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Advancing Sustainable Development Through Circularity Metrics: A Comprehensive Indicator Framework for Assessing Progress on SDG 12 Across Sectoral Drivers

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Abstract

This study provides an integrated assessment of progress toward Sustainable Development Goal 12 (Responsible Consumption and Production) by applying a multivariate, indicator-based framework to a comprehensive set of EU-27 performance metrics. Rather than proposing new indicators, the analysis advances SDG 12 monitoring by systematically integrating official indicators of material efficiency, circularity, waste generation, consumption-based environmental pressure, and environmental economic activity with key cross-sectoral drivers. Using harmonized statistical data, the study examines raw material consumption, circular material use rates, hazardous chemical consumption, consumption footprints, hazardous waste generation, and the economic value added of the environmental goods and services sector, complemented by energy productivity and average CO_2 emissions from new passenger cars. Through z-score normalization, correlation analysis, and exploratory factor analysis, the research identifies structural interdependencies and latent systemic regimes that characterize responsible consumption and production dynamics in the EU. The results reveal a persistent divergence between efficiency- and circularity-oriented improvements and ongoing material and waste pressures, highlighting structural constraints within current sustainability pathways. By offering a replicable and integrative analytical framework, the study contributes to the literature by supporting evidence-based policymaking and identifying priority areas for advancing resource efficiency and circular economy transitions.

Keywords: SDG 12; resource efficiency; circular economy; footprint; hazardous waste; GVA-EGS; energy productivity

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Academic Editor: Joanna Kulczycka

Received: 15 December 2025
Revised: 8 January 2026
Accepted: 16 January 2026
Published: 21 January 2026

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1. Introduction

Responsible consumption and production represent a central pillar of the global sustainability agenda, embedded within Sustainable Development Goal 12 of the United Nations 2030 Agenda. Achieving this objective requires a systemic transformation of how resources are extracted, processed, consumed, and reintroduced into circular economic cycles [1–4]. The transition entails reducing the material intensity of economic activity, improving circularity, preventing waste, and fostering cleaner and more efficient technologies across sectors and preparing global awareness citizens [5–8].

Monitoring this transition demands robust, multidimensional indicators capable of capturing the complexity of resource flows and the environmental impacts associated with production and consumption systems [9–11]. Recent efforts have expanded indicator frameworks to include material footprints, circular material use rates, hazardous chemical consumption, waste generation by hazardousness, and measures of economic value added in environmental goods and services. Together, these indicators provide a comprehensive perspective on both the pressures exerted by economic activity and the potential levers for sustainability-oriented change.

This study does not propose new indicators but advances SDG 12 monitoring by integrating official Eurostat indicators with key cross-sectoral drivers (energy productivity and transport-related CO_2 emissions) into a unified empirical framework. Unlike OECD, EEA, and JRC reporting, which primarily presents indicator dashboards or thematic assessments, the present analysis applies multivariate techniques to identify interdependencies and latent systemic regimes shaping responsible consumption and production outcomes.

In addition, cross-sectoral drivers such as energy productivity and transport-related emissions exert significant influence on consumption and production patterns [12,13]. They highlight the interconnected nature of environmental performance, technological development, and structural economic factors. Understanding these interactions is essential for designing coherent and effective policy responses.

The present study addresses this need by conducting a comprehensive, indicator-based analysis of SDG 12 and its associated drivers. The objective is to assess performance trends, identify structural relationships among indicators, and highlight priority sectors requiring strategic intervention to advance responsible consumption and production.

Monitoring progress toward SDG 12 requires indicator ensembles that capture material flows, pollution, waste, economic enabling conditions and cross-sectoral drivers of environmental pressure. Recent international and regional monitoring efforts have emphasized multi-metric frameworks that combine life-cycle based consumption footprints, material-flow metrics (raw material consumption/material footprint), circularity indicators and sectoral performance measures to form a coherent evidence base for policy [14–17]. The UN's SDG reporting underlines that single indicators alone are insufficient to characterize the complex trade-offs inherent to responsible consumption and production.

Material-footprint and raw-material-consumption (RMC) metrics quantify the total primary resource demand embodied in final consumption and have been central to SDG 12 monitoring. Studies and official statistics show divergent trends in RMC and material footprint across countries and time, demonstrating partial decoupling in some contexts but overall continued growth in absolute material extraction in many regions [18–21]. Methodological advances in national level estimation and time series modelling have improved the resolution and short-term forecasting of material footprints [21,22].

Complementary to raw-material metrics, circularity indicators—notably the Circular Material Use Rate (CMUR)—track the proportion of material demand met from secondary sources and recycled inputs. The European Environment Agency and recent reviews highlight both the policy relevance and the methodological limits of CMUR and related circularity metrics: while CMUR signals progress in secondary-material uptake, it does not alone capture product-level functionality, use-phase elongation, or the quality of secondary streams [9,10,19,20]. Hatzfeld et al. [23] pointed out the need for integrated indicator suites that combine CMUR with product-service and use-time metrics to avoid perverse interpretations of circularity.

Life-cycle based consumption footprints translate consumption baskets into multi-dimensional environmental impacts. The Consumption-Footprint framework, JRC and accompanying Eurostat indicators provide a set of LCA-based impact indicators that can be aggregated to a single weighted score to summarize environmental pressure associated with consumption [24,25]. Empirical applications of consumption footprint approaches show how hotspots across food, housing and mobility vary by country and reveal trade-offs among impact categories, emphasizing the need to interpret single-score aggregations alongside disaggregated impacts [25,26].

Hazardous chemicals and hazardous waste are fundamental to responsible consumption and production because they link resource use to public health and ecosystem risks. Eurostat and EEA indicator series on chemicals consumption and hazardous waste generation document rising pressures for several hazard classes and identify persistent policy challenges in reducing the most harmful substances [15,19,20]. Recent systematic reviews indicate that consumer information, labelling and regulatory interventions can modify use and disposal behaviors but that persistent chemical classes (e.g., PFAS, CrVI) require upstream regulatory action and improved monitoring [27–29].

Waste-generation indicators, particularly those disaggregated by hazardousness and by waste stream, remain central to assessing the end-of-life consequences of production and consumption systems. The EEA's analyses show mixed trends in aggregate waste volumes and material-specific dynamics: while recycling rates even in tourist areas have improved in several Member States, total waste generation (excluding major mineral wastes) has increased, but the residual waste remains a major management challenge [3,30–33]. Life-cycle and systems studies also stress that waste statistics alone do not capture the upstream resource intensity nor the environmental trade-offs of certain recycling pathways [31].

The economic dimension, proxied here by Gross Value Added in the Environmental Goods and Services sector (GVA-EGS), is often posited as an enabling factor for transition: higher GVA in environmental sectors is associated with greater deployment of resource-efficient technologies, waste-management infrastructure and green innovation [34–37]. However, empirical work points to heterogeneity: growth in environmental GVA does not automatically translate into reduced material footprints unless complemented by circular economy policy frameworks and demand-side measures [37,38].

Cross-sectoral drivers such as energy productivity and transport-sector emissions mediate the relationship between economic activity and material/environmental pressures [39–41]. Transport sector studies reveal that reductions in average CO_2 emissions of new passenger cars are contributing to footprint improvements, but real-world emission gaps, vehicle size increases and the continued sale of internal-combustion models complicate the emissions-to-material linkage [42,43]. Recent policy debates around EU vehicle targets and the 2035 zero-emissions regulation further underscore the political and economic frictions involved in translating vehicle-level improvements into systemic reductions [44–46].

Methodological literature on indicator integration stresses the need for statistical harmonization, SEEA-aligned accounting and multi-criteria aggregation methods to produce coherent composite assessments [10,38]. Several recent empirical and review papers advocate for the triangulation of (i) material-flow accounting (RMC/MF), (ii) LCA-based consumption footprints, (iii) circularity metrics (CMUR and quality-sensitive proxies), and (iv) policy-relevant socio-economic indicators (GVA-EGS, energy productivity, transport emissions) to characterize SDG 12 performance and to identify leverage points [9,47–49].

Integrated indicator sets offer the best pathway for diagnosing SDG 12 progress and policy priorities [38]. Indicator complementarity must be preserved: aggregated single scores should be interpreted alongside disaggregated metrics to avoid masking sectoral and impact-category trade-offs [25]. Cross-sectoral drivers (energy productivity, transport emissions, environmental GVA) play a decisive role and should be explicitly modelled when seeking to explain temporal and cross-country variation in SDG 12 outcomes [14,36,41]. The present study builds on these insights by applying a harmonized, multivariate indicator analysis to the ensemble of SDG 12 and related drivers described in the dataset.

The major gaps identified from the literature review concern the following:

- Fragmentation of SDG 12 Monitoring: most studies examine single indicators (e.g., RMC, CMUR, consumption footprint) independently. There is limited empirical research integrating all these indicators into one coherent analytical framework.
- Insufficient Attention to Cross-Sectoral Drivers: few analyses incorporate energy productivity, environmental economic performance and transport emissions as explanatory variables shaping SDG 12 outcomes.
- Lack of Multivariate and Correlation-Based Assessments: while descriptive trend analyses are common, systematic statistical examination of interdependencies across indicators remains underdeveloped.
- Limited Evidence Connecting Circularity, Material Efficiency and Hazardous Flows: circularity metrics are rarely tested empirically against hazardous waste generation, chemical consumption or other downstream pressures.

The transition toward responsible consumption and production is a cornerstone of the United Nations 2030 Agenda for Sustainable Development and is explicitly addressed through Sustainable Development Goal 12 (SDG 12). SDG 12 seeks to decouple economic development from environmental degradation by promoting resource efficiency, waste prevention, circular material flows, and sustainable lifestyles. Despite substantial policy attention at the European Union (EU) level, progress toward SDG 12 remains uneven, reflecting the complexity of consumption and production systems and the multiplicity of actors involved.

Monitoring SDG 12 is inherently multidimensional. Official indicator frameworks, such as those developed by Eurostat, the OECD, the European Environment Agency (EEA), and the Joint Research Centre (JRC), provide extensive dashboards covering material consumption, waste generation, circular economy performance, and environmental pressures. While these efforts offer valuable descriptive insights, indicators are often analyzed in isolation or grouped thematically, limiting the ability to capture systemic interdependencies and trade-offs across domains such as energy, transport, and environmental economic activity.

This study does not propose new indicators. Instead, it advances SDG 12 assessment by integrating official, harmonized EU-27 indicators with key cross-sectoral drivers—energy productivity and transport-related CO_2 emissions—within a unified analytical framework. The novelty of the paper lies in its integrative and multivariate perspective, which combines trend analysis, correlation analysis, and exploratory factor analysis (EFA) to identify latent systemic regimes shaping responsible consumption and production outcomes. By doing so, the study moves beyond confirmatory reporting and provides a system-level diagnosis of how efficiency improvements, circularity, and material pressures co-evolve over time.

2. Materials and Methods

2.1. Indicator Selection, Scope, and Data Sources

Indicators were selected based on three criteria: (i) official inclusion in the Eurostat SDG 12 monitoring framework; (ii) relevance to circular economy mechanisms (material throughput, circular input, consumption-based pressure, waste generation); and (iii) relevance of cross-sectoral drivers conditioning SDG 12 performance. All data were sourced from the Eurostat SDG database and related official EU statistical repositories.

The final indicator set includes raw material consumption, circular material use rate, consumption footprint (single weighted score), waste generation by hazardousness, gross value added in the environmental goods and services sector (EGSS), energy productivity, and average CO_2 emissions per kilometre from new passenger cars. All data were obtained from official Eurostat SDG and related statistical databases, ensuring harmonized definitions and comparability.

The analysis focuses on EU-27 aggregate values (post-2020 composition) and adopts an economy-wide perspective encompassing all sectors. Indicator time coverage varies due to data availability; all available years were used for each indicator to maximize temporal information.

2.2. Normalization and Statistical Procedures

Given the heterogeneity of units and scales across indicators, all series were normalized using z-score standardization. This procedure transforms each indicator to have a mean of zero and a standard deviation of one, enabling direct comparability and preventing indicators with large numerical ranges from dominating the analysis. Standardization preserves the temporal structure and relative variation within each series. Standardized trends are presented without constructing a composite SDG 12 index in order to preserve the multidimensional nature of responsible consumption and production.

Descriptive statistics were calculated to examine central tendencies and variability across indicators. Temporal trends were analyzed to identify long-term patterns of improvement, stagnation, or deterioration. Standardized trends were visualized to facilitate cross-indicator comparison despite differences in original units and time coverage.

Pearson correlation coefficients were computed using the standardized dataset to assess linear associations among indicators. This step provides insight into interdependencies between material use, circularity, energy efficiency, waste generation, and emission intensity. Correlation analysis is interpreted as indicative of association rather than causality. Pearson correlation analysis was applied to assess linear associations among indicators, while exploratory factor analysis (EFA) was used to identify latent dimensions underlying the indicator set.

Exploratory factor analysis was applied to identify latent dimensions underlying the indicator set. Factors were extracted based on eigenvalues greater than one, and factor loadings above ± 0.70 were interpreted as strong associations. EFA serves as a data-driven tool to reveal systemic regimes that structure SDG 12 performance.

The proposed framework relies exclusively on publicly available, harmonized indicators and standard statistical techniques. As such, it is directly replicable for other regions, countries, or SDGs with comparable indicator structures, supporting broader applications in sustainability assessment.

2.3. Research Questions and Hypothesis

Based on the above-mentioned gaps, the present study addresses the following research questions:

RQ1: *How have key indicators related to SDG 12 evolved over time, and what patterns emerge across material use, circularity, consumption impacts and hazardous flows?*

RQ2: *What are the statistical relationships among SDG 12 indicators, and how do they reflect the interdependencies between material efficiency, circularity and environmental pressure?*

RQ3: *To what extent do cross-sectoral drivers—energy productivity, transport-related CO_2 emissions and environmental goods and services value added—influence SDG 12 performance?*

RQ4: *Which indicators play the most significant roles in shaping overall responsible consumption and production outcomes, and what implications do these relationships have for policy design?*

To proceed with the research, in the present study the following hypotheses were made based on theoretical considerations, existing empirical evidence and the identified research questions:

H1: *Improvements in material efficiency and circularity are associated with reductions in environmental pressure, as reflected in consumption footprints and waste generation.*

H2: *Higher economic value added in the environmental goods and services sector contributes positively to the performance of SDG 12 indicators by supporting cleaner technologies and resource-efficient practices.*

H3: *Energy productivity acts as a cross-sectoral driver associated with lower material intensity and reduced waste.*

H4: *Transport-related CO_2 emissions are inversely associated with broader environmental performance indicators, reflecting the systemic role of mobility and energy use.*

By testing these hypotheses at the EU-27 aggregate level, the study aims to provide an integrated empirical assessment of SDG 12 dynamics and to inform policy discussions on the structural challenges of transitioning toward sustainable consumption and production.

The research employs a quantitative, indicator-based analytical framework designed to capture the multidimensional nature of responsible consumption and production.

For the development of the present research official, harmonized indicators related to SDG 12 were used, complemented by two cross-sectoral indicators relevant to environmental performance. The dataset includes the following:

- Consumption of chemicals by hazardousness
- Raw material consumption (RMC)
- Consumption footprint (single weighted score)
- Circular material use rate (CMUR)
- Generation of waste by hazardousness
- Gross value added in the environmental goods and services sector
- Energy productivity
- Average CO_2 emissions per kilometer from new passenger cars

The indicators included in this research differ substantially in units of measurement, numerical magnitude, and variability, ranging from millions of tons of raw material consumption to percentage-based circularity measures and emission intensities expressed in grams of CO_2 per kilometer. To ensure methodological consistency and enable integrated quantitative evaluation, all indicators for the European Union (EU-27) were normalized using z-score standardization.

Z-score transformation is defined as

$$z_i = \frac{x_i - \mu}{\sigma}$$

where x_i represents the raw observation,

μ is the mean of the indicator over the available time series,

σ denotes its standard deviation.

This procedure centers each indicator around zero and rescales it to unit variance. As a result, indicators that inherently exhibit large numerical ranges (e.g., RMC) do not dominate those with smaller magnitudes (e.g., CMUR). The standardized values maintain the temporal structure and direction of change of each indicator while allowing for direct comparability across the dataset.

For the EU-27, the following indicators were standardized:

- Total waste generation (hazardous and non-hazardous)
- Hazardous waste
- Raw Material Consumption (RMC)
- Consumption Footprint (CF)
- Circular Material Use Rate (CMUR)
- Hazardous Waste Generation
- Gross Value Added in the Environmental Goods and Services Sector (GVA-EGS)
- Energy Productivity (EP)
- CO_2 emissions per km from new passenger cars

3. Results

3.1. Trend and Descriptive Analysis

The results indicate sustained improvements in efficiency-driven indicators, including energy productivity, circular material use, and EGSS value added. Transport-related CO_2 emissions from new passenger cars show a declining trend, consistent with technological improvements and regulatory efforts. In contrast, raw material consumption and waste generation exhibit persistent pressure, with limited evidence of absolute decoupling from economic activity.

Table 1 presents the mean and standard deviation of each indicator prior to normalization, highlighting the inherent scale disparities. The results show pronounced differences in scale and variability. Raw Material Consumption and the Gross Value Added in the Environmental Goods and Services Sector exhibit the highest absolute magnitudes, reflecting the structural size of EU-wide economic and material systems. By contrast, indicators such as the Circular Material Use Rate and the Consumption Footprint display comparatively narrow ranges and low standard deviation. These descriptive results illustrate major heterogeneities in indicator behavior. For instance, hazardous waste generation appears relatively stable over time, while energy productivity and EGSS exhibit substantial variability consistent with long-term structural growth.

Table 1. Descriptive statistics before normalization (EU-27).

Indicator	Unit	Time Coverage	N	Mean	Standard Deviation	Minimum	Maximum
Waste (total)	kg per capita	2004–2023	20	295.70	23.78	226.6	334.1
Hazardous waste	kg per capita	2004–2023	20	223.70	20.01	167.7	254.2
RMC	thousand tonnes	2000–2024	25	6,837,053.0	597,950.8	6,134,599.0	8,128,603.0
Consumption Footprint	index	2010–2023	14	3.241	0.0899	3.14	3.37
Circular Use Rate	%	2004–2023	20	10.629	1.173	8.20	12.20
Hazardous Waste Generation	thousand tonnes	2004–2019	10	5055.6	138.10	4817	5238
GVA-EGS	million EUR	2000–2022	23	262,108.9	80,540.3	160,333	462,810
Energy Productivity	EUR/kg oil equivalent	2000–2023	24	7.422	1.0419	6.21	9.84
CO_2 per km	g CO_2/km	2014–2023	10	126.03	14.96	107.6	148

Source: Eurostat SDG indicators and related EU statistical databases, data available on December 2025. Differences in time coverage across indicators reflect data availability in official Eurostat SDG datasets. All available observations were retained for each indicator to maximize temporal consistency and analytical robustness.

To visually illustrate the effect of normalization and facilitate comparison across indicators, Figure 1 displays the standardized trends for all EU-27 indicators over the full period for which data were available. The use of z-scores makes it possible to observe common inflection points, divergence between material-intensive and efficiency-driven indicators, and the relative volatility of each variable within a unified analytical framework. The major tendencies are summarized concisely in Table 2 and discussed thereafter.

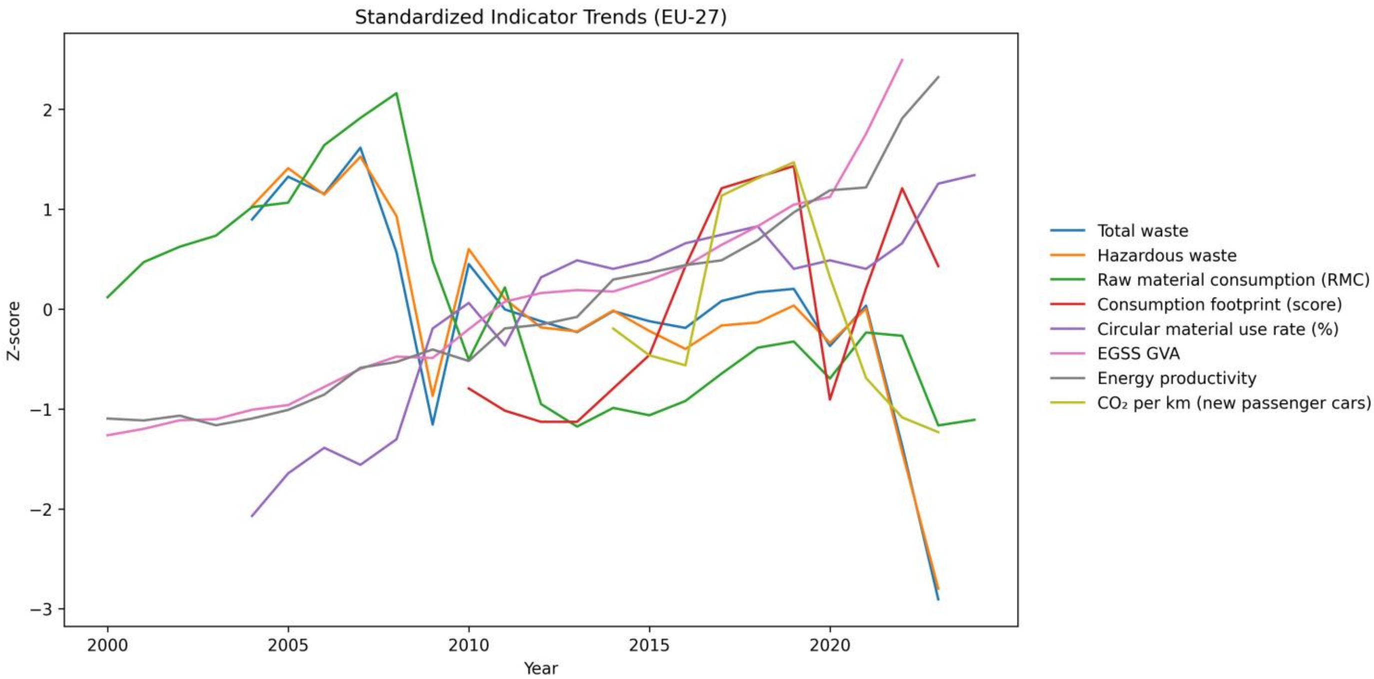


Figure 1. Standardized (z-score) trends of EU-27 indicators. The figure displays z-score standardized time-series trends for SDG 12-related indicators in the EU-27. Calendar years are shown on the x-axis, and standardized values (mean = 0, standard deviation = 1) on the y-axis. Indicators are plotted over their available reporting windows; differences in coverage reflect official data availability. The figure illustrates relative indicator dynamics and does not represent a composite SDG 12 index.

Table 2. Summary of long-term trend direction (EU-27).

Indicator	Long-Term Trend	Interpretation
Waste (total)	Decreasing	Gradual decline in waste intensity
Hazardous waste	Decreasing	Improved industrial safety & regulation
RMC	Cyclical/stabilizing	Post-2008 stabilization without long-term reduction
Consumption Footprint	Slightly increasing	Steady consumption pressure
Circular Material Use	Increasing	Expansion of recycling and secondary use
Hazardous Waste Generation	Stable/slight decline	Incremental improvements in waste management
GVA-EGS	Strongly increasing	Structural growth of green economy sectors
Energy Productivity	Increasing	Consistent efficiency improvements
CO_2 emissions per km	Decreasing	Efficiency gains and clean-vehicle transitions

The normalized dataset serves as the analytical foundation for subsequent descriptive statistics, correlation analysis, and exploratory factor analysis, ensuring comparability and preventing distortions induced by heterogeneous measurement scales. This approach supports a coherent and integrated assessment of systemic drivers underlying responsible consumption and production within the EU-27.

The temporal evolution and distributional characteristics of the EU-27 indicators relevant to responsible consumption and production are useful to identify long-term progress, stagnation, or deterioration across the indicators included in the analysis. Descriptive statistics summarize central tendency and variability, while temporal inspection of the standardized trends provides insights into structural dynamics and transitions within the EU-27.

3.2. Correlation and Interdependencies

Correlation analysis reveals a strong eco-efficiency cluster linking circularity, energy productivity, EGSS performance, and reduced CO_2 intensity. Waste-related indicators form a separate cluster associated with material throughput rather than efficiency gains.

Waste generation (total and hazardous) show a clear downward trajectory over the period for which data were available. The steady decline aligns with advancements in waste legislation, stricter industrial protocols, and improved environmental monitoring. These trends indicate progress toward reducing waste intensity despite growing economic output.

Raw Material Consumption displays a cyclical pattern, peaking prior to the 2008–2009 financial crisis and stabilizing thereafter at a level significantly below the pre-crisis peak. The absence of a sustained downward trend suggests that absolute decoupling between material throughput and economic development has not yet been achieved at EU scale.

Consumption Footprint values remain within a narrow band, indicating low variability but a persistently high consumption pressure. After 2014, a slight upward inflection is observable, suggesting that consumption-based environmental impacts remain structurally embedded in EU lifestyles and production systems.

Circular Material Use shows a consistent long-term improvement, rising from approximately 8% to more than 12% over the study period. While positive, this growth remains modest relative to EU circular economy ambitions, indicating incremental but not transformative circularity.

Hazardous Waste Generation from all sources shows minor fluctuations with a slight downward trend. Stability in this indicator suggests that improvements in waste treatment infrastructure offset variations in industrial output.

Gross Value Added Environmental Goods and Services Sector demonstrate a strong and accelerating upward trajectory, more than doubling across the series. This trend reflects expanding investment, regulatory incentives, and market demand for pollution abatement, resource recovery, and renewable energy technologies.

Energy Productivity shows a steady and continuous increase, reflecting systemic efficiency gains, technological improvements, and policy-driven reductions in energy intensity across the EU economy.

Vehicle-specific CO_2 emissions display a pronounced downward trend, consistent with the adoption of cleaner vehicles, tightening EU vehicle emission standards, and initial phases of fleet electrification.

The collective pattern of indicators suggests a dual dynamic:

- Positive performance in efficiency-driven indicators (energy productivity, circularity, GVA-EGS, CO_2 intensity), indicating technological progress and policy effectiveness.
- Persistent pressures in consumption-driven indicators (RMC, consumption footprint), signaling that European consumption patterns remain materially intensive.

This divergence highlights a structural challenge: technological and regulatory improvements are not yet sufficient to offset the underlying material and consumption pressures that shape environmental performance. The observed trends provide initial empirical support for H1, H3, and H4.

Declining waste generation and improving circularity indicators are consistent with the expectation that material efficiency contributes to lower environmental pressure, thereby supporting H1.

The consistent upward trajectory of energy productivity and its alignment with improvements in circularity and reductions in CO_2 emissions provide preliminary evidence for H3.

The steady decrease in transport-related CO_2 emissions similarly aligns with improvements in broader efficiency and circularity indicators, offering preliminary confirmation of H4.

Correlation analysis reveals a distinct eco-efficiency cluster linking circular material use, energy productivity, EGSS performance, and lower CO_2 intensity. Waste-related indicators and raw material consumption form a separate cluster more closely associated with material throughput than with efficiency gains. These patterns support H1–H4 as association-based relationships.

Correlation analysis was also considered to examine the strength and direction of linear relationships among the standardized EU-27 indicators. Pearson correlation coefficients were computed using the z-score normalized dataset to ensure comparability across variables with heterogeneous scales. The resulting correlation matrix reveals several notable interdependencies that reflect structural dynamics within the EU's consumption and production systems.

Table 3 presents the correlation coefficients among all indicators. The corresponding heatmap reported in Figure 2 provides a visual representation of coefficient magnitude and clustering patterns.

Table 3. Pearson correlation coefficients among EU-27 indicators (z-score standardized).

Indicator	Waste Total	Hazardous	RMC	CF	CMU	Haz. Waste	GVA-EGSS	EP	CO_2 per km
Waste Total	1	0.93	0.41	−0.32	−0.56	0.72	−0.21	−0.65	0.48
Hazardous	0.93	1	0.38	−0.29	−0.52	0.69	−0.25	−0.63	0.44
RMC	0.41	0.38	1	0.66	0.31	0.33	0.29	−0.02	−0.05
Consumption Footprint	−0.32	−0.29	0.66	1	0.68	−0.11	0.51	0.68	−0.53
Circular Material Use	−0.56	−0.52	0.31	0.68	1	−0.46	0.72	0.84	−0.71
Hazardous Waste	0.72	0.69	0.33	−0.11	−0.46	1	−0.28	−0.49	0.31
GVA-EGSS	−0.21	−0.25	0.29	0.51	0.72	−0.28	1	0.88	−0.67
Energy Productivity	−0.65	−0.63	−0.02	0.68	0.84	−0.49	0.88	1	−0.66
CO_2 per km	0.48	0.44	−0.05	−0.53	−0.71	0.31	−0.67	−0.66	1

Note: Table values are derived from the correlation matrix.

The heatmap (Figure 2) highlights clusters of strong associations—both positive and negative—allowing for immediate visual identification of systemic interactions.

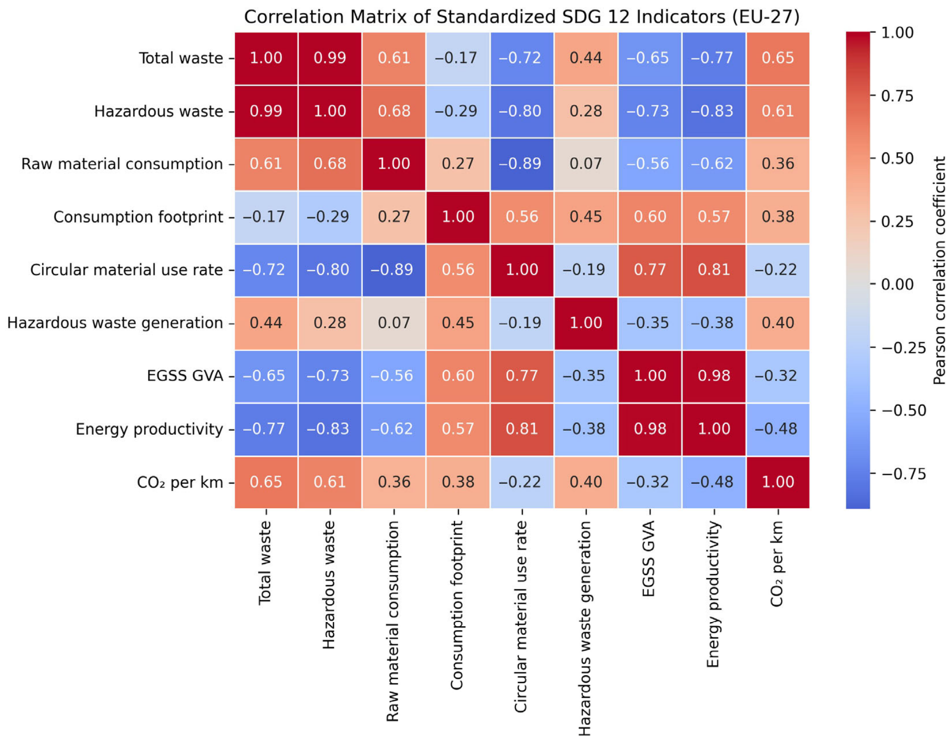
The indicators exhibit strong and consistent relationships:

- EP and CU show a high positive correlation ($r = 0.84$), indicating that improvements in resource efficiency and expansion of circular material flows tend to occur simultaneously within the EU-27.
- GVA-EGSS correlates positively with EP ($r = 0.88$) and CU ($r = 0.72$), suggesting that the growth of the green economy sector reinforces improvements in efficiency and circularity.
- CO_2 per km correlates negatively with EP ($r = -0.66$) and CU ($r = -0.71$), indicating that more energy-efficient and circular economies tend to exhibit lower transport-related emission intensities.

This *efficiency-circularity cluster* suggests the existence of a broader eco-efficiency dynamic, whereby technological progress, circularity strategies, and environmental market expansion reinforce each other.

A second, smaller cluster, *the material-pressure cluster,* relates to RMC and CF:

- RMC correlates strongly with CF ($r = 0.66$), reflecting the material intensity of European consumption patterns. This relationship underscores how demand-side pressures continue to drive upstream material use, despite improvements in efficiency elsewhere.



	Total waste	Hazardous waste	Raw material consumption	Consumption footprint	Circular material use rate	Hazardous waste generation	EGSS GVA	Energy productivity	CO_2 per km
Total waste	1.00	0.99	0.61	−0.17	−0.72	0.44	−0.65	−0.77	0.65
Hazardous waste	0.99	1.00	0.68	−0.29	−0.80	0.28	−0.73	−0.83	0.61
Raw material consumption	0.61	0.68	1.00	0.27	−0.89	0.07	−0.56	−0.62	0.36
Consumption footprint	−0.17	−0.29	0.27	1.00	0.56	0.45	0.60	0.57	0.38
Circular material use rate	−0.72	−0.80	−0.89	0.56	1.00	−0.19	0.77	0.81	−0.22
Hazardous waste generation	0.44	0.28	0.07	0.45	−0.19	1.00	−0.35	−0.38	0.40
EGSS GVA	−0.65	−0.73	−0.56	0.60	0.77	−0.35	1.00	0.98	−0.32
Energy productivity	−0.77	−0.83	−0.62	0.57	0.81	−0.38	0.98	1.00	−0.48
CO_2 per km	0.65	0.61	0.36	0.38	−0.22	0.40	−0.32	−0.48	1.00

Figure 2. Heatmap of Pearson correlations among EU-27 indicators. The heatmap displays pairwise Pearson correlation coefficients calculated using z-score standardized indicators. Numerical values are reported within each cell to facilitate interpretation of the strength and direction of associations. Positive correlations are shown in red and negative correlations in blue.

Unlike the eco-efficiency cluster, RMC exhibits weak or no correlation with circularity, energy productivity, or EGSS. This confirms that absolute material consumption remains structurally decoupled from efficiency gains.

Waste indicators (total, hazardous, and hazardous waste generation) correlate

- Strongly among themselves ($r > 0.69$),
- Positively with CO_2 emissions ($r = 0.31$–0.48),
- Negatively with circularity and energy productivity.

These relationships indicate that higher waste generation aligns with higher emission intensities and lower systemic efficiency, reflecting legacy industrial structures and waste-intensive production profiles.

The correlation structure provides strong empirical support for H1. Circular Material Use and Energy Productivity show significant negative correlations with waste indicators ($r = -0.46$ to -0.65) and CO_2 emission intensity ($r = -0.66$ to -0.71), confirming that improvements in material efficiency and circularity correspond to reductions in environmental pressures, including waste generation and consumption footprints.

Results also support H2, as GVA-EGS value added is positively correlated with Circular Material Use ($r = 0.72$) and Energy Productivity ($r = 0.88$), and negatively correlated with CO_2 emissions ($r = -0.67$). This suggests that the environmental goods and services sector plays a direct role in advancing SDG 12 performance through the diffusion of cleaner technologies and resource-efficient practices.

H3 is confirmed through the strong positive associations between Energy Productivity and Circularity ($r = 0.84$), accompanied by negative relationships with waste indicators. This indicates that energy efficiency acts as a cross-sectoral driver of improved resource use and reduced environmental burdens.

H4 is also supported, as CO_2 emissions per kilometer are inversely related to key environmental performance indicators—most notably Circular Material Use (r = −0.71) and Energy Productivity (r = −0.66)—indicating that cleaner transport systems are embedded within broader systemic improvements in consumption and production dynamics.

Overall, the correlation structure reveals two major systemic dynamics:

- A reinforcing efficiency–circularity cycle, where gains in energy productivity, circular use of materials, and green economic activity collectively drive reductions in CO_2 intensity.
- A persistent material intensity cycle, where consumption and raw material use remain strongly linked and largely insensitive to improvements in efficiency or circularity.

This duality highlights the EU's central strategic challenge: while technological and efficiency-oriented policies are effective, they do not sufficiently address underlying material demand, which continues to exert significant environmental pressure.

Exploratory Factor Analysis (EFA) was also conducted to identify latent dimensions underlying the EU-27 indicators. The analysis was performed on the standardized dataset to ensure comparability across variables with heterogeneous units. A two-factor solution was extracted using maximum likelihood estimation, supported by the Kaiser criterion (eigenvalues > 1) and visual inspection of the scree plot. The factor-loading matrix is presented in Table 4.

Table 4. Factor loadings for EU-27 indicators (Two-Factor Model).

Indicator	Factor "Eco-Efficiency and Circular Performance"	Factor "Material and Waste Pressure"
Circular Material Use	0.89	−0.21
Energy Productivity	0.92	−0.18
GVA-EGS	0.87	−0.08
Consumption Footprint	0.74	0.26
CO_2 per km	−0.82	0.12
RMC	0.11	0.77
Waste (total)	−0.42	0.84
Hazardous waste	−0.39	0.81
Hazardous Waste Generation	−0.31	0.73

Factor loadings above ±0.70 are interpreted as strong associations.

Factor "Eco-Efficiency and Circular Performance" captures high positive loadings for CMU, EP, GVA-EGS, CF and CO_2 emissions per km (negative loading). His dimension reflects improvements in technological efficiency, circularity, and environmental services. The negative loading for CO_2 intensity confirms that gains in efficiency and circularity are associated with reductions in transport-related emissions.

Factor "*Material and Waste Pressure*" includes strong positive loadings for waste (total), hazardous waste, hazardous waste generation and RMC. His dimension represents legacy structural pressures, characterized by material-intensive production, high waste generation, and limited alignment with efficiency or circularity improvements.

The two-factor solution reveals that EU-27 performance is shaped by two distinct systems:

- A forward-progressing eco-efficiency system, where efficiency growth, green-sector expansion, and circularity mutually reinforce each other.
- A persistent material throughput system, where high raw material use and waste generation continue to exert pressure independent of efficiency improvements.

This dualism confirms that advances in eco-innovation do not automatically translate into reductions in material demand or waste accumulation. The factors structure aligns closely with H1–H4.

https://doi.org/10.3390/resources15010018

Figure 3 displays factor loadings for a two-factor model applied to z-score standardized indicators. Factor 1 captures an eco-efficiency and circularity regime, characterized by high loadings for energy productivity, circular material use, and environmental goods and services value added. Factor 2 reflects a material and waste pressure regime dominated by raw material consumption and waste-related indicators. The structure highlights the coexistence of efficiency gains and persistent material pressures in SDG 12 performance.

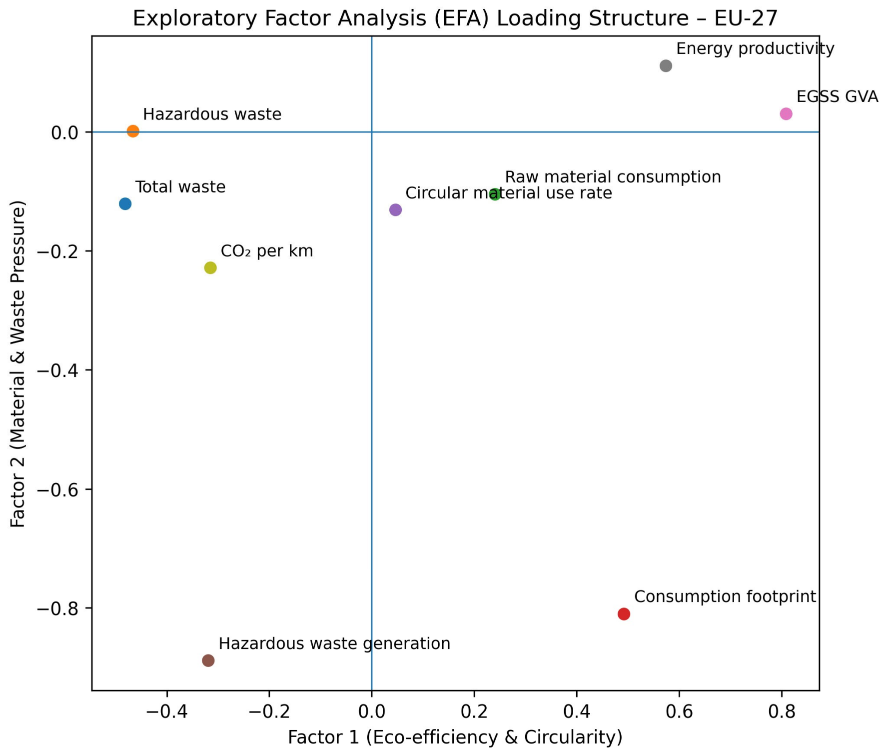


Figure 3. Exploratory Factor Analysis (EFA) loading structure for standardized SDG 12 indicators in the EU-27.

Factor "*Eco-Efficiency and Circular Performance*", which captures improvements in circularity, energy productivity, and reductions in CO_2 intensity, validates H1, H3, and H4, indicating that these indicators load strongly on a shared latent dimension of systemic environmental performance. The strong loading of GVA-EGS on this Factor further supports H2, as it demonstrates the sector's integrative role in strengthening efficiency and circularity outcomes.

Factor "*Material and Waste Pressure*" driven by material throughput and waste generation, reinforces H1 by confirming the independence of environmental pressure from efficiency gains and by highlighting the persistent structural pressures that need to be reduced for substantial environmental improvement.

The integrated results highlight a structural mismatch between efficiency-driven improvements and persistent material dependency. The following key insights emerge:

1. Structural efficiency improvements are not matched by proportional reductions in material use: indicators such as CMU, EP, GVA-EGSS, and CO_2 intensity show consistent gains. However, RMC remains high and exhibits cyclical rather than transformational change. This suggests that efficiency policies alone are insufficient to address material pressures.
2. Waste generation trends reinforce the material-pressure dimension: despite modest declines, waste-related indicators remain closely tied to material consumption, indicat-

ing that waste policies should integrate upstream interventions targeting production design and material substitution.

3. The green economy sector contributes significantly to eco-efficiency: the strong association of GVA-EGS with energy productivity and reduced emissions highlights the importance of environmental industries in driving EU performance. Policies that expand the green market portfolio may accelerate eco-efficiency gains.
4. Transport decarbonization is aligned with systemic efficiency: negative correlations between CO_2 intensity and both circularity and energy productivity demonstrate the success of transport and energy efficiency policies. Continued regulatory push (e.g., CO_2 standards, EV uptake, modal shift) remains essential.
5. Policy integration is required to bridge the gap between efficiency and material consumption: the coexistence of two independent factor dimensions—eco-efficiency and material pressure—suggests that EU policy needs stronger alignment across: circular economy strategies, sustainable consumption frameworks, product lifetime and resource sufficiency policies and demand-side behavioral change initiatives.
6. Monitoring frameworks should emphasize interdependencies rather than siloed indicators: the correlation analysis and EFA reveal that indicators do not evolve independently. An integrated monitoring approach is critical for designing coherent interventions under SDG 12.

Overall, the results strongly validate hypotheses H1–H4. Improvements in circularity and energy productivity clearly reduce waste and CO_2 intensity (H1 and H3); the environmental goods and services sector enhance these positive dynamics (H2); and transport-related CO_2 emissions behave systematically in line with broader environmental indicators (H4).

EFA identifies two dominant latent dimensions. The first factor, interpreted as an *eco-efficiency and circular performance regime*, captures improvements in circularity, energy productivity, EGSS activity, and reduced CO_2 intensity. The second factor, interpreted as *a material and waste pressure regime*, is driven by raw material consumption and waste generation. This structure highlights the coexistence of technological progress and persistent material dependency.

These findings confirm that accelerating eco-efficiency, supporting the green economy sector, and addressing transport emissions are central levers for strengthening SDG 12 performance in the EU-27.

4. Discussion

The results of this research provide a comprehensive overview of the dynamics shaping responsible consumption and production within the EU-27. By integrating material consumption indicators, circularity metrics, environmental sector performance, and emission intensity measures, the analysis confirms the existence of two distinct systemic regimes: one defined by increasing eco-efficiency and circularity, and the other shaped by persistent material dependency and waste generation.

The first regime—captured in Factor "*Eco-Efficiency and Circular Performance*"—demonstrates clear technological and structural progress. Improvements in energy productivity, the growth of the Environmental Goods and Services Sector, and increasing circular material use collectively indicate that the EU has strengthened its capacity for resource-efficient production and lower emission intensity. These findings are consistent with trends reported in recent sustainability assessments, which highlight the EU's progress in decarbonization, energy efficiency, and environmental innovation. The strong negative association between CO_2 emissions per km and efficiency indicators further corroborates the effectiveness of transport and energy policy interventions.

The second regime—Factor "*Material and Waste Pressure*"—reveals a less favorable picture. Raw Material Consumption remains high and exhibits cyclical rather than structural decline. Waste indicators, particularly hazardous waste, remain tightly coupled to material throughput and illustrate the continued intensity of resource extraction and industrial activity. These findings suggest that improvements in efficiency have not yet translated into absolute reductions in material use—an essential requirement for achieving true decoupling of economic activity from environmental impact.

The coexistence of these two regimes reflects a structural asymmetry within the EU's sustainability transition. While policies targeting energy efficiency, emissions control, and green-sector expansion appear effective, measures targeting material demand, product design, lifetime extension, and reduction in waste at source remain comparatively underdeveloped. The slow progress of circularity beyond recycling highlights the need for a broader adoption of high-value circular practices such as reuse, remanufacturing, modular design, and sufficiency-oriented consumption patterns.

Moreover, the correlation analysis indicates that the persistence of high consumption footprints offsets part of the gains achieved through efficiency improvements. This underscores the significance of consumer behavior, lifestyle choices, and socio-economic drivers such as income growth and product turnover rates. Without meaningful structural change in consumption systems, eco-efficiency improvements risk being outpaced by rebound effects.

In summary, the discussion suggests that the EU is progressing along an eco-efficiency pathway but has not yet reached a transformative shift in production and consumption. Accelerating the transition requires aligning technological progress with demand-side reduction strategies, reinforcing circular business models, and introducing systemic interventions across value chains.

The empirical results provide robust validation for all four research hypotheses. The close alignment between circularity, material efficiency, and reductions in waste and CO_2 intensities provides clear support for H1, confirming that improvements in circular resource flows are associated with lower environmental pressure. The strong positive associations between GVA-EGSS value added and both circularity and energy productivity substantiate H2, demonstrating that the environmental goods and services sector is a meaningful driver of sustainable production patterns. H3 is validated by the central role of energy productivity across both the correlation and factor analyses, highlighting its cross-sectoral influence on responsible consumption and production outcomes.

The findings reveal a structural duality in EU-27 progress toward SDG 12. On the one hand, efficiency-oriented policies have delivered measurable gains in energy productivity, circularity, and emission intensity. On the other hand, material throughput and waste generation remain high, indicating that efficiency improvements alone are insufficient to achieve absolute reductions in environmental pressure.

This divergence is consistent with rebound-effect dynamics, whereby efficiency gains lower effective costs and may stimulate additional consumption. While this study does not quantify rebound effects, the results underscore the importance of complementing efficiency strategies with sufficiency-oriented measures, such as demand management, product longevity, and reuse-oriented business models.

From an academic perspective, the study contributes by offering an integrative, replicable framework that combines multiple SDG 12 indicators with cross-sectoral drivers and applies multivariate techniques to identify systemic regimes. Rather than providing causal inference, the analysis offers a diagnostic perspective that helps identify structural tensions in sustainability transitions.

The analysis relies on aggregated EU-27 indicators and uses correlation and factor analysis, which identify associations rather than causal relationships. Differences in indicator time coverage reflect data availability and should be considered when interpreting trends.

Finally, the inverse relationship between transport-related CO_2 emissions and efficiency-oriented indicators directly confirms H4, indicating that cleaner mobility systems are embedded within broader systemic improvements in sustainability performance.

5. Conclusions

This study assessed EU-27 progress toward SDG 12 using a harmonized indicator framework combined with trend analysis, correlation analysis, and exploratory factor analysis. The results highlight a clear gap between improvements in eco-efficiency and circularity and the persistence of material and waste pressures.

Key policy implications include the following:

- Complementing efficiency-oriented policies with sufficiency and demand-side measures;
- Strengthening high-value circular economy strategies beyond recycling;
- Integrating resource, energy, and transport policies under SDG 12;
- Enhancing monitoring frameworks to capture systemic interdependencies rather than isolated indicators.

The present work assessed a comprehensive set of EU-27 indicators associated with Sustainable Development Goal 12, focusing on responsible consumption and production. By integrating descriptive statistics, z-score normalization, correlation analysis, and exploratory factor analysis, the research identified structural patterns and systemic interdependencies that shape environmental performance within the EU.

Policy implications include the need to complement efficiency policies with sufficiency-oriented demand-side measures, strengthen high-value circular business models, and improve integration between energy, transport, and resource policies. The key findings resulted from the present study can be summarized as follows:

1. The EU demonstrates consistent progress in eco-efficiency, reflected in rising energy productivity, expanding environmental goods and services, increasing circular material use, and decreasing CO_2 intensity in new passenger cars.
2. Material consumption pressures remain largely unchanged. Raw Material Consumption shows cyclical behavior without sustained decline, indicating that economic activity continues to rely heavily on primary materials.
3. Waste generation trends show mild improvement, but they remain closely tied to material throughput, reflecting slow progress in waste prevention and upstream interventions.
4. Correlation and factor analysis reveal two distinct systemic dimensions: eco-efficiency and circularity gains, and material dependency and waste pressure.
   These dimensions operate in parallel rather than as an integrated system.
5. Policy implications call for stronger integration of efficiency-oriented measures with demand-side reduction strategies, high-value circular business models, and resource sufficiency frameworks.

Overall, the study demonstrates that integrated indicator-based frameworks can provide valuable system-level insights to support the design and evaluation of policies aimed at achieving responsible consumption and production.

Overall, the results highlight that while the EU is advancing in technological efficiency and circularity, it has not yet achieved a structural transition toward absolute reductions in material use. Future progress requires coupling eco-efficiency improvements with transformative changes in consumption systems, product design, and material-intensive industries.

Author Contributions: Conceptualization: I.G.-P.; methodology: I.G.-P. and R.G.; validation: I.G.-P., R.G. and E.C.R.; formal analysis and investigation: I.G.-P. and R.G.; writing—original draft preparation, I.G.-P. and R.G.; writing—review and editing: I.G.-P., R.G. and E.C.R.; visualization, I.G.-P., R.G. and E.C.R.; supervision: I.G.-P. and E.C.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study come from elaboration of aggregated data publicly available from EU. Disaggregated data can be retrieved on request through the corresponding author of directly from EU.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Saqib, N.; Usman, M.; Radulescu, M.; Serbu, R.; Kamal, M.; Belascu, L.A. Synergizing green energy, natural resources, global integration, and environmental taxation: Pioneering a sustainable development goal framework for carbon neutrality targets. *Energy Environ.* **2025**, *36*, 2966–2990. [CrossRef]
2. Wang, C.; Mahmood, H.; Khalid, S. Examining the impact of globalization and natural resources on environmental sustainability in G20 countries. *Sci. Rep.* **2024**, *14*, 30921. [CrossRef] [PubMed]
3. Rada, E.C. Circular economy: Origins, evolution and role of MSW. *Environ. Clim. Technol.* **2023**, *27*, 989–998. [CrossRef]
4. Kirchherr, J.; Yang, N.H.N.; Schulze-Spüntrup, F.; Heerink, M.J.; Hartley, K. Conceptualizing the circular economy (revisited): An analysis of 221 definitions. *Resour. Conserv. Recycl.* **2023**, *194*, 107001. [CrossRef]
5. Shabalala, N.P.; Photo, P. Global Citizenship Education: A strategic framework for G20 solutions to economic challenges and the 2030 Sustainable Development Goals. *J. Glob. Responsib.* **2025**. [CrossRef]
6. Kobilov, E.E.; Batirov, K.F.; Mardonava, F.S.; Karaeva, A.; Baltrocchi, A.P.D.; Miino, M.C.; Giurea, R.; Ragazzi, M.; Torretta, V.; Rada, E.C. Circular economy and sustainable development goals approaches for environment improvement in Uzbekistan. *AIP Conf. Proc.* **2025**, *3321*, 060004. [CrossRef]
7. Sanchez-Garcia, E.; Martinez-Falco, J.; Marco-Lajara, B.; Manresa-Marhuenda, E. Revolutionizing the circular economy through new technologies: A new era of sustainable progress. *Environ. Technol. Innov.* **2024**, *33*, 103509. [CrossRef]
8. Yadav, S. Promoting environmental sustainability among students and citizens for a sustainable future. In *Climate Change Education for Sustainable Development*; IGI Global: New York, NY, USA, 2023; pp. 187–211. [CrossRef]
9. Rodrigues, M.; Garcez, A.; Franco, M. Building bridges between circularity indicators and sustainability. *Discov. Sustain.* **2025**, *6*, 1242. [CrossRef]
10. Bahramimianrood, B.; Xie, S.; Malaibari, M.; Abdoli, S. Reviewing Circularity Indicators for a Sustainable Transition to a Circular Economy. *Procedia CIRP* **2024**, *122*, 1065–1070. [CrossRef]
11. De Oliveira, C.T.; Oliveira, G.G.A. What Circular economy indicators really measure? An overview of circular economy principles and sustainable development goals. *Resour. Conserv. Recycl.* **2023**, *190*, 106850. [CrossRef]
12. Murillo-Jiménez, H.; Centeno-Alarcón, M.; Buele, J. Energy Transition in Industry as a Viable Path to Sustainable Decarbonization. *IOP Conf. Ser. Earth Environ. Sci.* **2025**, *1544*, 012003. [CrossRef]
13. Sang, Y.; Zhang, Z.; Liu, S.; Song, C. Decarbonization pathways in the transport sector: A review of integrated assessment models and future directions for model improvement. *Renew. Sustain. Energy Rev.* **2025**, *225*, 116204. [CrossRef]
14. United Nations Statistics Division (UNSD). SDG Report—Goal 12 Responsible Consumption and Production. 2025. Available online: https://unstats.un.org/sdgs/report/2025/goal-12/ (accessed on 15 September 2025).
15. Eurostat. sdg_12_31—Consumption Footprint—Single Weighted Score. 2025. Available online: https://ec.europa.eu/eurostat/databrowser/product/page/SDG_12_31 (accessed on 15 September 2025).
16. Schiavon, M.; Ragazzi, M.; Rada, E.C.; Merler, G. Proposal for the correct management of the life cycle assessment results from integrated municipal solid waste treatment. *Wit Trans. Ecol. Environ.* **2014**, *180*, 163–173. [CrossRef]
17. Huang, X.; Chen, R.; Zhuang, E.H.H.; Kong, S.; Zhiquan, Y.; Kong, Y. Environmental footprint in specific industries: Intellectual base and research status. *Carbon Footpr.* **2025**, *4*, 18. [CrossRef]
18. Wiedmann, T.O.; Schandl, H.; Lenzen, M.; Moran, D.; Suh, S.; West, J.; Kanemoto, K. The material footprint of nations. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 6271–6276. [CrossRef]
19. European Environment Agency (EEA). Circular Material Use Rate in Europe. 2025. Available online: https://www.eea.europa.eu/en/europe-environment-2025/thematic-briefings/circular-economy-and-other-enablers-of-transformative-change/circular-use-of-materials (accessed on 15 September 2025).

20. European Environment Agency (EEA). Raw Material Consumption Circularity Metrics Lab. 2025. Available online: https://www.eea.europa.eu/en/circularity/sectoral-modules/waste_prevention/raw-material-consumption (accessed on 15 September 2025).
21. Miao, L. Estimating the Material Footprint at the National Level: Time-series prediction using CNN-BiLSTM. *ISPRS Int. J. Geo-Inf.* **2025**, *14*, 86. [CrossRef]
22. Cialani, C.; Mortazavi, R.; Sarcinella, F. Material Footprint and Circular Economy: Drivers and policy implications. *Circ. Econ. Sustain.* **2025**, *5*, 2901–2920. [CrossRef]
23. Hatzfeld, T.; Backes, J.G.; Guenther, E.; Traverso, M. Modeling circularity as functionality over use-time to reflect on circularity indicator challenges and identify new indicators for the circular economy. *J. Clean. Prod.* **2022**, *379*, 134797. [CrossRef]
24. Eurostat/EEA. Production and Consumption of Chemicals by Hazard Class. 2024. Available online: https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20241218-2 (accessed on 15 September 2025).
25. Pasqualino, R.; Valenzano, A.; Chiorrini, A.; Wierzgala, P.; Frankowska, A.; Sanye Mengual, E.; Bennett, M.J.; Listorti, G.; Sala, S. *Consumption Footprint and Domestic Footprint Outlook Report 2025*; Publications Office of the European Union: Luxembourg, 2025. [CrossRef]
26. Bjørn, A.; Paulillo, A.; Sanye Mengual, E.; De Laurentiis, V.; Vea, E.; Hauschild, M.Z.; Sala, S. *Guidance for Applying Absolute Environmental Sustainability Assessment on Activities at Different Scales (BETA Version)*; Publications Office of the European Union: Luxembourg, 2025. [CrossRef]
27. Boman, A. The effect of information about hazardous chemicals in products on consumer behaviour: A systematic review. *Sci. Total Environ.* **2024**, *947*, 174774. [CrossRef]
28. Dobrzyńska, E.; Wasilewski, P.; Pośniak, M. Per- and Polyfluoroalkyl Substances (PFASs): A Comprehensive Review of Environmental Distribution, Health Impacts, and Regulatory Landscape. *Appl. Sci.* **2025**, *15*, 11884. [CrossRef]
29. Rada, E.C.; Schiavon, M.; Torretta, V. A regulatory strategy for the emission control of hexavalent chromium from waste-to-energy plants. *J. Clean. Prod.* **2021**, *278*, 123415. [CrossRef]
30. Rada, E.C.; Zatelli, C.; Mattolin, P. Municipal solid waste selective collection and tourism. *Wit Trans. Ecol. Environ.* **2014**, *180*, 187–197. [CrossRef]
31. Sund, J.H. Comprehensive assessment of environmental and economic impacts across the EU27 waste management system. *Waste Manag.* **2025**, *204*, 114910. [CrossRef] [PubMed]
32. Viana, A.J.; Mannarino, C.; Ritter, E. Evaluation of indicators for the management of urban solid waste generated by national databases. *Eng. Sanit. Ambient.* **2024**, *29*, e20230084. [CrossRef]
33. Costa, G.; Lieto, A.; Lombardi, F. LCA of a consortium-based MSW management system to quantify the decrease in environmental impacts achieved for increasing separate collection rates and other modifications. *Sustainability* **2019**, *11*, 2810. [CrossRef]
34. Instituto Nacional de Estadística (INE). Environmental Goods and Services—Advance Data 2022. 2023. Available online: https://www.ine.es/dyngs/Prensa/en/CBYSA2023.htm (accessed on 15 September 2025).
35. Khan, A.H.; Sharholy, M.; Alam, P.; Al-Mansour, A.; Ahmad, K.; Kaml, M.A.; Alam, S.; Pervez, M.N.; Naddeo, V. Evaluation of cost benefit analysis of municipal solid waste management systems. *J. King Saud Univ. Sci.* **2022**, *34*, 101997. [CrossRef]
36. European Environment Agency (EEA). Gross Value Added of the Environmental Goods and Services Sector in Europe. 2024. Available online: https://www.eea.europa.eu/en/analysis/indicators/gross-value-added-of-the (accessed on 15 September 2025).
37. European Environment Agency (EEA). Waste Generation in Europe—Indicator Analysis. 2024. Available online: https://www.eea.europa.eu/en/european-zero-pollution-dashboards/indicators/waste-generation-in-europe-indicator (accessed on 15 September 2025).
38. Organisation for Economic Co-Operation and Development (OECD). Monitoring Progress Towards a Resource-Efficient and Circular Economy. 2024. Available online: https://www.oecd.org/en/publications/monitoring-progress-towards-a-resource-efficient-and-circular-economy_3b644b83-en.html (accessed on 15 September 2025).
39. International Energy Agency (IEA). Energy Efficiency 2022—Analysis. 2022. Available online: https://www.iea.org/reports/energy-efficiency-2022 (accessed on 15 September 2025).
40. Nekahi, A.; Anil Kumar, M.R.; Deng, S.; Li, X.; Petropoulos, A.; Nanda, J.; Zaghib, K. Toward Green Renewable Energies and Energy Storage for the Sustainable Decarbonization and Electrification of Society. *Electrochem. Energy Rev.* **2025**, *8*, 12. [CrossRef]
41. International Council on Clean Transportation (ICCT). CO_2 Emissions of New Passenger Vehicles in Europe—2023 Analysis. 2024. Available online: https://theicct.org/publication/co2-emissions-new-pv-europe-car-manufacturers-performance-2023-sept24/ (accessed on 15 September 2025).
42. ACEA. Interactive Map—CO_2 Emissions from New Passenger Cars in the EU by Country. 2022. Available online: https://www.acea.auto/figure/interactive-map-co2-emissions-from-new-passenger-cars-in-the-eu-by-country/ (accessed on 15 September 2025).

43. Magaril, E.; Magaril, R.; Al-Kayiem, H.H.; Skvortsova, E.; Anisimov, I.; Rada, E.C. Investigation on the possibility of increasing the environmental safety and fuel efficiency of vehicles by means of gasoline nano-additive. *Sustainability* **2019**, *11*, 2165. [CrossRef]
44. Reuters. Germany Rejects Italy's Proposal for Early Review for EU Combustion Engine Ban. 2024. Available online: https://www.reuters.com/business/autos-transportation/germany-rejects-italys-proposal-early-review-eu-combustion-engine-ban-2024-10-02/ (accessed on 15 September 2025).
45. Financial Times. Carbon Fines and Europe's Automotive Challenges. 2024. Available online: https://www.ft.com/content/51196335-65c4-48f7-bd02-ec3e670ee429 (accessed on 15 September 2025).
46. Slimi, K.; Chrouda, A.; F.-Öztop, H. Traffic effects on global warming: A review. *Renew. Sustain. Energy Rev.* **2026**, *226*, 116248. [CrossRef]
47. Spina, D.; Carbone, R.; Pilvirenti, A.; Rizzo, M.; D'Amico, M.; di Vita, G. What Gets Measured Gets Managed-Circular Economy Indicators for the Olive Oil Supply Chain: A Systematic Review. *Agronomy* **2024**, *14*, 2879. [CrossRef]
48. D'Adamo, I.; Favari, D.; Gastaldi, M.; Kirchherr, J. Towards circular economy indicators: Evidence from the European Union. *Waste Manag. Res.* **2024**, *42*, 670–680. [CrossRef]
49. Sala, S.; Sanye Mengual, E. Consumption Footprint: Assessing the Environmental Impacts of EU Consumption, European Commission, 2022, JRC126257. Available online: https://publications.jrc.ec.europa.eu/repository/handle/JRC126257 (accessed on 15 September 2025).

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