (landfilling, incineration, waste-to-energy) exacerbate material loss and emissions, challenging SDG 12 targets to substantially reduce waste generation	FAO	Kilotons of CO_2
SDG-12 Targets	SDG 12.2	Raw material consumption	Indirect emissions associated with the extraction, processing, and transport of food system raw materials highlight inefficiencies in resource use, critical to achieving sustainable material footprint targets under SDG 12.2	Eurostat	Kilotons (kt)
	SDG 12.5	Circular material use rate	Measures the emissions reductions achieved through recycling, reuse, and material recovery practices. A higher circular material use rate indicates lower emissions per unit of consumption, directly supporting SDG 12.5 goals	Eurostat	Percentage (%)
	SDG 12.8	Consumption footprint	Reflects the per capita environmental impact of food consumption behaviors, integrating lifecycle CO_2 emissions into an indicator for promoting sustainable lifestyle education under SDG 12.8	Eurostat	Per Inhabitant

Table 1 outlines key variables capturing direct and indirect carbon emissions across the food production, processing, distribution, and consumption stages, alongside key SDG 12 indicators (12.2, 12.5, and 12.8) related to resource efficiency, waste reduction, and sustainable consumption patterns. Kilotons of CO_2 refers to thousands of metric tons of carbon dioxide equivalents. Percentage (%) indicates the rate of reduction or efficiency. Per Inhabitant refers to the environmental impact per person

Here, V_i represents emission from food production, process, and consumption stages. N represents the selected eight EU countries and D_{ij} represents the CO_2 emission value from each country.

Thereafter, the emission value in Figs. 4 and 5 was transformed into a percentage (%) using the following formula:

$$PercentageV_i = \frac{TotalEmissionsV_i}{TotalEmissions} X100 \tag{4}$$

At this point, *TotalEmissions* is the sum of emissions from 8 selected EU countries. After converting the value into a percentage, the emission rate became better understandable.

Building on these analyses, the sustainability index (Fig. 6) was calculated by first normalizing all eleven variables to ensure comparability across different scales:

$$\boldsymbol{Z_{ij}} = \frac{\boldsymbol{X_{ij} - \mu_j}}{\boldsymbol{\sigma_j}} \tag{5}$$

The normalized value of each variable is j for a specific observation i, denoted as Z_{ij}, is derived from the original value of the variable X_{ij}. This normalization process involves subtracting the mean of the variable j, represented as $\boldsymbol{\mu_j}$, from the original value X_{ij} and then dividing by the standard deviation of the variable j, denoted as $\boldsymbol{\sigma_j}$. This method ensures that the variable is standardized, facilitating comparisons across different observations and variables.

The normalized variables were then input into principal component analysis (PCA) (Table 2) to determine their respective weights, as expressed below:

$$Y_i = \sum\nolimits_{j=1}^{11} Z_{ij} \times C_j \tag{6}$$

The PCA score for a specific observation i, denoted as Y_i, is calculated using the normalized values of the variables. For each variable j, the normalized value for observation ii is represented as Z_{ij}. The loading coefficient, or eigenvector, for variable j is denoted as C_j. The PCA score Y_i is obtained by summing the products of the normalized values Z_{ij} and their corresponding loading coefficients C_j across all variables j. This process allows for the reduction of dimensionality while retaining the most valuable information from the original dataset.

The proportion of variance explained by each component determined the weights:

$$w_k = \frac{\lambda_k}{\sum\nolimits_{k=1}^{p} \lambda_k} \tag{7}$$

The weight assigned to the k-th principal component is denoted as w_k. This weight is determined by the variance explained by the k-th component, represented as λ_k. The total number of principal components is denoted as p. These weights are crucial in understanding the contribution of each principal component to the overall variance in the dataset, aiding in the interpretation and dimensionality reduction of the data.

Finally, the Sustainability Index (SI) aggregated all weighted PCA scores:

$$SI_i = \sum\nolimits_{k=1}^{p} (Y_{ik} \times w_k) \tag{8}$$

The Sustainability Index (Fig. 6) for a specific observation i, denoted as SI_i, is calculated using the scores of the principal components. For the k-th principal component, the score for observation i is represented as Y_{ik}, and the weight assigned to this component is denoted as w_k. This index is computed for all countries and years, providing a unified metric to compare sustainability performance across different observations.

Subsequently, an analytical framework centered on the Logarithmic Mean Divisia Index (LMDI) was utilized to understand the dynamics of carbon emission changes across the studied period (Figs. 7 and 8). This methodology enabled the decomposition of annual emission variations into three key effects: (1) the Activity Effect, which isolates the impact of changes in economic output; (2) the Structural Effect, reflecting the influence of shifts in the economic composition, quantified via a sustainability index; and (3) the Sustainability Effect, capturing technological and efficiency improvements. The total carbon emissions for each country and year were computed by summing all variables:

$$TE_{i,t} = \sum\nolimits_{j \in \{\text{food processing,food packaging,...}\}} E_{ij} \tag{9}$$

The total carbon emissions ($TE_{i,t}$) for country i in year t were calculated by aggregating emissions from individual contributing factors, such as food processing and transportation: $TE_{i,t} = \sum_j E_{ij}$ and for 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 $TE_{i,t}$ for the observation i are obtained.

The activity effect ($AE_{c,t}$) quantifying the contribution of economic activity, was derived from the logarithmic difference in total emissions between consecutive years:

$$\mathrm{AE}_{c,t} = \log\left(\frac{E_t}{E_{t-1}}\right) \tag{10}$$

Here, c is expressed as country and t as year. 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 ($\mathrm{SE}_{c,t}$) was determined by the logarithmic change in a sustainability index:

$$\mathrm{SE}_{c,t} = \log\left(\frac{S_t}{S_{t-1}}\right) \tag{11}$$

The Structural Effect, denoted as $\mathrm{SE}_{c,t}$, 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 ($\mathrm{SusE}_{c,t}$) measures the contribution of sustainability practices. It was calculated by multiplying the changes in emissions and sustainability index:

$$\mathrm{SusE}_{c,t} = \log\left(\frac{E_t}{E_{t-1}}\right) \times \log\left(\frac{S_t}{S_{t-1}}\right) \tag{12}$$

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

Collectively, these analytical procedures provided a comprehensive framework for examining carbon emissions and sustainability performance across the EU food system, ensuring that each analytical step logically builds on the previous one and contributes to the overall research objectives.

3 Analysis and results

Figure 1 (calculated through Eq. (1)) depicts the country comparison of mean carbon emission (in kilotons, kt) across various food-related sectors, revealing significant variations in environmental impact among selected eight European nations.

The emission profiles of the Czech Republic, Hungary, and Portugal reveal comparatively reduced outputs in all evaluated sectors. For example, the food processing sector in both Hungary and Portugal produce under 3,000 kt of emissions, a trend mirrored in Czechia, though some sectors like household food consumption show marginally higher emissions (approximately 3,500 kt). The comparatively lower emissions in these countries could be attributed to a combination of factors such as diverse agricultural practices, a greater prevalence of small-scale or less industrialized food processing, and variations in how food is consumed.

Poland and Spain show medium-level emission levels across the eight examined categories. For instance, household food consumption contributes around 8,000 kt in Poland and 3,500 kt in Spain. When it comes to food processing, both Poland and Spain have lower emissions than Germany and Italy, but their contributions remain substantial at around 10,000 kt and 6,000 kt, respectively.

In contrast to the moderate emitters, France stands out with higher emission levels, notably in food processing at around 37,000 kt. On-farm energy use also contributes significantly (approximately 12,000 kt), and food transport adds a moderate 11,000 kt. However, household food consumption and food retail remain lower, below 6,000 kt. This pattern suggests a strong presence of intensive industrial food processing within France's food sector.

Similarly, Germany and Italy exhibit the highest overall emissions in most categories compared to the other countries. Specifically, Germany's household food consumption is the dominant source, accounting for approximately 28,000 kt, which is significantly higher than any other country reports for this category. Italy's food processing sector is a substantial source of emissions, estimated at around 36,000 kt, placing it as the second-largest emitter in this category, after France. Moreover, household food consumption in Italy contributes significantly to its overall emissions, reaching approximately 11,000 kt.

Pesticides manufacturing and agrifood systems waste disposal are consistently among the lowest contributors to carbon emissions across all countries. These categories generally range from 2,000 kt to 3,000 kt across the analyzed nations. These findings suggest that direct farming activities may contribute to a lesser extent to overall emissions than post-harvest processing and distribution activities. Food packaging emissions vary significantly among nations, with Germany showing higher values around 6,000 kt compared to other countries. This difference could arise from Germany's large consumer market and extensive packaging requirements.

The trends emerging from these country-level comparisons underscore the shifting dynamics of industrial development and food system priorities within Europe.

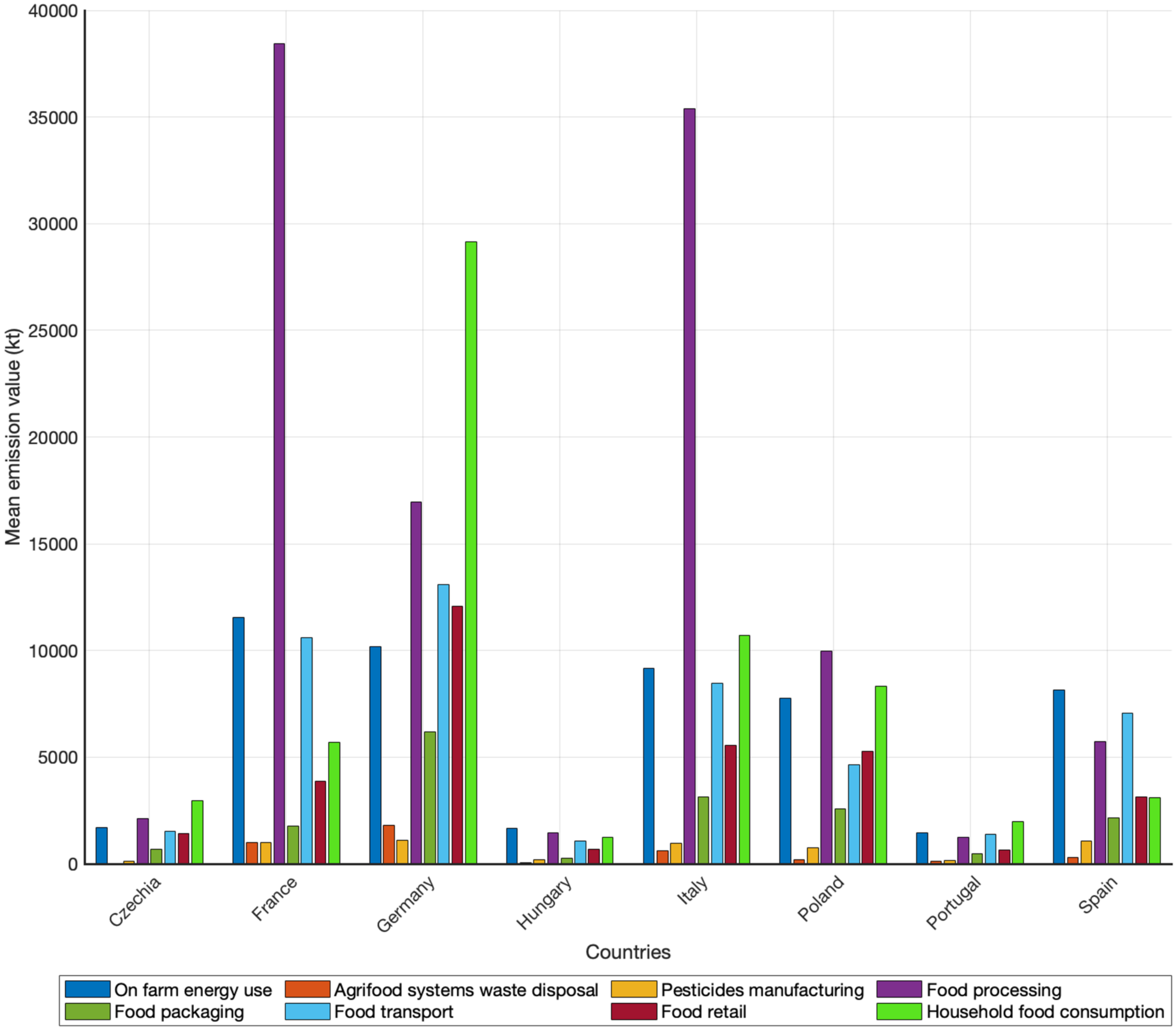


Fig. 1 Carbon emissions by food system supply chain stage

Western European nations typically exhibit higher emissions in the processing and distribution sectors, while Eastern European countries generally demonstrate lower overall emissions across the analyzed categories. These patterns are indicative of varying stages of industrial development, population demographics, and the structural organization of food systems across the continent.

The SDG-12 progress across eight European countries, as depicted in Fig. 2 (calculated through Eq. (1)), provides a nuanced perspective on the relative performance of each nation concerning raw material consumption, consumption footprint, and circular material use rate. The data, normalized to a scale of 0 to 1, facilitates direct comparisons while accounting for the inherent differences in the absolute magnitudes of these indicators.

The observed normalized raw material consumption value of 1.0 in Germany underscores its leadership, reflecting the relationship between its strong industrial infrastructure and significant resource utilization. France follows with a value of approximately 0.7, indicating a substantial but comparatively lower level of raw material utilization. Furthermore, Italy, Poland, and Spain exhibit moderate consumption levels at 0.48, 0.45, and 0.29, respectively. These values suggest a balanced approach to resource use, potentially reflecting efforts to align industrial activities with sustainable practices and resource efficiency goals. In contrast, Czechia and Portugal

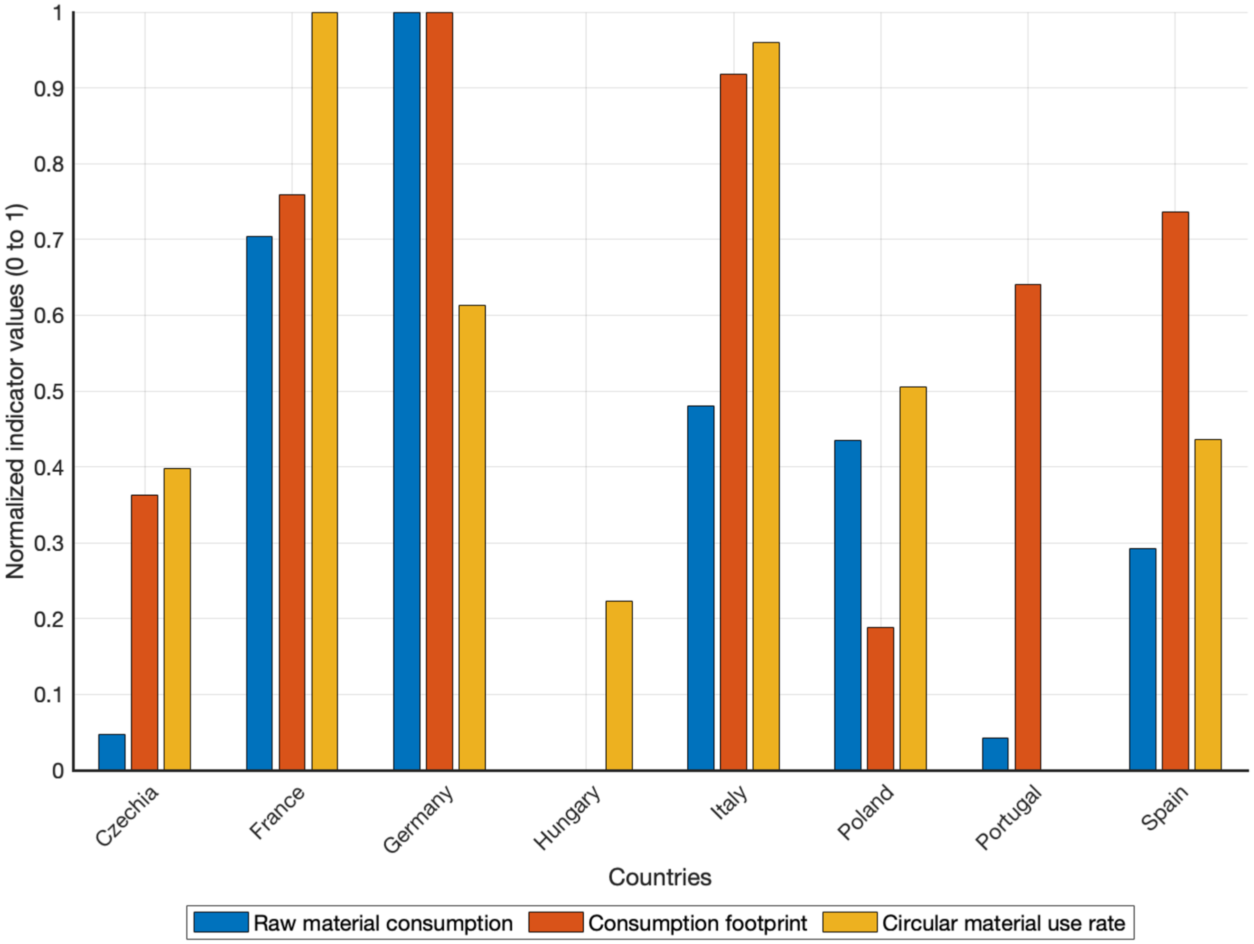


Fig. 2 SDG 12 indicator performance across food system domains

demonstrate minimal raw material consumption, with values near 0.05 and 0.2, respectively, underscoring the influence of differing economic structures and industrial capacities.

The consumption footprint indicator shows a similar distribution of variance. Germany and Italy again lead with normalized values of 1.0 and 0.91, signifying substantial environmental pressures resulting from their consumption activities. France closely follows with a value reaching 0.75, while Spain exhibits a slightly lower footprint at around 0.73. Poland stands out with the lowest footprint among the examined countries, registering below 0.2, which may be attributed to its relatively modest economic output and reduced industrial activity.

Understanding the circular material use rate is fundamental to assessing the implementation of circular economy principles in these EU nations. France and Italy exabit leading performance with an exceptional normalized value of 1.0 and 0.95, indicative of advanced recycling systems and material reuse initiatives. Germany exhibits a robust performance in this category, reaching a value of around 0.61. Poland and Spain demonstrate comparatively lower values, recorded at approximately 0.51 and 0.45, respectively. Conversely, Czechia and Hungary show significantly lower rates of circular material use, with values around 0.2 and 0.4, respectively, highlighting critical shortcomings in their recycling infrastructure and circular economy policies.

The findings highlight significant opportunities for cross-country collaboration and the exchange of best practices in advancing SDG-12 goals. France's outstanding performance in circular material use (1.0) makes it a benchmark. In comparison, Czechia and Hungary show values of approximately 0.2 and 0.4, respectively. This indicates significant potential for these countries to enhance their adoption of circular economy principles. By leveraging France and Italy's advanced recycling systems and material reuse strategies, these nations could accelerate progress in developing robust circular economy infrastructures.

Similarly, Poland's notably low consumption footprint (below 0.2) offers valuable insights for higher-consuming nations like Germany and Italy, whose footprints reach 1.0 and 0.91, respectively, on strategies to reduce environmental pressures without undermining economic productivity. Czechia and Portugal's approach could inform policies aimed at decoupling economic growth from resource consumption, particularly in nations with more resource-intensive industrial sectors.

Figure 3 (calculated through Eq. (2)) shows the correlation network. This reveals a complex relationship between carbon emissions and key variables linked to sustainable consumption and production (SDG-12) in the food system. At the center of the network lies the consumption footprint and raw material consumption, which serves as a pivotal node connecting multiple interconnected variables.

The strongest correlations appear between raw material consumption and several key elements. The relationship between raw material consumption with food packaging ($r = 0.88, p = 0.0001$) and agrifood systems waste disposal shows a particularly robust correlation ($r = 0.93, p = 0.0001$). These connections underscore the critical role of raw material management in addressing carbon emissions across various stages of production and consumption. Additionally, it indicates that increases in raw material use strongly align with greater waste generation. Raw material consumption also demonstrates significant ties to on-farm energy use ($r = 0.88, p = 0.0001$).

Food transport emerges as another crucial component, displaying strong correlations with circular material use rate ($r = 0.71, p = 0.0001$) and raw material consumption ($r = 0.96, p = 0.0001$). These connections suggest that transportation activities in the food system significantly influence both resource utilization and material circularity. The relationship between food processing and circular material use rate ($r = 0.88, p = 0.0001$) points to the substantial impact of processing activities on resource efficiency.

Similarly, consumption footprint emerges as another influential variable, strongly linked to food retail ($r = 0.55, p = 0.0001$). This highlights the role of retail

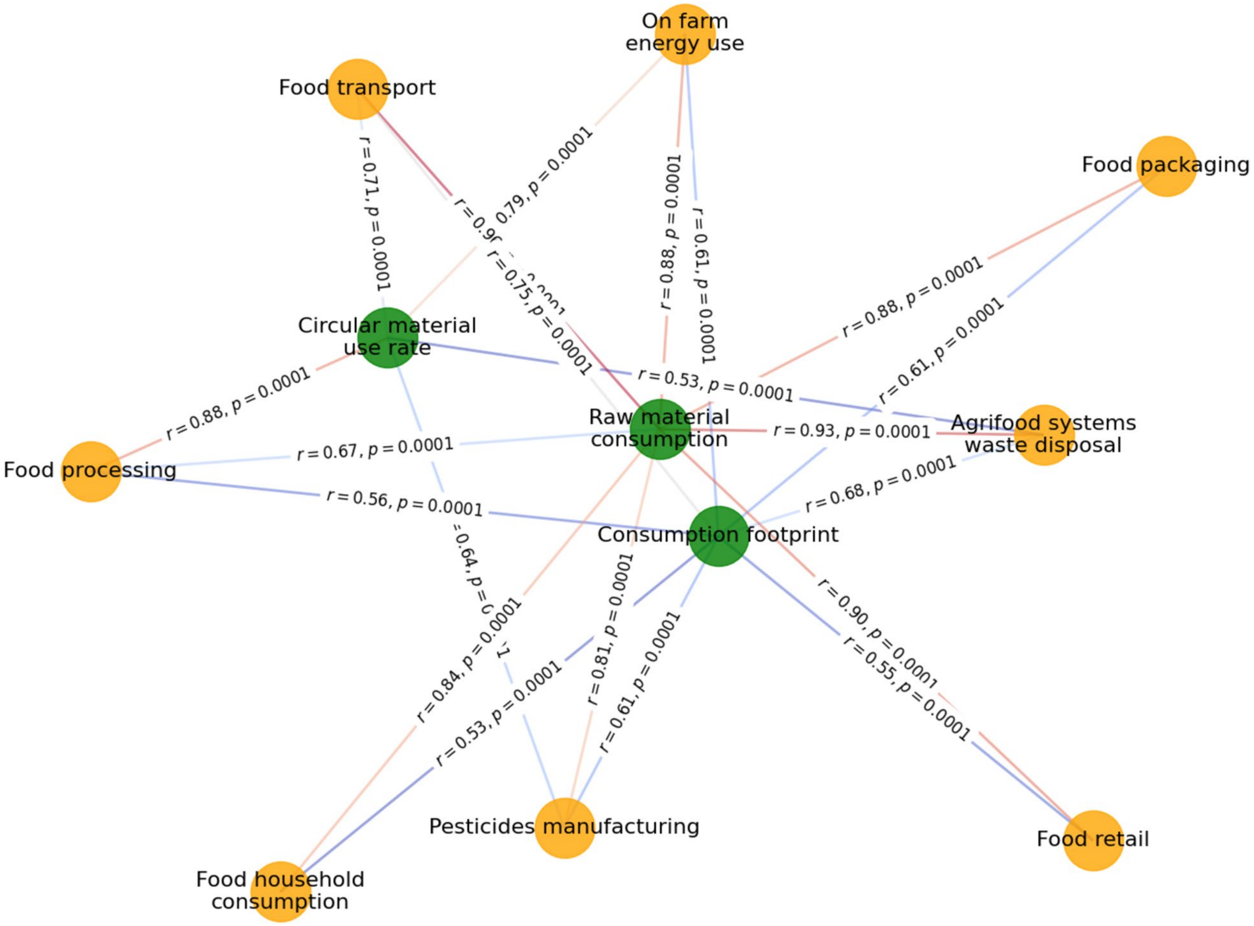


Fig. 3 Network analysis of correlations between carbon emission sources and SDG-12 indicators

operations in overall system sustainability. However, pesticides manufacturing maintains significant correlations with consumption footprint ($r = 0.61, p = 0.0001$). This emphasizes the environmental implications of agricultural chemical production. Household food consumption has a moderate correlation with the consumption footprint ($r = 0.53, p = 0.0001$), thereby emphasizing the importance of consumer behavior in determining system-wide environmental impacts.

The network structure reveals that interventions in one area affect multiple other components due to these strong interconnections. By mapping these interdependencies, the analysis identifies key leverage points for reducing emissions within the SDG-12 framework. The relationships between variables such as food processing, transport, packaging, and waste disposal underscore the interconnectedness of production systems. The presence of strong correlations throughout the network indicates that integrated approaches are likely more effective because they address the interconnected nature of the system, unlike isolated interventions that only focus on single components.

Figure 4 shows the sectoral breakdown of carbon emissions across eight EU countries (calculated via Eqs. (3) and (4)), highlighting significant variation in emission contributions from different parts of the EU food system. Each pie chart provides an understanding of how individual sectors contribute to the overall emissions profile for each country.

Food processing consistently stands out as the leading contributor to carbon emissions. For example, in France, food processing accounts for a noticeable 52% of total sectoral emissions. Similarly, Italy and Poland also report high contributions from food processing at 47.8% and 25.2%, respectively. This trend highlights the resource-intensive nature of food manufacturing, potential inefficiencies in manufacturing and production practices, and its substantial carbon footprint. In contrast, agrifood systems waste disposal and pesticides manufacturing contribute minimally to total emissions, often below 2.0% in most countries, indicating their comparatively less environmental impact. For instance, Czechia reports a mere 0.3% of emissions from agrifood systems waste disposal, and Poland shows only 0.5% for the same sector.

Portugal and Hungary demonstrate high contributions from on-farm energy use, with 19.5% and 25.2% of total emissions, respectively. The prominence of agricultural emissions reflects Portugal and Hungary's rural economy and its dependence on energy-intensive farming practices. In addition, this points to inefficiencies or reliance on energy-intensive farming practices. Meanwhile, carbon emissions from household food consumption are a significant sector in countries like Germany (32.2%), Czechia (28.1%), and Portugal (26.7%), reflecting the downstream impact of consumer behavior and energy use at the household level. However, Germany's household consumption emissions align with a high standard of living and energy use in residential settings. The substantial share of household consumption indicates the critical role of end-use behaviors in influencing carbon emissions within Czechia. In addition, Portugal should focus on household consumption patterns that emphasize the importance of consumer behaviors in addressing carbon emissions.

Furthermore, the analysis reveals a relatively less optimal overall environmental performance in selected EU countries such as France (52.0%) and Italy (47.8%), where disproportionately high emissions from the food processing sector potentially suggest industrial inefficiencies or elevated energy consumption in food production. Food Household food Consumption consistently ranks among the top contributors across most countries, highlighting the importance of consumer behavior in driving food system emissions. However, while some countries like Hungary and Poland show higher contributions from on-farm energy use due to their strong agricultural sectors, others like France exhibit a higher share from food processing.

The complexity of carbon emissions in EU food systems is evident in this sectoral analysis, which highlights crucial areas where focused interventions hold the potential for significant emission reductions and progress towards SDG-12 sustainability objectives.

Figure 5 (calculated using Eqs. (3) and (4)) presents a sectoral breakdown of three key SDG-12 indicators: raw material consumption, consumption footprint, and circular material use rate. Each pie chart illustrates the relative contribution of these indicators to the overall sustainability performance of each country during the study period. To ensure comparability across countries, all indicator values were normalized using a 0–1 scaling method.

In Czechia, raw material consumption emerges as the leading contributor to achieving SDG-12, accounting for a significant 49.4% of the total performance. Consumption Footprint follows closely behind with a contribution of 31.7%, while circular material use rate contributes a smaller but notable share of 18.9%. This distribution highlights the centrality of resource use efficiency and consumption patterns in shaping Czechia's sustainability profile, with circular economy practices playing a relatively secondary role. In contrast, France shows a distinct pattern, where the Circular Economy uses has a dominant share of 59.0%. This reflects the country's advanced circular economy policies and robust infrastructure for recycling and material reuse. Raw material consumption and consumption footprint contribute 22.8% and 18.2%, respectively, highlighting a strong emphasis on material recirculation as a cornerstone of France's sustainability strategy.

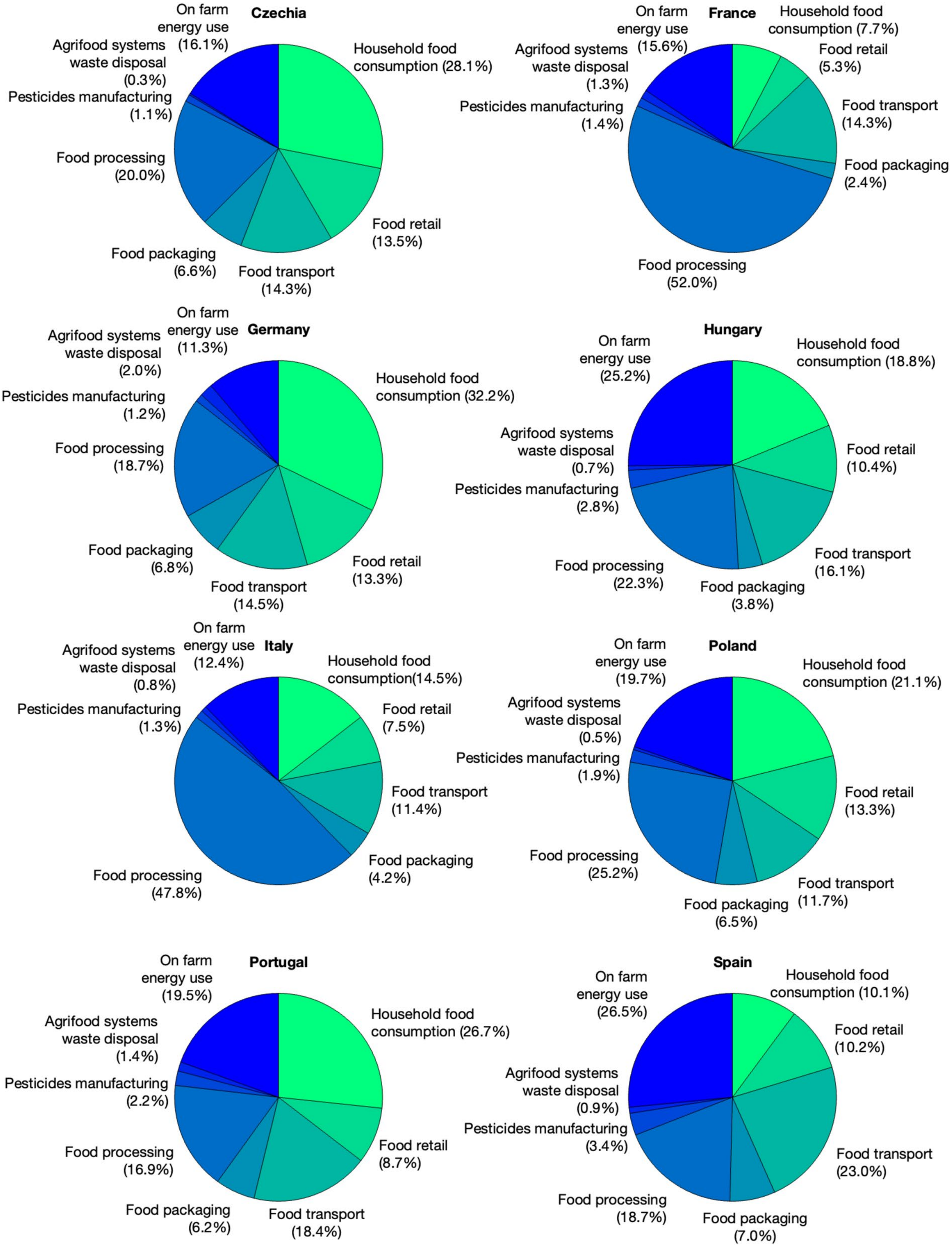


Fig. 4 Sectoral breakdown of total carbon emissions from food system

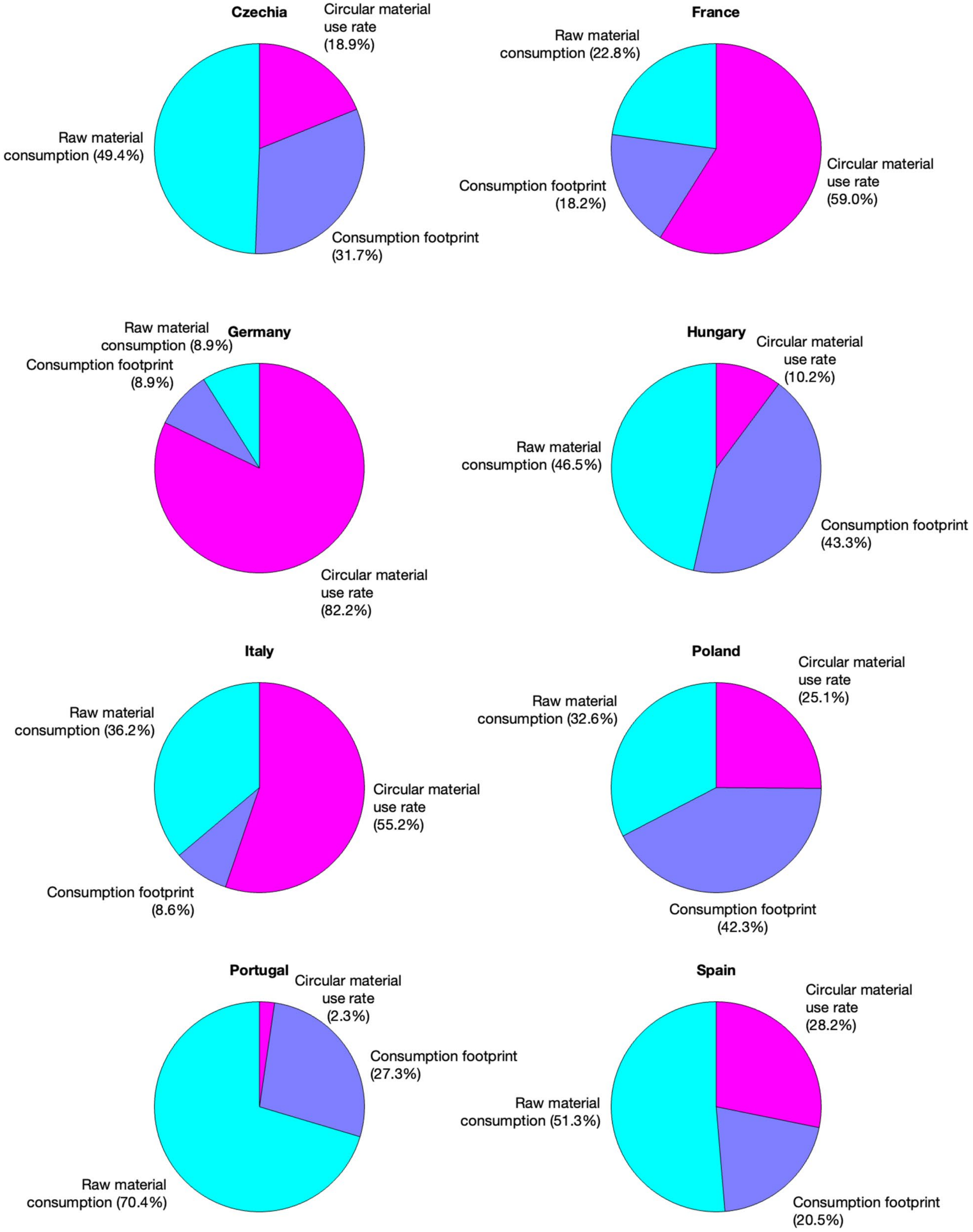


Fig. 5 Contributions of SDG 12 indicators to national sustainability scores

The unique position of Germany can be attributed to its exceptionally high circular material use rate, which constitutes 82.2% of its overall SDG-12 performance. In addition, both raw material consumption and consumption footprint account for equal shares of 8.9%, indicating Germany's significant reliance on circular economy practices to achieve its sustainability objectives. This outlier status reflects Germany's advanced implementation of closed-loop systems and industrial interdependency networks.

Hungary exhibits a more balanced distribution among the three indicators. Raw material consumption accounts for 46.5% of its SDG-12 performance, closely followed by consumption footprint at 43.3%, while circular material use rate contributes only 10.2%. Hungary's progress in sustainability appears to be primarily driven by resource efficiency and consumption patterns rather than circular economy initiatives.

Italy mirrors France in its reliance on circular material use rate as the largest contributor to SDG-12 performance at 55.2%. Raw material consumption accounts for 36.2%, while consumption footprint contributes a modest 8.6%. This distribution highlights Italy's prioritization of circular practices as a key driver of its sustainability agenda.

Poland presents a relatively balanced approach across all three indicators. Raw material consumption contributes 32.6%, consumption footprint accounts for 42.3%, and circular material use rate represents 25.1% of its SDG-12 performance. This even distribution reflects Poland's efforts to address all dimensions of sustainable resource use comprehensively.

Portugal stands out due to its heavy reliance on raw material consumption, which constitutes a substantial 70.4% of its SDG-12 performance. Consumption footprint follows at 27.3%, while circular material use rate makes up only 2.3%. This distribution suggests that Portugal's sustainability efforts are predominantly focused on improving resource efficiency, with limited integration of circular economy principles.

Finally, Spain demonstrates a more evenly distributed profile compared to Portugal but remains skewed toward resource use efficiency. Raw material consumption accounts for 51.3% of its SDG-12 performance, followed by circular material use rate at 28.2% and Consumption Footprint at 20.5%. Spain's configuration indicates incremental progress toward balancing resource efficiency with circular practices.

The findings presented in Fig. 5 highlight substantial inter-country variability in the relative contributions of raw material consumption, consumption footprint, and circular material use rate to SDG-12 performance within the EU framework. These disparities underscore differing national priorities and capacities in advancing sustainable resource management practices aligned with global sustainability targets.

In terms of cross-country observations, there are several patterns emerging from this analysis. In most countries (e.g., Czechia, Hungary, Portugal, and Spain), raw material consumption is the largest contributor to SDG-12 performance, reflecting the importance of resource efficiency in driving sustainability. Strong circular practices in several EU countries like France, Germany, and Italy demonstrate a significant reliance on circular material use rates as key drivers of their SDG-12 performance. However, balanced contributions in Poland exhibits a relatively equalized sharing among all three indicators, suggesting a more holistic approach to achieving SDG-12 goals. In contrast, limited circular practices (2.3%) in Portugal highlights significant room for improvement in adopting circular economy practices.

To provide a more in-depth understanding of the factors influencing sustainability performance, Table 2 uses Principal Component Analysis (PCA) to synthesize sustainability index data into key components.

Table 2 Principal component loadings and variable interpretations for sustainability index

No	Variable	PC1	PC2	PC3	Explanation
V1	On farm energy use	0.3278	-0.2604	0.2180	Measures the energy consumed in agricultural activities on farms
V2	Agrifood systems waste disposal	0.2256	0.4008	-0.0212	Evaluates the practices and impacts of waste disposal within agrifood systems
V3	Pesticides manufacturing	0.2444	-0.0012	0.7925	Assesses the environmental impacts associated with the production of pesticides
V4	Food processing	0.2394	-0.4256	0.0121	Quantifies emissions generated during the processing of food products
V5	Food packaging	0.2638	-0.3239	-0.1025	Measures the environmental impact of materials and processes used in food packaging
V6	Food transport	0.2962	0.5417	0.2036	Accounts for greenhouse gas emissions resulting from the transportation of food
V7	Food retail	0.2540	-0.3186	-0.1369	Evaluates emissions from the operations of retail food outlets
V8	Household food consumption	0.3653	0.0009	0.0442	Captures emissions related to household food consumption activities
V9	Raw material consumption	0.3818	0.2489	-0.3050	Reflects the consumption of raw materials in various industrial processes
V10	Consumption footprint	0.3391	0.1291	-0.3868	Indicates the overall environmental footprint of consumption activities
V11	Circular material use rate	0.3294	-0.1097	-0.0919	Measures the rate at which materials are reused or recycled in a circular economy

The PCA results in Table 2 (calculated through Eqs. (6) and (7)) highlight the relative importance of various factors in determining overall sustainability performance.

PC1, accounting for 75.58% of the total variance, represents the primary dimension of sustainability in our analysis. The high positive loadings across all variables in PC1 suggest that this component captures an overall measure of sustainability performance. Notably, variables V9 (raw material consumption, 0.3818), V8 (household consumption-related emissions, 0.3653), and V10 (consumption footprint, 0.3391) show the strongest positive correlations with PC1. This indicates that consumption patterns and resource use play a dominant role in differentiating sustainability performance among the countries in our study.

PC2, explaining an additional 12.47% of the variance, appears to contrast different aspects of the food system and consumption. It shows strong positive loadings for V6 (food transport emissions, 0.5417) and V2 (agrifood waste disposal, 0.4008), while having notable negative loadings for V4 (food processing emissions, -0.4256) and V5 (food packaging impact, -0.3239). This component might be interpreted as distinguishing between countries with emissions dominated by transport and waste versus those where processing and packaging are more significant contributors.

PC3, accounting for 4.64% of the variance, is strongly influenced by V3 (pesticide manufacturing impacts, 0.7925) and shows moderate negative loadings for V10 (consumption footprint, -0.3868) and V9 (raw material consumption, -0.3050). This component could be highlighting a distinction between agricultural input intensity and overall consumption levels.

The weights derived from these PCA results (PC1: 0.7558, PC2: 0.1247, PC3: 0.0464) were used to construct the composite sustainability index, ensuring that the index captures the most significant patterns of variation in the multidimensional dataset. This approach allows to synthesize complex sustainability data into a single, interpretable measure while retaining the nuanced contributions of various factors to overall sustainability performance.

Integrating these loadings with the sustainability index (Fig. 6) reveals the underlying factors of sustainability

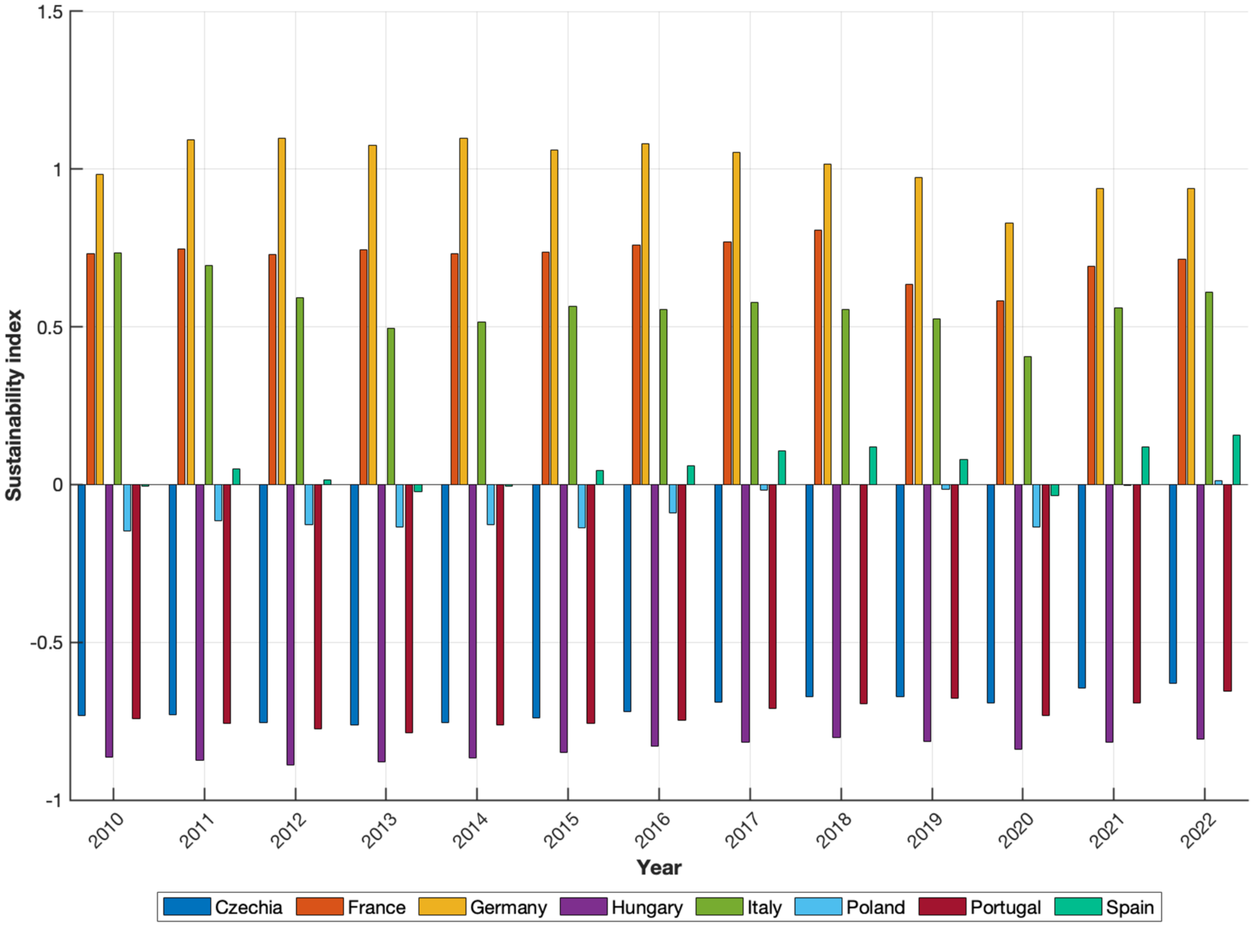


Fig. 6 Trends in food system sustainability index: A measure of environmental performance

performance variations across selected EU countries and time, providing a basis for targeted policy recommendations and identifying areas for national sustainability strategy enhancement.

The Sustainability Index trends, as depicted in Fig. 6 (calculated through Eqs. (5) and (8)) compare positive contributions to sustainability with negative impacts, reflecting the balance between resource use, waste management, and other ecological factors. Germany demonstrated a consistent pattern of high sustainability index values, fluctuating between 0.8 to 1.2 throughout the observed period. This indicates Germany's strong commitment to sustainable practices and efficient resource management. France follows closely, with index values typically fluctuate between 0.6 and 0.8, showcasing its robust sustainability initiatives and circular economy efforts.

Italy exhibits moderate sustainability performance, with index values generally falling between 0.3 and 0.7. Italy shows steady progress but also reveals opportunities for improvement in areas such as waste reduction and energy efficiency. Spain's sustainability index shows slight fluctuations, ranging from approximately 0.1 to 0.3 over the years. These variations indicate inconsistency in the nation's sustainability strategies and their implementation.

Poland's performance is characterized by a mixed trend. The index values fluctuate around the zero threshold and occasionally decline to negative range (as low as -0.2) in several years. This indicates challenges in consistently implementing sustainable practices across various sectors. Czechia, Hungary, and Portugal consistently rank lower on the sustainability index. Their sustainability scores are predominantly in the negative range, often between -0.4 and -0.8. These statistics suggest that there are significant barriers in adopting and maintaining sustainable practices, possibly due to economic constraints or policy gaps.

The temporal analysis reveals relatively stable patterns for most countries from 2010 to 2022, with no dramatic shifts in sustainability performance. Germany, for instance, maintains its high index values (around 0.9) throughout the period, while Hungary's values remain consistently low (around -0.6). This stability suggests that while leading countries have established effective long-term sustainability strategies, lower-performing nations face persistent challenges in improving their sustainability metrics.

While Fig. 6 provides a broad overview of sustainability index trends within the EU, a more detailed analysis is required to elucidate the underlying drivers of these trends. Figure 7 addresses this need by decomposing carbon emissions into their constituent elements: economic activity, structural changes, and sustainability practices across EU member states.

Figure 7 illustrates the Logarithmic Mean Divisia Index (LMDI) decomposition (calculated through Eqs. (9)–(12)) of carbon emissions across eight EU countries.

The contribution of economic activity (orange line) to carbon emissions shows significant variability across countries. Czechia's trajectory remains relatively stable near zero throughout the period but shows a slight increase post-2020. Notably, the economic activity effect in 2013 dropped to -0.1, followed by a slight increase to + 0.1 in 2021. Similarly, France and Germany maintained a consistently moderate profile, with values oscillating between -0.1 and + 0.1 over the observed period. However, Hungary's activity effect was close to zero over the years. In contrast, Italy exhibited negative activity contributions during certain years, such as -0.1 in 2013 and 2020. This implies that emissions were decreased due to less economic activity during these periods. Nevertheless, economic activity was higher (+ 0.1) in 2021. The contributions from Poland remained close to zero, highlighting the decline of economic activity in contributing to carbon emissions. Portugal tracked a similar but with more moderate pattern, fluctuating between 0.17 and -0.18. Spain's trends displayed a similar fluctuating pattern, with values oscillating within the interval of -0.09 to + 0.09. Overall, these activity trends demonstrate the significant influence of economic cycles on carbon emissions in Italy, Portugal, and Spain, when compared with other countries.

The impact of economic structure (blue line) on carbon emissions reflects changes in structural and sectoral composition. Nevertheless, the pattern is comparatively more moderate in most EU countries. Czechia again shows significant variability, with a sharp decline to -0.62 in 2020, followed by a rapid rise to + 0.42 in 2021. This indicates a considerable structural transformation of its economy over this timeframe. France's structural effect showed peaks of approximately + 0.3 in 2013 and + 0.4 in 2021, with a sharp fluctuation to -0.3 in 2015, reflecting major economic structural shifts. Germany showed a similar spike with effect values + 0.27 in 2011 and + 0.38 in 2021, indicating substantial changes in the economic composition, potentially due to increased industrialization or related structural reform. Hungary exhibited considerable negative structural shifts, fluctuating between -0.3 and -0.4 from 2013 to 2020, followed by a rise to approximately + 0.3 in 2021. This observation indicates that structural impacts on carbon emissions are subject to temporal variation. In contrast, Italy experienced complex negative structural activity effects, such as -0.1 in 2016 and -0.4 in 2020, and followed by a convergence towards zero. Poland is slightly volatile but remains

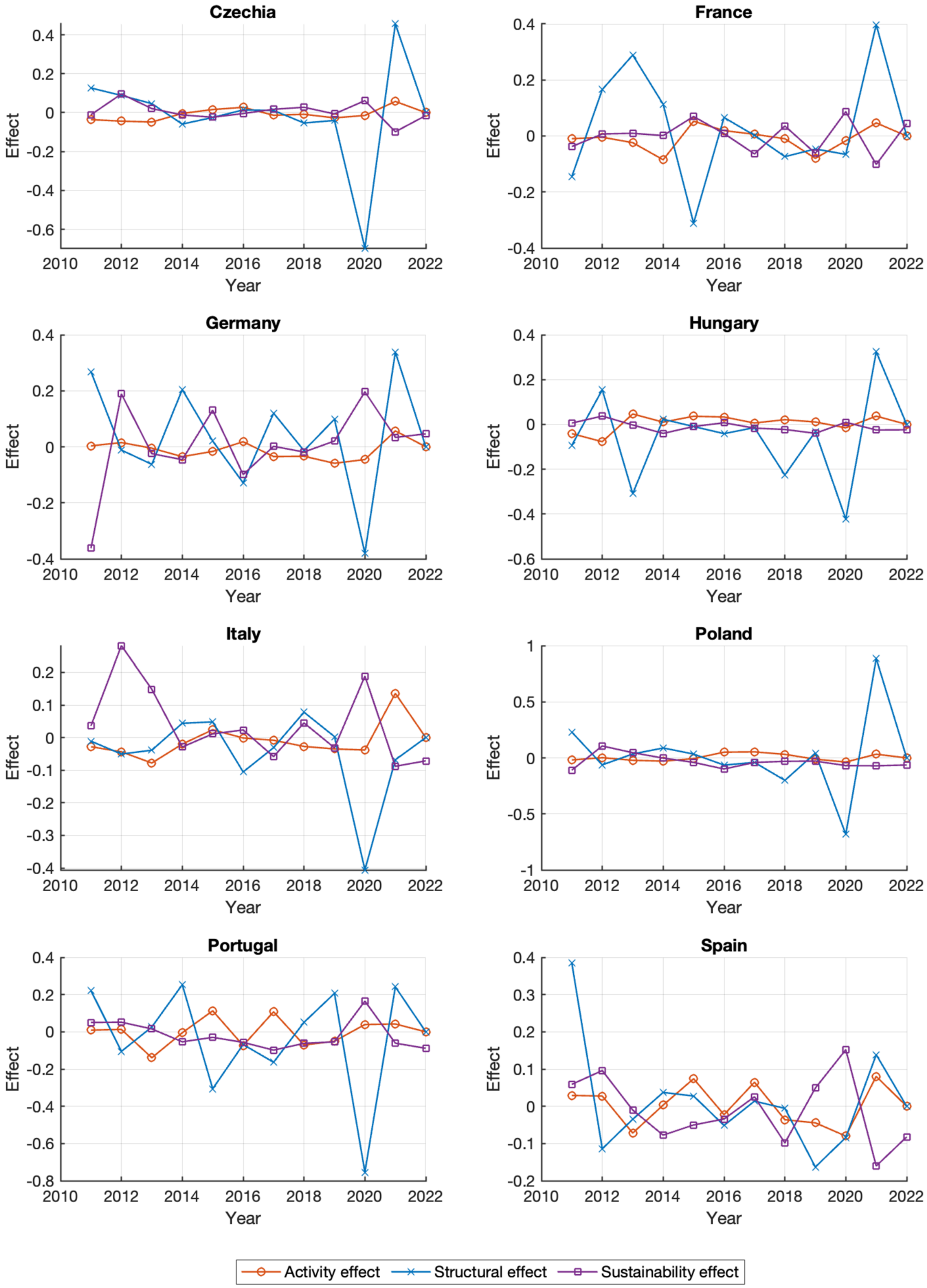


Fig. 7 Decomposition of carbon emission changes by supply chain activity

within a narrow range of -0.7 to + 0.8 in 2020 and 2021. Portugal's structural activity exhibited significant fluctuations, peaking around + 0.21 in 2013, 2019, and 2021, and reaching a low of approximately -0.8 in 2020, highlighting the influence of industrial and economic dynamics. Furthermore, Spain exhibited positive structural effects throughout the observed period, with a maximum value of + 0.4 recorded in 2011.

Furthermore, the decomposition of carbon emission changes through the lens of sustainability practices (purple line), captures the influence of environmental practices, energy efficiency improvements, and adoption of cleaner technologies. The Czechia exhibited a stable trend around -0.01 to + 0.08 in between 2012 and 2021, which is attributable to sustainability practices. France showed a minimal positive trend, with values around + 0.1 in 2020 and -0.1 in 2021. This indicates that sustainability initiatives like energy efficiency measures and renewable energy adoption started to have their effects. Germany exhibited a fluctuating pattern, with values oscillating within the interval of -0.4 and + 0.2 throughout the study period. Hungary had some minimal negative impact measuring -0.03 in 2014 and 2019. These values suggest challenges in the widespread implementation of sustainability measures. In contrast, Italy experienced positive fluctuations in sustainability effects, with peaks of + 0.3 in 2012 and + 0.2 in 2020. This means that Italy's sustainability practices had a positive impact on reducing carbon emissions, and this impact varied over time. Additionally, Poland presents a sustainability pattern similar to Hungary, with contributions near zero. In contrast, Portugal exabited little deviation, peaking at + 0.2 in 2020 and subsequently declining marginally to -0.1 in 2022. Spain's trends displayed a comparatively higher positive fluctuating pattern within a range of ± 0.15. This shift indicates less energy-intensive industries or an increase in tourism (which can have varying sustainability impacts) can affect emission trends.

Furthermore, to validate the robustness and accuracy of the LMDI decomposition analysis presented in Fig. 7, Table 3 provides a comprehensive set of model validation metrics for the carbon emissions analysis across the eight EU countries.

Table 3 represents the validation results for the decomposition model applied to carbon emissions analysis demonstrating a robust evaluation of model's fit to the observed data across different EU countries. The combination of R^2, RMSE, and MAE ensures a comprehensive assessment of model performance. High R^2 values for Hungary (0.975) and Poland (0.960) indicate a strong model fit, suggesting the model effectively explains emission trends in these countries. Czechia (0.768) and Germany (0.617) show moderate fit, indicating the model's reasonable ability to present the observed data in these contexts. France (0.342), Portugal (0.301), and Italy (0.238) exhibit weaker fits, implying that additional factors might influence carbon emissions in these countries beyond the variables included in the model. Spain, with an R^2 close to zero (0.00002), highlights a significant limitation in the model's ability to explain emission variations, necessitating further refinement. These findings emphasize the importance of country-specific considerations in refining the decomposition framework for carbon emissions.

Table 3 Decomposition model validation metrics for carbon emissions analysis

Country	RMSE	MAE	R^2
Czechia	202.09	195.12	0.768
France	5166.6	4914.2	0.342
Germany	8198.9	7008.5	0.617
Hungary	369.99	368.57	0.975
Italy	1924.5	1774.4	0.238
Poland	1883.7	1519.2	0.960
Portugal	455.67	410.09	0.301
Spain	2383.4	2178.3	0.00002

Figure 8 (calculated through Eqs. (9)–(12)) provides a detailed decomposition analysis of the three key sustainability indicators, such as raw material consumption, consumption footprint, and circular material use rate. Each subplot represents one country, showing how these factors have individually contributed to sustainability over time.

Raw material consumption (green line) trends reveal relatively stable or minor fluctuations for most countries. Czechia exhibits minor variability clustering near zero throughout the timeline, while France shows higher oscillation between -0.15 and + 0.2. Germany displays extreme peaks from 2010 to 2012, with decomposition effect values reaching ± 38, indicating significant volatility in material consumption practices. This could be due to considerable changes in industrial output, or significant changes in imports and exports of raw materials. Hungary maintains a consistent trajectory close to zero, suggesting minimal changes in raw material usage. Italy and Portugal show negligible variation, with values remaining flat near zero for most years. Poland oscillates between -0.3 and + 0.2, reflecting moderate shifts in raw material dependency. Post-2016, Spain demonstrates a consistent trend approximating zero.

Consumption footprint (orange line) effects exhibit diverse patterns across the countries analyzed. Czechia shows moderate fluctuations with values ranging from -0.3 to + 0.18, with minor negative decline below -0.3

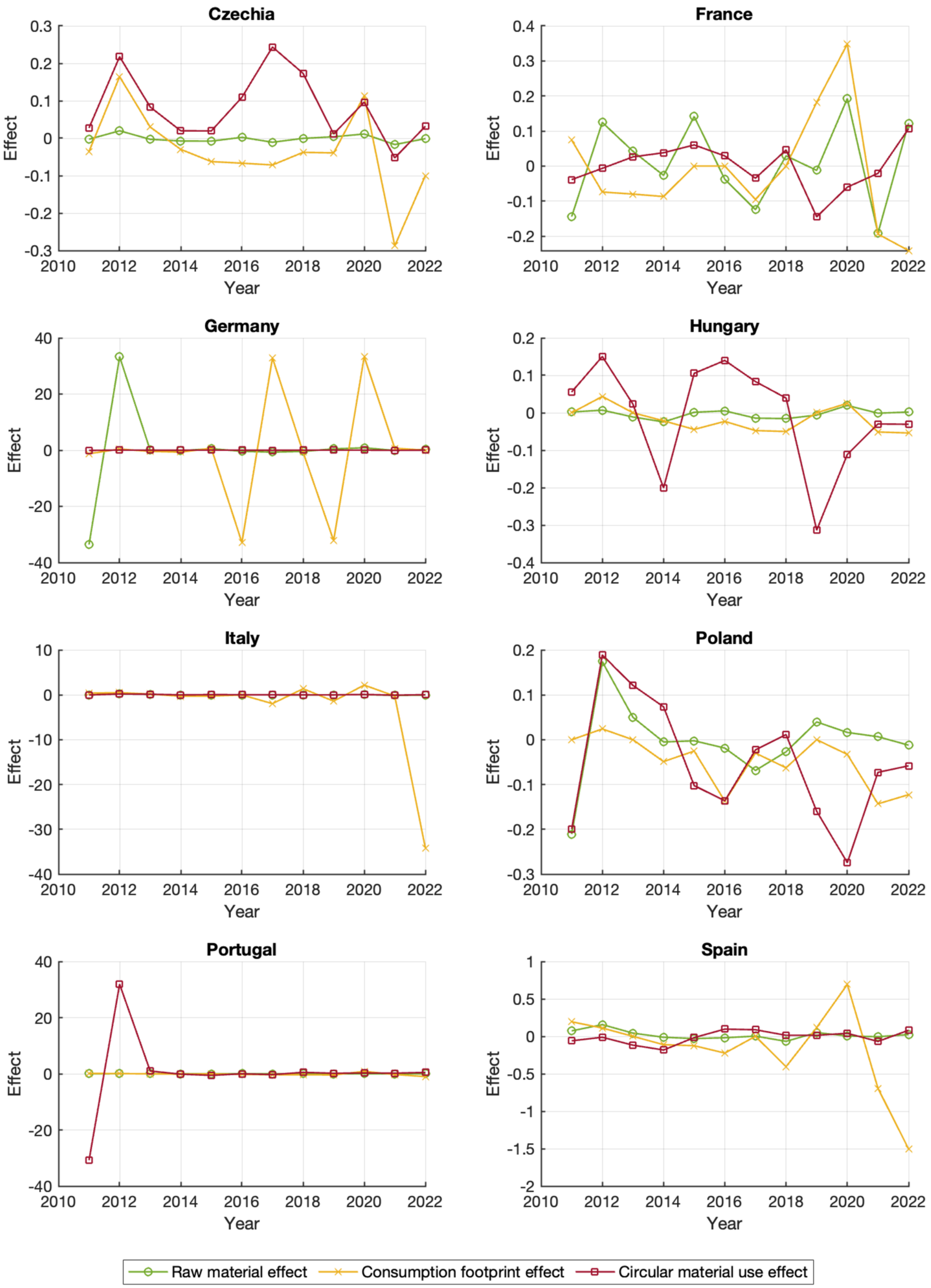


Fig. 8 Decomposition of SDG 12 indicator changes by supply chain stage

in 2021. France experienced sharp spikes around 2020 (+0.35) but declined to -0.21 in 2022. Germany's consumption footprint effect is highly volatile, fluctuating by ± 39 due to abrupt changes in consumption patterns or economic disruptions. Hungary's footprint remains relatively stable with minor negative dips below -0.02 during certain periods. Italy displayed a sharp decline in 2022 (-35), marking a significant reduction in consumption impact during that year. Poland shows consistent variability between -0.15 and + 0.01, while Portugal demonstrates a trend of stabilization near zero. Spain demonstrates sharp declines post-2018 (-0.5 to -1.5), signaling improvements in consumption efficiency.

Circular material use rate (maroon line) trends highlight progress toward resource efficiency and recycling within food systems. Czechia's circularity effect fluctuates between -0.2 and + 0.25 but remains positive overall in 2022, indicating advancements in circular practices. France shows consistent positive contributions post-2013 (+0.02 to + 0.1), reflecting steady improvements in material reuse strategies. Germany maintains a stable trajectory near zero. Hungary exhibits extreme variability similar to other indicators, oscillating sharply between -0.3 and + 0.15 due to systemic shifts or policy interventions affecting circularity rates. However, marginal decreases below -0.3 are observed intermittently, specifically during transitional periods such as 2014 and 2019. Italy's circular material use remains flat near zero. Poland fluctuates moderately between -0.3 and + 0.2, reflecting incremental progress toward circularity goals despite challenges in certain years like 2015–2019 (-0.15). Portugal's circular effect spiked anomalously in 2012 (+30) but stabilizes near zero thereafter. In contrast, Spain shows consistent positive contributions post-2016 (+0 to + 0.01), signaling robust adoption of circular economy principles within its food systems.

Furthermore, to validate the robustness and accuracy of the decomposition analysis presented in Fig. 8, Table 4 provides a comprehensive set of model validation metrics for the SDG-12 performance analysis across the eight EU countries.

Table 4 represents the validation results for the decomposition model applied to SDG-12 analysis which further strengthens the robustness of the model assessment. An R^2 of 0.994 for Spain indicates an exceptionally strong model fit, while Poland (0.742) and Italy (0.666) also exhibit high model fits, indicating the model successfully explains key SDG-12 performance patterns in these nations. Germany (0.475) and Czechia (0.420) demonstrate moderate model fit, suggesting that while the model explains a significant portion of the variance, there is still room for improvement. Conversely, France (0.032), Portugal (0.086), and Hungary (0.125) exhibit weaker fits, implying that additional factors impacting SDG-12 performance may not be fully captured. These insights highlight the necessity of refining the model to enhance its explanatory power in regions with weaker fits, while maintaining its effectiveness in regions with strong fits.

Table 4 Decomposition model validation metrics for SDG-12 performance analysis

Country	RMSE	MAE	R^2
Czechia	0.06299	0.04673	0.420
France	0.01660	0.01496	0.032
Germany	0.02391	0.01985	0.475
Hungary	0.03932	0.03359	0.125
Italy	0.06537	0.05729	0.666
Poland	0.08945	0.08061	0.742
Portugal	0.13397	0.12897	0.086
Spain	0.05288	0.04581	0.994

4 Discussions

The investigation of carbon emissions across EU food systems unveils a heterogeneous landscape, characterized by distinct patterns and challenges shaped by the unique food production and consumption dynamics of each member state. A key outcome of this investigation highlights the considerable role of the food processing sector in generating carbon emissions within EU food systems, representing an average of 30.5% of the total and reaching notable peaks of 52% in France and 47.8% in Italy (Fig. 4). This sectoral significance reflects potential inefficiencies in manufacturing processes, a reliance on carbon-intensive energy sources, and considerable opportunities for technological innovation in food transformation activities, within the context of each nation's unique food production and consumption landscape.

Quantitative analysis reveals that household food consumption contributes substantially to overall emissions, exceeding 25% of the total in Germany (32.2%), Czechia (28.1%), and Portugal (26.7%) (Fig. 4). This observation underscores the salient role of consumer dietary practices in shaping the environmental impact of food systems. The moderate correlation between household consumption and consumption footprint ($r = 0.53$, Fig. 3) emphasizes the need for interventions targeting dietary preferences, cooking practices, and food waste reduction at the consumer level. In this context, Vigneshwar et al. (2022) have shown how food waste can be converted into value-added products such as biofuels, bioplastics, and nutraceuticals through biorefinery concepts. Integrating such approaches could significantly reduce CO_2 emissions while creating economic opportunities. Notably, moderate emissions in this category are correlated with meat-based diets and inefficient cooking appliances and food waste. These results highlight the importance of consumer awareness and education campaigns, as well as the adaptation of energy-efficient appliances, in promoting environmental friendliness. Alternatively, shifting towards a more plant-based diet and reductions in food waste would lead to substantial reductions in emissions, especially in EU regions where they have a higher impact on carbon emissions (Carr et al. 2025). Additionally, government-supported initiatives, such as subsidies to replace energy-intensive household appliances and community-driven programs to reduce food waste, can encourage sustainable consumption practices that significantly reduce emissions. Similarly, evidence from Bryant et al. (2024) demonstrates the transient nature of shifts in food consumption patterns. These findings suggest that achieving long-term behavioural change requires persistent efforts, including the implementation of supportive policies and economic incentives.

In contrast to regions with lower overall agricultural emissions, on-farm energy utilization contributes substantially to the emission profiles of several nations. Notably, Hungary (25.2%) and Portugal (19.5%) demonstrate substantial contributions from this sector, as illustrated in Fig. 4, reflecting the energy-intensive nature of agricultural practices and the prevalent reliance on fossil fuels for key operations such as irrigation, fertilization, and mechanized farming. The moderate correlation between on-farm energy use and raw material consumption ($r = 0.88$, Fig. 3) suggests opportunities for simultaneous resource efficiency improvements in agricultural practices. Furthermore, these emissions are driven using fossil fuels for irrigation, fertilization, and other on-farm activities. The integration of precision agriculture technologies and renewable energy systems, such as solar-powered irrigation and bioenergy solutions, could enhance efficiency and reduce dependence on fossil fuels. However, a study by Priyadharsini et al. (2022) discusses the experimental study of some performance parameters of a constant speed stationary diesel engine using ethanol–diesel blends as fuel, which is well aligned with the goal of reducing the carbon footprint of the food sector.

Furthermore, the correlation network analysis revealed intricate relationships between carbon emissions and SDG-12 variables, with particularly strong connections between raw material consumption and food packaging ($r = 0.88$) and waste disposal ($r = 0.93$) (Fig. 3). These robust correlations underscore the systemic nature of food-related emissions and highlight potential leverage points for intervention. The adoption of energy-efficient agricultural equipment for farming and the commencement of training programmes for farmers on sustainable practices are 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.

Application of Principal Component Analysis to generate a Sustainability Index revealed notable regional variations. The resulting index values (Fig. 6) consistently positioned Germany as exhibiting the strongest sustainability performance (0.8–1.2), with France (0.6–0.8) and Italy (0.3–0.7) following in descending order. In contrast, Eastern European countries like Hungary, Czechia, and Portugal consistently ranked lower on the sustainability spectrum, with index values predominantly in the negative range (-0.4 to -0.8). This divergence reflects the differences in progress on sustainable food systems. The main trigger in the sustainability performance of these countries was food processing. However, Germany demonstrated exceptional circular material use (82.2% of its SDG-12 performance), while Hungary showed a more balanced distribution between raw material consumption (46.5%) and consumption footprint (43.3%). France exhibited strong circular economy practices (59.0% of its sustainability profile) (Fig. 5), reflecting advanced recycling systems and material reuse initiatives. High-performing countries benefit from strong public awareness, advanced technologies, regulatory frameworks, and effective policy support. In contrast, lower-performing regions are constrained by structural challenges and limited financial resource and inadequate infrastructure, which hinder progress toward sustainability. To address these disparities, the sustainability index emphasizes the targeted policy interventions such as financial incentives for the use of circular materials and investments in renewable energy to accelerate the adoption of sustainable practices. In addition, cross-border cooperation, where high-performing countries share best practices and technologies with their neighbour countries, could foster collective progress. Harmonising sustainability policies across the EU and setting clear benchmarks for emissions reductions could also ensure a more equitable and consistent approach to achieving SDG 12 targets.

The importance of incorporating sustainability into economic planning is evident from the LMDI decomposition analysis. The results of this analysis (Fig. 7) reveal that both structural economic shifts and the implementation of sustainability practices have been significant drivers of emissions reductions. Analysis of the economic activity effect reveals notable temporal volatility across the examined countries. Italy showed significant fluctuations, ranging from -0.1 in 2013 and 2020 to + 0.1 in 2021. Similarly, Portugal exhibited a range of -0.18 to + 0.17, while Spain showed oscillations between -0.09 and + 0.09.

Structural effects were more moderate in most countries but exhibited substantial variations in certain periods, reflecting shifts in economic composition and industrial patterns. For instance, Czechia experienced a sharp decline to -0.62 in 2020, followed by a rapid rise to + 0.42 in 2021. France showed peaks of approximately + 0.3 in 2013 and + 0.4 in 2021, with a sharp fluctuation to -0.3 in 2015. Germany exhibited spikes of + 0.27 in 2011 and + 0.38 in 2021 (Fig. 7). This includes promoting innovation in low-carbon technologies and incentivising private sector participation in sustainability initiatives.

The decomposition analysis of SDG-12 indicators (Fig. 8) indicated diverse trends across the analysed nations. While raw material consumption trends generally exhibited relative stability or minor fluctuations, Germany presented a notable exception, displaying extreme volatility with values reaching ± 38. In addition, consumption footprint effects revealed heterogeneous patterns across the studied countries. Germany's footprint exhibited considerable instability, with fluctuations reaching ± 39 due to the dynamics revealed by the decomposition effect. In contrast, Italy experienced a significant contraction in its footprint in 2022, with a value of -35. Circular material use rate trends highlighted progress toward resource efficiency. France showed consistent positive contributions after 2013, ranging from + 0.02 to + 0.1. Similarly, Spain demonstrated robust adoption of circular economy principles after 2016, with contributions from + 0 to + 0.01.

Furthermore, understanding the diverse carbon emission profiles within EU food systems is key to actionable sustainability insights. The country-level analysis uncovered specific patterns and challenges, directly informing tailored interventions and policy reforms for more effective emissions reduction and progress towards sustainability goals. The principal findings and policy recommendations derived from this study are presented below:

1. France's emission profile is dominated by the food processing sector, which accounts for 52% of total emissions (around 37,000 kilotons of CO_2 annually) (Figs. 1 and 4). Additionally, France's strong SDG 12 performance is driven by a high circular material use rate of 59.0% (Fig. 5), reflecting advanced adoption of circular economy practices. The country has shown consistent positive contributions in circular material use rate since 2013 (+ 0.02 to + 0.1), indicating steady improvements in material reuse strategies (Fig. 8). Therefore, implementing energy-efficient technologies and renewable energy sources in food processing is recommended to further reduce emissions, supporting the Green Deal's prioritization of energy efficiency and renewable energy development in industrial applications.
2. In Germany, household consumption is the primary contributor, representing 32.2% of sectoral emissions (about 28,000 kilotons annually) (Figs. 1 and 4). Germany also exhibits an exceptionally high circular material use rate of 82.2% (Fig. 5), highlighting advanced circular economy implementation and strong SDG-12 performance in line with the Green Deal's circular economy objectives. However, the country experiences extreme volatility in raw material consumption and consumption footprint, with values oscillating between ± 38 and ± 39 (Fig. 8). Targeted consumer education programs and incentives are suggested to address household consumption emissions.
3. Italy's carbon emission profile is similarly dominated by the food processing sector, responsible for 47.8% of national emissions (approximately 36,000 kilotons) (Figs. 1 and 4). Italy's SDG-12 performance is shaped by a circular material use rate of 55.2% and a raw material consumption rate of 36.2% (Fig. 5), demonstrating strong alignment with the Green Deal's circular economy principles. Notably, Italy achieved a significant negative -35 effect size in its consumption footprint in 2022, indicating a substantial reduction in impact (Fig. 8). Consequently, targeted efforts to implement optimized techniques and adopt cleaner technologies within the food processing sector represent a key opportunity for further mitigating Italy's carbon footprint.
4. Spain presents a more balanced sectoral emission profile (Fig. 4). Its SDG-12 performance is led by raw material consumption (51.3%) and a circular material use rate of 28.2% (Fig. 5). Spain has shown consistent positive contributions to circular material use rate since 2016 (+ 0 to + 0.01), reflecting sustained adoption of circular economy principles aligned with the Green Deal's circular economy targets (Fig. 8). To further enhance its sustainability profile, efforts should focus on improving raw material efficiency and expanding circular economy initiatives.
5. Industrial agriculture and food processing account for 25.2% of total emissions in Poland (Fig. 4). Poland's SDG-12 performance shows a relatively balanced approach, with consumption footprint contributing 42.3%, raw material consumption 32.6%, and circular material use rate 25.1% (Fig. 5). Their sustainability effect fluctuates moderately between -0.3 and + 0.2, reflecting incremental progress toward sustainability goals (Fig. 8). They should implement a balanced approach to reduce emissions across indus-

trial agriculture, food processing, and consumption sectors while maintaining the relatively even distribution in SDG-12 performance.

6. Moderate carbon emissions exhibit in the Czechia. The household food consumption accounts for 28.1% of total emissions (Fig. 4). Czechia's SDG-12 performance is dominated by raw material consumption at 49.8%, followed by consumption footprint at 31.7% (Fig. 5). The circular material use rate fluctuates between -0.2 and + 0.25 but remains positive overall in 2022, indicating progress in circular practices (Fig. 8). They should prioritize reducing household food consumption emissions through awareness campaigns and energy-efficient appliance adoption, while improving circular economy practices to support the Green Deal's consumer-focused sustainability initiatives.
7. Hungary's statistics indicates high on-farm energy use, accounting for 25.2% of total emissions (Fig. 4). SDG-12 performance is balanced between raw material consumption (46.5%) and consumption footprint (43.3%), while the circular material use rate is comparatively low at 10.2% (Fig. 5). Hungary shows significant variability in this rate, oscillating between -0.3 and + 0.15 (Fig. 8). They should invest in renewable energy and energy-efficient technologies for on-farm operations to reduce the high 25.2% emissions from on-farm energy use.
8. Household food consumption (26.7%) and on-farm energy use (19.5%) is the most significant carbon emission source in Portugal (Fig. 4). Portugal's SDG-12 performance is heavily reliant on raw material consumption, constituting 70.4% (Fig. 5). Integrating circular economy strategies, targeted efficiency improvements, and consumer engagement can drive further progress toward sustainability goals (Fig. 8), supporting the Green Deal's integrated approach to food system transformation.

These country-specific recommendations align with the EU Green Deal's key objectives to achieve climate neutrality by 2050 and reduce greenhouse gas emissions by at least 55% by 2030 (European Commission 2024a). The Farm to Fork Strategy's specific targets, including 50% reduction in chemical pesticides, 20% reduction in fertilizers, and 25% organic farming by 2030, provide clear benchmarks for measuring progress (European Commission 2024b; WWF 2021; AREPO 2020; IFOAM Organics Europe 2023). However, standardized emission monitoring in food processing is a prerequisite for effective reduction. Advancing SDG-12 requires prioritizing circular economy, resource reduction, and consumption footprint, considering sector-specific emissions. Collaborative knowledge transfer and region-adapted approaches are crucial for equitable and efficient progress.

5 Conclusion

The intricate landscape of carbon emissions and SDG-12 performance across the EU's food system has been illuminated through this detailed examination. The observed diversity in emission profiles and sustainability pathways among member states underscores the critical need for nuanced, nation-centric approaches to effectively pursue the EU's overarching climate and sustainability ambitions.

This investigation has unearthed several pivotal insights. Firstly, the sources of emissions exhibit marked variability across countries. In France and Italy, for instance, food processing emerges as the predominant contributor, accounting for 52% and 47.8% of total emissions respectively. Conversely, Germany and Czechia demonstrate significant contributions from household consumption, at 32.2% and 28.1% respectively. This divergence highlights the complexity of addressing emissions within the food system and the need for tailored interventions. These findings provide a comprehensive answer to RQ1, which investigates the key drivers of carbon emissions in the EU food system across production, processing, distribution, and consumption.

Secondly, the progress in circular economy practices displays considerable variance. Nations such as France and Germany have made substantial progresses, with circular material use rates of 59.0% and 82.2% respectively. In stark contrast, Hungary and Portugal grapple with more modest rates of 10.2% and 2.3%, indicating significant room for improvement in their circular economy initiatives. The study found strong correlations between raw material consumption and downstream activities, such as food packaging ($r = 0.88$) and waste disposal ($r = 0.93$). The Sustainability Index revealed significant regional disparities, with Germany consistently performing well (index values between 0.8 and 1.2), while Hungary and Portugal faced persistent challenges (index values predominantly in the negative range -0.4 to -0.8). These findings provide a detailed response to RQ2, which aims to identify the variations in circular material use rates, alongside raw material consumption and consumption footprints, which influence the sustainability performance of EU countries.

The research outcomes provide valuable implications for crafting and executing effective policy interventions. There is an evident need for integrated policies that simultaneously address emission reduction and promote sustainable consumption and production practices. The research suggests that a multifaceted approach, combining technological innovation, robust policy interventions, and consumer education, will be essential for achieving substantial emissions reductions.

However, this study has several limitations. The geographical focus on eight EU countries presents a potential limitation, as it may not fully represent the diversity across all member states. Another limitation lies in the study's scope of indicators, which may not capture all relevant aspects of food system sustainability, especially social dimensions. Moreover, the study could benefit from a more comprehensive inclusion of the diverse perspectives of all food system stakeholders. To overcome these limitations and advance the field, future research should consider incorporating real-time data and expanding its scope to include socio-economic dimensions, leading to a more comprehensive understanding of sustainability performance. In addition, longitudinal studies are needed to evaluate the long-term effectiveness of implemented policies and technologies in driving sustainability.

Synthesizing these diverse elements, this study enhances the understanding of sustainable food systems and provides a strong evidence base for policymakers and stakeholders to create effective strategies for a low-carbon, sustainable EU food system. These findings are a key catalyst for future research and policy development, advancing progress towards SDG-12 targets and broader climate objectives.

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Author's contributions
The author confirms sole responsibility for the conception and design of the study, the acquisition and analysis of data, the development of the manuscript, and the preparation of the final version for publication.

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Data availability
Data supporting the findings of this study are publicly accessible through the following online repositories: FAOSTAT (https://www.fao.org/faostat/en/#data/GT) for carbon emission metrics, and Eurostat's Sustainable Development Indicators database (https://ec.europa.eu/eurostat/web/sdi/database) for SDG-12 related information.

Declarations

Competing interests
The authors have no relevant financial or non-financial interests to disclose.

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References

Acs S, Costa Leite J, Sanyé-Mengual E, Caivano A, Catarino R, Druon J-N, Di Marcantonio F, De Jong B, Guerrero I, Gurría P, M'barek R, Panagos P, Puerta-Piñero C, Tamosiunas S, Wollgast J and Tóth K, (2025) Towards sustainable food systems: developing a monitoring framework for the EU. Frontiers in Sustainable Food Systems 8:1502081. https://doi.org/10.3389/fsufs.2024.1502081

AREPO (2020) Farm to Fork Strategy. https://www.arepoquality.eu/politics/farm-to-fork-strategy/ Accessed 13 June 2025

Aziz R Al, Arman MdH, Karmaker CL, Morshed SM, Bari ABMM and Islam ARMdT (2025) 'Exploring the challenges to cope with ripple effects in the perishable food supply chain considering recent disruptions: Implications for urban supply chain resilience'. J Open Innov: Technol, Mark, Complex 11(1):100449. https://doi.org/10.1016/j.joitmc.2024.100449

Baldassarre B (2025) Circular economy for resource security in the European Union (EU): Case study, research framework, and future directions. Ecol Econ 227:108345. https://doi.org/10.1016/j.ecolecon.2024.108345

Bryant C, Couture A, Ross E, Clark A, Chapman T (2024) A review of policy levers to reduce meat production and consumption. Appetite 203:107684. https://doi.org/10.1016/J.APPET.2024.107684

Carr TW, Zárate-Ortiz AG, Reuzé A, O'Donovan G, Mahfouz H, Nájera Espinosa S, Green R and Scheelbeek PFD (2025) 'Eating habits and sociodemographic factors impact household dietary greenhouse gas emissions reduction in Great Britain'. Commun Earth Environ 6(1):312. https://doi.org/10.1038/s43247-025-02252-x.

Castillo-Díaz FJ, Belmonte-Ureña LJ, López-Serrano MJ, Camacho-Ferre F (2023) Assessment of the sustainability of the European agri-food sector in the context of the circular economy. Sustainable Production and Consumption 40:398–411. https://doi.org/10.1016/j.spc.2023.07.010

Cerutti N, Lamb WF, Crippa M, Leip A, Solazzo E, Tubiello FN, Minx JC (2023) Food system emissions: a review of trends, drivers, and policy approaches, 1990–2018. Environ Res Lett 18(7):074030. https://doi.org/10.1088/1748-9326/acddfd

Cifuentes-Faura J (2025) 'Building an index based on key SDG 12 indicators to promote the transition to a circular economy'. Finance Res Lett 82:107610. https://doi.org/10.1016/j.frl.2025.107610

Corona B, Tunn VSC, van den Broek KL (2024) Integrating consumer behaviour into the environmental assessment of circular packaging: a scoping review. The International Journal of Life Cycle Assessment 29(1):80–98. https://doi.org/10.1007/s11367-023-02218-1

Dagevos H and Onwezen MC (2025) 'Toward consumer-focused food policies: a toolbox for encouraging the protein transition'. Sustain: Sci, Pract Policy 21(1). https://doi.org/10.1080/15487733.2025.2454060

Directorate-General for Environment (2023) Field to fork: global food miles generate nearly 20% of all CO2 emissions from food, https://environment.ec.europa.eu/news/field-fork-global-food-miles-generate-nearly-20-all-co2-emissions-food-2023-01-25_en Accessed 31 Dec 2024

Distefano T, Lodi L, Biggeri M (2024) Material footprint and import dependency in EU27: Past trends and future challenges. J Clean Prod 472:143384. https://doi.org/10.1016/j.jclepro.2024.143384

European Commission (2024a) The European Green Deal. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en Accessed 13 June 2025

European Commission (2024b) EU: Trends. https://food.ec.europa.eu/plants/pesticides/sustainable-use-pesticides/farm-fork-targets-progress/eu-eutrends_en Accessed 13 June 2025

Eurostat (2023) 'Database - Eurostat', eurostat datbase, https://ec.europa.eu/eurostat/data/database

Gautam P, Salunke D, Lad D, Gautam A (2025) Convergent synergy of carbon capture within the circular economy paradigm: a nexus for realizing multifaceted sustainable development goals. Carbon Research 4(1):3. https://doi.org/10.1007/s44246-024-00178-1

Guillaume A, Appels L, Latka C, Kočí V, Geeraerd A (2024) Mitigating environmental impacts of food consumption in the European Union: Is the power truly on our plates? Sustainable Production and Consumption 47:570–584. https://doi.org/10.1016/J.SPC.2024.04.027

IFOAM Organics Europe (2023) Environmental impacts of achieving 25% organic land - A study. https://www.organicseurope.bio/news/study-on-the-environmental-impacts-of-achieving-25-organic-land-by-2030-published/ Accessed 13 June 2025

Jiang M, Wang B, Hao Y, Chen S (2023) Wen Y and Yang Z (2024) 'Quantification of CO2 emissions in transportation: An empirical analysis by modal shift from road to waterway transport in Zhejiang, China.' Transp Policy 145:177–186. https://doi.org/10.1016/j.tranpol.2023.10.026

Knorr D (2024) Food processing: Legacy, significance and challenges. Trends Food Sci Technol 143:104270. https://doi.org/10.1016/j.tifs.2023.104270

Kristia K, Rabbi MF (2023) Exploring the synergy of renewable energy in the circular economy framework: a bibliometric study. Sustainability 15(17):13165. https://doi.org/10.3390/su151713165

Kristia K, Kovács S, Bács Z, Rabbi MFA (2023) Bibliometric analysis of sustainable food consumption: historical evolution, dominant topics and trends. Sustainability (Basel, Switzerland) 15:8998

Langlais A (2023) The new common agricultural policy: reflecting an agroecological transition. The legal perspective. Review of Agricultural, Food and Environmental Studies 104(1):51–66. https://doi.org/10.1007/s41130-022-00183-1

Liu T-C, Wu Y-C, Chau C-F (2023) An overview of carbon emission mitigation in the food industry: efforts, challenges, and opportunities. Processes 11(7):1993. https://doi.org/10.3390/pr11071993

Liu K, Wang P, Zhang B, Yan K, Shao L (2024) Network structures and mitigation potential of trade linked global agricultural greenhouse gas emissions. Sci Rep 14(1):30973. https://doi.org/10.1038/s41598-024-82050-1

Marrucci L, Marchi M, Daddi T (2020) Improving the carbon footprint of food and packaging waste management in a supermarket of the Italian retail sector. Waste Manage 105:594–603. https://doi.org/10.1016/j.wasman.2020.03.002

Máté D, Rabbi MF, Novotny A, Kovács S (2020) Grand challenges in central Europe: the relationship of food security, climate change, and energy use. Energies 13(20):5422. https://doi.org/10.3390/en13205422

Mensah K, Wieck C, Rudloff B (2024) Sustainable food consumption and sustainable development goal 12: Conceptual challenges for monitoring and implementation. Sustain Dev 32(1):1109–1119. https://doi.org/10.1002/sd.2718

Panigrahi SS, Luthra K, Singh CB, Atungulu G, Corscadden K (2023) On-farm grain drying system sustainability: current energy and carbon footprint assessment with potential reform measures. Sustainable Energy Technol Assess 60:103430. https://doi.org/10.1016/j.seta.2023.103430

Poyntz-Wright IP, Harrison XA, Johnson A, Zappala S, Tyler CR (2023) Pesticide pollution associations with riverine invertebrate communities in England. Sci Total Environ 903:166519. https://doi.org/10.1016/j.scitotenv.2023.166519

Priyadharsini P, Dawn SS, Arun J (2022) Four stroke diesel engine performance and emission studies of ethanol recovered from Kappaphycus alvarezii reject -solid food waste mixed substrates and its blends. Chemosphere 291:132689. https://doi.org/10.1016/j.chemosphere.2021.132689

Punia Bangar S, Whiteside WS, Chaudhary V, Parambil Akhila P, Sunooj KV (2023) Recent functionality developments in Montmorillonite as a nanofiller in food packaging. Trends Food Sci Technol 140:104148. https://doi.org/10.1016/j.tifs.2023.104148

Rabbi MF (2024) Unveiling environmental crime trends and intensity in the EU countries through a sustainability lens. Eur J Crim Policy Res. https://doi.org/10.1007/s10610-024-09607-8

Rabbi MF, Amin MB (2024) Circular economy and sustainable practices in the food industry: A comprehensive bibliometric analysis. Cleaner and Responsible Consumption 14:100206. https://doi.org/10.1016/j.clrc.2024.100206

Rahaman MA, Bin AM, Taru RD, Ahammed MR, Rabbi MF (2023) An analysis of renewable energy consumption in Visegrád countries. Environmental Research Communications 5(10):105013. https://doi.org/10.1088/2515-7620/acff40

Raihan A (2024) The interrelationship amid carbon emissions, tourism, economy, and energy use in Brazil. Carbon Research 3(1):11. https://doi.org/10.1007/s44246-023-00084-y

Raihan A, Rahman J, Tanchangya T, Ridwan M, Bari ABMM (2024) Influences of economy, energy, finance, and natural resources on carbon emissions in Bangladesh. Carbon Research 3(1):71. https://doi.org/10.1007/s44246-024-00157-6

Raman R, Pattnaik D, Achuthan K, Hughes L, Al-Busaidi AS, Dwivedi YK, Ramesh MV, Nedungadi P (2024) Mapping research in the Journal of Innovation & Knowledge to sustainable development goals. J Innov Knowl 9(3):100538. https://doi.org/10.1016/j.jik.2024.100538

Rodríguez-Espinosa T, Papamichael I, Voukkali I, Gimeno AP, Candel MBA, Navarro-Pedreño J, Zorpas AA, Lucas IG (2023) Nitrogen management in farming systems under the use of agricultural wastes and circular economy. Sci Total Environ 876:162666. https://doi.org/10.1016/j.scitotenv.2023.162666

Simon WJ, Hijbeek R, Frehner A, Cardinaals R, Talsma EF, van Zanten HHE (2024) Circular food system approaches can support current European protein intake levels while reducing land use and greenhouse gas emissions. Nature Food 5(5):402–412. https://doi.org/10.1038/s43016-024-00975-2

Sund JH, Albizzati PF, Scheutz C and Tonini D (2025) 'Comprehensive assessment of environmental and economic impacts of the entire EU waste management system'. Waste Manag 204:114910. https://doi.org/10.1016/j.wasman.2025.114910

United Nations (2023) FAOSTAT, https://www.fao.org/faostat/en/#data/GT Accessed 6 Jan 2024

Vandermeersch T, Alvarenga RAF, Ragaert P, Dewulf J (2014) Environmental sustainability assessment of food waste valorization options. Resour Conserv Recycl 87:57–64. https://doi.org/10.1016/j.resconrec.2014.03.008

Vigneshwar SS, Swetha A, Gopinath KP, Goutham R, Pal R, Arun J, SundarRajan P, Bhatnagar A, Lan Chi NT, Pugazhendhi A (2022) Bioprocessing of biowaste derived from food supply chain side-streams for extraction of value added bioproducts through biorefinery approach. Food Chem Toxicol 165:113184. https://doi.org/10.1016/j.fct.2022.113184

Widayat, Handayanto E, Irfani AD, Masudin I (2025) 'A systematic literature review and future research agenda on the dynamics of food waste in the context of consumer behavior'. Sustain Futures 9:100491. https://doi.org/10.1016/j.sftr.2025.100491

WWF (2021) Farm to Fork's targets well within reach, confirms JRC study. https://www.wwf.mg/?4180941%2FFarm-to-Forks-targets-well-within-reach-confirms-JRC-study Accessed 13 June 2025

Xie J, Zhou S, Teng F, Gu A (2023) The characteristics and driving factors of household CO2 and non-CO2 emissions in China. Ecol Econ 213:107952. https://doi.org/10.1016/j.ecolecon.2023.107952

Zhang X, Zhang S, Li A, Zhu F, Zhao Y, Ma D, Meng B, Liu M (2024) The impact of replacing chemical nitrogen fertilizer with monosodium glutamate waste liquid residue on yield, quality, and carbon emission of rice production. Carbon Research 3(1):75. https://doi.org/10.1007/s44246-024-00154-9

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