



Original Research Articles

Drivers of circular economy transition towards sustainability: A panel data analysis across 18 EU countries

Judit Oláh^{a,b,c}, Mohammad Bin Amin^{d,e,i,*} , Mehedi Hasan^{f,*} , Md. Saddam Hossain^g,
Md. Atikur Rahaman^{h,j}

^a Doctoral School of Management and Business Administration, John von Neumann University, 6000 Kecskemét, Hungary

^b Faculty of Economics and Business, University of Debrecen, Böszörményi street 138, Debrecen 4032, Hungary

^c Department of Trade and Finance, Faculty of Economics and Management, Czech University of Life Sciences Prague, Czech Republic

^d Doctoral School of Management and Business, Faculty of Economics and Business, University of Debrecen, Debrecen 4032, Hungary

^e Department of Business Administration, Faculty of Business Studies, Bangladesh Army University of Science and Technology, Saidpur 5310, Nilphamari, Bangladesh

^f Department of Economics, Faculty of Social Science, Mawlana Bhashani Science and Technology University, Santosh, Tangail, 1902, Bangladesh

^g Department of Economics, Faculty of Social Science, Gopalganj Science and Technology University, Gopalganj 8100, Bangladesh

^h School of Economics and Management, Jiujiang University, 551 Qianjin Donglu, Jiujiang, Jiangxi 332005, China

ⁱ Department of Business Studies, State University of Bangladesh, 696 Kendua, Kanchan, Rupganj, Narayanganj, Dhaka, 1461, Bangladesh

^j Department of Innovation and Entrepreneurship, Daffodil International University, Daffodil Smart City, Birulia, Savar, Dhaka, 1216, Bangladesh

ARTICLE INFO

Keywords:

Circular economy
Sustainable development
Ecological modernization
CO₂ emissions
Unemployment
Panel data
European union
SDGs

ABSTRACT

The transition to a circular economy (CE) is increasingly promoted as a strategy for achieving sustainable development, yet empirical evidence on its simultaneous impacts across environmental, economic, and social dimensions remains limited. Anchored in Ecological Modernization Theory, this study examines how CE adoption influences sustainability outcomes in 18 European Union countries over 2010–2019 using two-way fixed-effects panel regressions on data from Eurostat, World Bank, and OECD sources. Circular material uses rate serves as the core CE indicator, with key drivers including renewable energy shares, renewable energy in transport, municipal waste, and socio-economic controls. Results show that a 1% increase in circular material use is associated with a 0.048% reduction in CO₂ emissions ($p = 0.002$), confirming significant environmental benefits (SDG 13, SDG 12). Renewable energy in transport exerts a stronger mitigating effect (-0.104% , $p < 0.001$), supporting sectoral decarbonization (SDG 7). Economic growth strongly drives CE adoption (0.806% , $p = 0.001$), but CE shows no significant direct effect on GDP per capita, indicating relative rather than absolute decoupling. Socially, CE modestly reduces unemployment (-0.097% , $p = 0.022$), while efficient waste management generates substantial labor-market benefits (-0.728% , $p < 0.001$), aligning with SDG 8 and SDG 10. However, renewables in transport associate with higher unemployment (0.217% , $p = 0.001$), highlighting transitional displacement risks. The findings affirm CE's potential to deliver environmental and social co-benefits under deliberate policy steering, while underscoring persistent growth-emissions coupling and spatial constraints (negative density effect: -2.580% , $p = 0.011$). These results extend Ecological Modernization Theory by revealing both synergies and trade-offs in European CE transitions and provide evidence-based guidance for integrated policies that maximize multi-dimensional sustainability outcomes.

1. Introduction

The pursuit of sustainable development has become a central concern in global economic and environmental policy debates as accelerating resource consumption, environmental degradation, and

ecological pressures increasingly challenge long-term development pathways (WCED, 1987). Sustainability challenges have evolved over several decades alongside industrial expansion and growing energy demand, intensifying pressures on natural systems and socio-economic stability (Sun et al., 2024; Shi et al., 2024; Byaro et al., 2023). In

* Corresponding authors.

E-mail addresses: olah.judit@econ.unideb.hu (J. Oláh), binamindu@gmail.com, binaminbd@mailbox.unideb.hu (M.B. Amin), mehedihasan.econ43@mbstu.ac.bd (M. Hasan), atik@jju.edu.cn (Md.A. Rahaman).

<https://doi.org/10.1016/j.horiz.2026.100192>

Received 21 November 2025; Received in revised form 1 April 2026; Accepted 6 April 2026

2772-7378/© 2026 The Author(s). Published by Elsevier B.V. on behalf of Eastern Institute of Technology, Ningbo. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

response to these global concerns, the United Nations introduced the 17 Sustainable Development Goals (SDGs) in 2015 to promote balanced progress across environmental protection, economic prosperity, and social well-being (Sodhi and Tang, 2024; Preston, 2024). Achieving these goals remains difficult due to structural constraints such as resource scarcity, inefficient production systems, infrastructure limitations, and institutional challenges faced by many economies (Masood et al., 2023; Mpofu, 2022).

A major contributor to these sustainability challenges is the pre-dominance of the linear economic model, characterized by a “take–make–dispose” production system that assumes unlimited resource availability and generates significant environmental externalities. This model has led to increased pollution, material depletion, and carbon emissions, thereby undermining sustainable growth prospects (Geissdoerfer et al., 2017). As an alternative, the Circular Economy (CE) has emerged as a promising framework for decoupling economic growth from resource consumption through strategies that emphasize reuse, recycling, resource efficiency, and waste minimization (Pearce and Turner, 1989; Ellen MacArthur Foundation, 2015). Policymakers and institutions increasingly recognize CE as a practical pathway toward achieving sustainability objectives and advancing SDG implementation (Rodríguez-Antón et al., 2022; Dantas et al., 2021).

The European Union (EU) has assumed a leading role in promoting circular economy transitions through coordinated regulatory and policy initiatives, particularly following the adoption of the EU Circular Economy Action Plan in 2015 (Bianchi and Cordella, 2023; Rodríguez-Antón et al., 2022). These initiatives aim to simultaneously address environmental degradation, economic competitiveness, and employment generation. Prior studies highlight that CE practices contribute to several SDGs, including good health and well-being (SDG 3), affordable and clean energy (SDG 7), decent work and economic growth (SDG 8), sustainable cities and communities (SDG 11), responsible consumption and production (SDG 12), and life on land (SDG 15) (Knäble et al., 2022; Rodríguez-Antón et al., 2022; Dantas et al., 2021). Consequently, circular economy transition is increasingly viewed as an integrative mechanism linking environmental performance with socio-economic development outcomes.

Despite growing scholarly attention, empirical evidence examining how circular economy transitions jointly influence environmental, economic, and social sustainability dimensions remains limited. Existing research often focuses on partial relationships, such as economic–environmental or environmental–social interactions, rather than providing a comprehensive assessment across all sustainability pillars (Gandolfo and Lupi, 2021; Kuo and Chang, 2021; Bai et al., 2022; Walker et al., 2021). Moreover, the role of specific CE drivers, including renewable energy adoption, waste management efficiency, economic development, and labor market dynamics in shaping multidimensional sustainability outcomes has not been sufficiently examined within a unified empirical framework (Chary et al., 2023). This fragmentation creates a gap between theoretical discussions of circular economy transition and quantitative evaluations aligned with SDG performance.

Consequently, this study seeks to answer: To what extent does the transition toward a circular economy simultaneously drive environmental, economic, and social sustainability in the European context? To address this gap, the present study investigates the extent to which circular economy transition contributes to sustainable development across environmental, economic, and social dimensions using panel data from 18 European Union countries over the period 2010–2019. Anchored in Ecological Modernization Theory (EMT), the study conceptualizes circular economy adoption as a modernization process through which technological innovation, institutional transformation, and energy transition enable compatibility between economic growth and environmental protection (Buttel, 2000; Spaargaren and Mol, 2020). The empirical analysis evaluates how key CE drivers, including circular material use, renewable energy, renewable energy in transport, municipal waste dynamics, life expectancy, education, and population

density, affect carbon emissions, GDP performance, and unemployment outcomes.

This study contributes to the sustainability and circular economy literature in three main ways. First, it provides an integrated empirical assessment of circular economy impacts across the environmental, economic, and social dimensions of sustainability within a cross-country EU framework. Second, it operationalizes the linkage between CE drivers and SDG-related outcomes using harmonized macroeconomic and environmental indicators. Third, by employing fixed-effects panel estimation techniques, the study generates robust within-country evidence on how circular transitions interact with energy structures and socio-economic conditions to influence sustainability performance. These contributions advance ongoing debates regarding whether circular economy strategies can deliver simultaneous environmental improvement, economic resilience, and social inclusion.

The remainder of this paper is structured as follows. Section 2 presents the theoretical framework underpinning the analysis and develops the conceptual foundations linking circular economy drivers to sustainability outcomes. Section 3 reviews relevant literature and develops research hypotheses. Section 4 describes the data and methodological approach. Section 5 presents descriptive statistics and correlation analysis, while Section 6 reports regression results and discussion. Section 7 discusses the implications of the findings. Section 8 concludes the study with a summary of key findings and policy recommendations. Section 9 outlines study limitations and directions for future research.

2. Theoretical framework

2.1. Ecological modernization theory and sustainable development

This study adopts Ecological Modernization Theory (EMT) as the primary theoretical lens for examining the relationship between circular economy transition and sustainable development outcomes. EMT argues that environmental protection and economic development are not inherently contradictory but can evolve jointly through technological innovation, institutional reform, and structural economic transformation (Buttel, 2000; Murphy and Gouldson, 2000). Rather than emphasizing limits to growth, ecological modernization perspectives suggest that modern economies can reduce environmental pressures through efficiency improvements, cleaner production systems, and environmentally oriented policy frameworks (Spaargaren and Mol, 2020; Jänicke, 2008).

A central premise of EMT is that governments, industries, and international institutions increasingly internalize environmental concerns within economic decision-making processes. Regulatory mechanisms, technological advancement, and societal awareness collectively encourage firms and economies to adopt environmentally efficient production practices (Fisher and Freudenburg, 2001; Berger et al., 2001). Consequently, modernization processes, when supported by innovation and governance structures, can simultaneously enhance competitiveness, environmental performance, and social welfare.

Within this framework, sustainability transitions emerge through systemic transformations rather than economic contraction. EMT therefore provides a suitable theoretical foundation for analyzing circular economy adoption as a mechanism through which environmental objectives can be integrated into economic and social development pathways.

2.2. Circular economy as a mechanism of ecological modernization

The Circular Economy (CE) operationalizes many of the core principles proposed by ecological modernization theory by promoting closed material loops, resource efficiency, renewable energy adoption, and waste reduction. CE replaces linear production systems with regenerative models designed to maintain materials and energy within economic cycles for as long as possible (Geissdoerfer et al., 2017; Kirchherr et al.,

2017).

From an EMT perspective, circular economy practices represent technological and institutional innovations capable of reducing ecological pressures without compromising economic productivity. Strategies such as recycling, remanufacturing, eco-design, renewable energy integration, and waste valorization enable economies to decouple growth from environmental degradation (Huber, 2008). These transformations are increasingly supported by environmental governance institutions, international organizations, and market incentives that encourage sustainable production and consumption patterns.

The European Union provides an illustrative example of ecological modernization in practice, where circular economy policies aim to simultaneously promote industrial competitiveness, emissions reduction, and employment generation through coordinated regulatory frameworks (Bianchi and Cordella, 2023; Sanz-Toró et al., 2025). Accordingly, CE transition can be interpreted as an institutional pathway through which modernization processes contribute to sustainable development objectives.

2.3. Contemporary debates and critiques of the circular economy

Although circular economy strategies are frequently associated with sustainability improvements, recent academic debates highlight that circularity does not automatically guarantee sustainable outcomes. Scholars emphasize potential rebound effects, trade-offs, and biophysical limitations that may constrain the environmental benefits of circular systems (Korhonen et al., 2018; Giampietro, 2019). For example, increased recycling or material recovery may still generate energy demand or externalize environmental costs across regions. Critics further argue that circular economy policies, if narrowly focused on material efficiency without addressing consumption levels, risk perpetuating growth-dependent economic structures rather than enabling the deeper systemic transformation required for genuine sustainability (Bauwens, 2021; D'Alisa and Kallis, 2020).

Recent contributions further stress the importance of innovation capability, entrepreneurial orientation, and institutional support in determining successful circular transitions (Castro-Lopez et al., 2025; Mazzoni and Sedita, 2025). Firm-level capabilities also matter: Liao et al. (2025) demonstrate how dynamic capabilities enable organizations to identify and exploit circular economy opportunities in technology-intensive sectors, while Sanz-Toró et al. (2025) show that resource efficiency in SMEs depends on integrated support measures combining green markets, technical assistance, and policy incentives. Similarly, policy coordination and national governance frameworks play a critical role in shaping circular economy performance across countries (Sanz-Toró et al., 2025). Emerging research also links circular economy adoption with corporate sustainability strategies, intangible organizational benefits, and evolving sustainability reporting practices aligned with SDG implementation (García-Sánchez et al., 2024; Gallego-Nicholls et al., 2025). These debates suggest that the sustainability outcomes of circular economy transition depend not only on technological adoption but also on broader socio-economic conditions, energy structures, and labor market dynamics. Consequently, empirical investigation is required to assess whether circular economy drivers generate simultaneous environmental, economic, and social benefits.

2.4. Circular economy and the three dimensions of sustainability

Sustainable development is commonly conceptualized through three interdependent dimensions: environmental sustainability, economic resilience, and social inclusion. Ecological modernization theory implies that circular economy transition may influence each of these dimensions through distinct mechanisms.

First, environmentally, circular practices reduce reliance on virgin resource extraction and fossil-fuel consumption, thereby lowering greenhouse gas emissions and environmental degradation. Renewable

energy deployment and circular material use contribute directly to climate mitigation objectives. From an SDG perspective, these environmental gains support SDG 12 (responsible consumption and production) through waste reduction and resource efficiency, SDG 13 (climate action) through emissions reductions, and SDG 7 (affordable and clean energy) through renewable energy integration.

Second, economically, circular economy adoption can enhance productivity and competitiveness by improving resource efficiency and stimulating innovation-driven growth. Investments in renewable energy systems, recycling infrastructure, and sustainable production technologies may strengthen long-term economic resilience. These economic mechanisms align with SDG 8 (decent work and economic growth) by fostering sustainable economic expansion and SDG 9 (industry, innovation, and infrastructure) through investments in sustainable industrial capacity.

Third, socially, circular economy activities generate employment opportunities in repair, reuse, recycling, and green technology sectors, supporting inclusive labor market outcomes and regional development. However, structural transitions may also create short-term labor displacement, highlighting the importance of examining social outcomes empirically. The employment and inclusion dimensions of circular transitions advance SDG 1 (no poverty) through income generation, SDG 5 (gender equality) by creating accessible employment across sectors, and SDG 10 (reduced inequalities) through regional development and inclusive labor market participation.

Recognizing these multidimensional interactions, the present study evaluates sustainability outcomes using three measurable indicators: carbon emissions (environmental dimension), GDP per capita (economic dimension), and unemployment rate (social dimension). By embedding circular economy analysis within Ecological Modernization Theory and explicitly linking each sustainability dimension to corresponding SDG targets, this study provides a theoretically grounded framework for assessing how circular transitions contribute to the multidimensional sustainability agenda embodied in the SDGs.

2.5. Conceptual framework

Building on the theoretical foundations established in the preceding sections, Fig. 1 presents the conceptual framework guiding this study.

This framework illustrates the theoretical relationships tested in the study, grounded in Ecological Modernization Theory. The analysis is organized around three sustainability dimensions, environmental, economic, and social each operationalized through specific econometric models.

It guides the econometric specification in Section 4, where fixed-effects panel regression estimates the magnitude and significance of these relationships across 18 EU countries (2010–2019). By explicitly linking each sustainability dimension to corresponding SDG targets, the visual representation provides a theoretically grounded basis for assessing how circular transitions contribute to the multidimensional sustainability agenda. This visual representation provides a theoretically grounded basis for assessing how circular transitions contribute to the multidimensional sustainability agenda embodied in the SDGs

3. Literature review and hypotheses development

3.1. Circular economy and environmental sustainability

A central objective of the circular economy is reducing environmental pressures from resource extraction and waste generation. Circular production systems close material loops through recycling and reuse, limiting dependence on virgin resources and reducing greenhouse gas emissions (Geissdoerfer et al., 2017; Kirchherr et al., 2017). Within Ecological Modernization Theory, technological innovation and resource efficiency enable decoupling of economic activity from environmental degradation (Jänicke, 2008; Spaargaren and Mol, 2020).

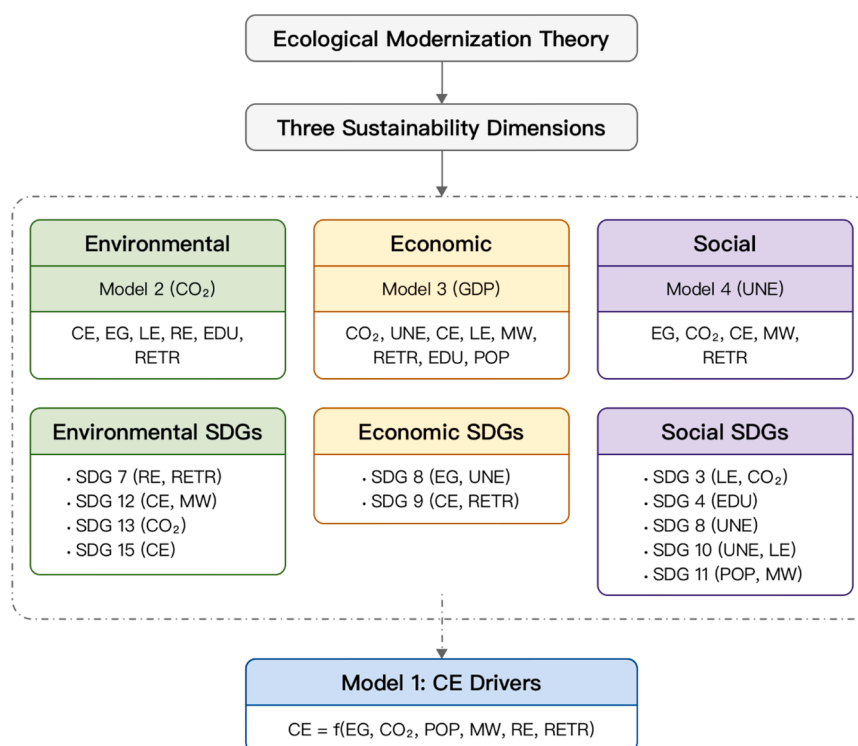


Fig. 1. Conceptual framework linking circular economy to sustainability dimensions and SDG outcomes.
Source: Authors' own elaboration.

Circular material use operationalizes this process, reflecting substitution of secondary for primary materials.

Empirical evidence supports these environmental benefits. [Knäble et al. \(2022\)](#) demonstrate that circular economy practices significantly reduce carbon intensity across 28 EU countries. [Hailemariam and Erdiaw-Kwasie \(2023\)](#) find that packaging waste circularity generates long-run emission reductions of 0.48–0.71%. [Liu and Zhang \(2026\)](#) confirm recycling-oriented circularity delivers significant emission reductions in G-20 economies, though short-run adoption may temporarily increase emissions due to infrastructure adjustment costs.

Mechanistically, circularity reduces emissions from raw material processing, landfill use, and energy-intensive production ([Cudjoe et al., 2021](#)). Material recovery avoids emissions from virgin extraction, which typically exceeds recycling energy requirements ([Chen et al., 2020](#)). Circular practices also generate systemic efficiency gains extending beyond direct material substitution ([Bouattour et al. 2025](#)).

However, environmental benefits depend critically on energy systems and may be attenuated by rebound effects. [Korhonen et al. \(2018\)](#) emphasize that recycling requires energy; if fossil-fuel derived, emission reductions diminish. [Giampietro \(2019\)](#) argues that "decoupling" claims often ignore thermodynamic realities. These contingencies suggest circular economy and energy transition should be pursued jointly, a proposition this study tests through renewable energy variables.

H1. Higher circular material use rates are associated with lower CO₂ emissions.

3.2. Renewable energy transition and environmental outcomes

Energy transition complements circular economy performance. Renewable energy adoption reduces fossil fuel reliance and emissions intensity ([Ali et al., 2023](#)). EMT posits that cleaner energy technologies enhance modernization processes by enabling sustainable industrial restructuring ([Huber, 2008](#); [Jänicke, 2008](#)).

Cross-country evidence confirms emissions reduction potential.

[Alola et al. \(2019\)](#) find renewable energy significantly reduces ecological footprint in Europe. [Ahmad et al. \(2021\)](#) demonstrate synergistic emission reductions from combining renewable energy and eco-innovation.

Renewable energy in transport plays a critical role due to mobility systems' high carbon intensity. The share of renewables in transport captures structural transformation toward sustainable mobility ([European Environment Agency, 2022](#)). Transport accounts for one-quarter of EU emissions, making sectoral decarbonization essential. Transport electrification and renewable fuel substitution contribute to emissions reduction aligned with SDG 7 and SDG 13.

[Bouattour et al. \(2025\)](#) demonstrate that green innovation, renewable energy, and circular economy jointly reduce emissions, with significant interaction effects suggesting complementarity. The emissions elasticity of renewable energy increases when circular indicators are included, indicating material and energy transitions reinforce one another. However, relationships are context-dependent. [Chen and Pao \(2022\)](#) find emissions-reducing effects strengthen over time as infrastructure matures.

H2. Higher renewable energy shares are associated with lower CO₂ emissions.

H3. A higher share of renewable energy in transport is associated with lower CO₂ emissions.

3.3. Circular economy and economic sustainability

Beyond environmental benefits, circular economy is viewed as a driver of economic resilience and productivity. Resource efficiency reduces costs, stimulates innovation, and creates new markets ([Gandolfo and Lupi, 2021](#); [Kuo and Chang, 2021](#)). EMT posits that environmental innovation enhances competitiveness while supporting long-term economic expansion ([Murphy and Gouldson, 2000](#); [Porter and van der Linde, 1995](#)).

Empirical evidence on the circular economy-growth nexus is more complex. Radivojević et al. (2024) find strong positive correlations between circular indicators and GDP across 27 EU countries, with resource productivity increases corresponding to 0.15–0.25% GDP growth. Chen and Pao (2022) report bidirectional causality: circular adoption stimulates growth, while wealthier economies invest more in circular infrastructure.

Jakubelskas and Skvarciany (2025) confirm circular material use positively affects GDP, though effect sizes vary, with newer member states showing smaller elasticities, suggesting institutional maturity moderates returns (Mazzoni and Sedita, 2025).

However, several studies report conditional findings. Knäble et al. (2022) find recycling rates show stronger growth associations than circular material uses in some specifications. Bouattour et al. (2025) demonstrate growth effects are mediated by green innovation, suggesting circularity without innovation yields limited benefits.

Theoretical debates on green growth versus post-growth further complicate interpretation. Proponents argue technological innovation progressively decouples emissions from growth (Chen et al., 2018; Dong et al., 2022). Post-growth scholars contend absolute decoupling remains elusive at climate-relevant scales (Bauwens, 2021; D'Alisa and Kallis, 2020).

GDP per capita serves as the economic sustainability indicator. The mixed evidence suggests the relationship may be conditional on technological readiness, institutional quality, and policy support.

H4. Higher circular material use rates are associated with higher GDP per capita.

3.4. Circular economy transition and social sustainability

Social sustainability links closely to labor market outcomes. Circular activities, repair, recycling, renewable energy deployment, waste management, are generally more labor-intensive than linear production (Bai et al., 2022; Walker et al., 2021), creating employment across skill levels.

Empirical research on circular employment effects has expanded rapidly. Multani et al. (2025) document growth in recycling and repair sectors even during downturns, suggesting counter-cyclical patterns contributing to labor market resilience. The ILO (2018) estimates circular transition could generate 6–8 million net new jobs globally by 2030.

Georgescu et al. (2025) find significant positive relationships between circular indicators and employment rates, while documenting that social exclusion negatively affects labor market outcomes. Their integrated approach demonstrates employment benefits are maximized when accompanied by inclusive policies.

However, circular transitions may generate labor displacement. Antikainen et al. (2018) note automation in recycling and renewable sectors could limit employment gains for lower-skilled workers. Walker et al. (2021) identify job displacement concerns in manufacturing and mining as circular economy scales. Nikou et al. (2025) find bidirectional causality between employment reforms and circular adoption, suggesting flexible labor markets facilitate transitions.

From an EMT perspective, green transformation generates new employment structures. However, net effects remain empirical questions requiring careful estimation.

Unemployment rate captures labor market inclusion consistent with SDG 8. The expectation is circular adoption reduces unemployment, though transitional displacement may delay benefits.

H5. Higher circular material use rates are associated with lower unemployment rates.

3.5. Waste intensity, linear structures, and circular performance

Municipal waste generation reflects persistence of linear

consumption patterns. High waste intensity signals inefficient material use and limited circular recovery (Korhonen et al., 2018), indicating incomplete loop closure and continued dependence on disposable systems.

EMT suggests successful sustainability transitions require reducing material inefficiencies. Higher waste volumes should therefore associate with weaker circular performance and poorer environmental outcomes.

Empirical evidence supports this. Liu and Zhang (2026) demonstrate packaging waste reductions and improved recovery significantly lower long-run emissions. Radivojević et al. (2024) find municipal waste per capita positively associates with GDP (reflecting consumption) while negatively associating with circular material use, consistent with waste as linear throughput marker.

Cudjoe et al. (2021) document substantial emission benefits from diverting waste to recycling, suggesting high waste represents foregone environmental and efficiency opportunities.

However, the waste-circularity relationship is not unidirectional. High waste may also provide feedstock for circular processes, potential that low-waste economies lack. This duality may explain positive but insignificant coefficients when both linear signal and circular potential create offsetting effects.

H6. Higher municipal waste generation is negatively associated with circular material use.

3.6. Summary of research hypotheses

Table 1 summarizes research hypotheses and maps each to dependent and independent variables for empirical testing in Section 4, ensuring consistency between theoretical framework, hypotheses, and econometric specifications.

4. Data and methodology

4.1. Research design and analytical approach

This study employs panel data econometrics to examine how circular economy (CE) transitions influence sustainability outcomes across environmental, economic, and social dimensions. Panel data methods are particularly well suited to this research question because they control for unobserved country-specific heterogeneity while isolating within-country variation over time (Arellano, 2005; Wooldridge, 2010; Baltagi, 2008). The analysis covers 18 European Union member states from 2010 to 2019, producing a balanced panel of 180 country-year observations. The selected countries- Austria, Belgium, Czechia, Denmark, Finland, France, Germany, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, the Netherlands, Poland, Slovakia, Slovenia, and Sweden- were chosen because they provide complete data series for all core variables, particularly the Eurostat circular material use rate indicator, which is not uniformly available for all EU members during the period. Exclusion of countries with missing observations ensures a balanced panel, which is essential for reliable fixed-effects estimation and avoids the biases associated with unbalanced designs.

4.2. Sustainability dimensions and variable operationalization

Building on the theoretical framework established in Section 2, the analysis is organized around three sustainability dimensions. Table 2 provides a comprehensive overview of all variables. The data were taken from Eurostat, the World Development Indicators (WDI), and the Organization for Economic Cooperation and Development (OECD).

All continuous variables are log-transformed to enable coefficient interpretation as elasticities. This transformation also helps normalize distributions and reduce heteroskedasticity (Wooldridge, 2010).

Table 1

Hypothesis summary and empirical specification.

Hypothesis	Statement	Dependent Variable	Key Independent Variable	Expected Sign	Model
H1	Higher circular material use → lower CO ₂	CO ₂ emissions	Circular material use (CE)	Negative	Model 2
H2	Higher renewable energy → lower CO ₂	CO ₂ emissions	Renewable energy share (RE)	Negative	Model 2
H3	Higher renewables in transport → lower CO ₂	CO ₂ emissions	Renewables in transport (RETR)	Negative	Model 2
H4	Higher circular material use → higher GDP	GDP per capita	Circular material use (CE)	Positive	Model 3
H5	Higher circular material use → lower unemployment	Unemployment rate	Circular material use (CE)	Negative	Model 4
H6	Higher municipal waste → lower circular use	Circular material use	Municipal waste (MW)	Negative	Model 1

Note: All models include control variables (life expectancy, education, population density) as specified in Section 4.

Table 2

Variable definitions, sources, and dimensional classification.

Variable	Abbreviation	Operational Definition	Unit	Dimension	Source
Circular material use rate	CE	Share of material recovered and fed back into the economy	%	CE driver	Eurostat
CO ₂ emissions	CO ₂	Carbon dioxide emissions from fossil fuel combustion and cement production	kt (log)	Environmental	WDI
Renewable energy	RE	Share of renewable energy in gross final energy consumption	%	Environmental	WDI
Renewable energy in transport	RETR	Share of energy from renewable sources in transport	%	Environmental	Eurostat
Municipal waste	MW	Municipal waste generation per capita	tonnes (log)	Environmental	OECD
Economic growth	EG	Gross domestic product per capita (constant 2015 US\$)	\$ (log)	Economic	WDI
Unemployment rate	UNE	Unemployed persons as % of labor force	% (log)	Social	WDI
Life expectancy	LE	Life expectancy at birth	years (log)	Social	WDI
Education	EDU	Secondary school enrollment rate	% (log)	Social	WDI
Population density	POP	Population per square kilometer	persons/km ² (log)	Control	WDI

4.3. Theoretical justification of variable selection

Variable selection is firmly grounded in Ecological Modernization Theory (EMT) and the SDG linkages articulated in Sections 2 and 3. CO₂ emissions serve as the primary environmental outcome measure (SDG 13), directly reflecting the climate impacts of material throughput and energy systems and providing a sensitive indicator of CE-driven decoupling. The circular material use rate (CE) operationalizes the core EMT principle of closing material loops and functions as both dependent and independent variable across models, consistent with H1, H4, and H5. Renewable energy shares (RE) and the transport-specific renewable share (RETR) capture the energy-transition mechanisms emphasized in H2 and H3, addressing SDG 7 while reducing emissions intensity in high-impact sectors (EEA, 2022). Municipal waste generation per capita (MW) proxies the persistence of linear flows and tests H6 by signaling incomplete circularity (Korhonen et al., 2018).

On the economic side, economic growth (EG) evaluates whether CE adoption supports green growth and decoupling (SDG 8 and SDG 9), as posited in H4. Social outcomes are captured through the unemployment rate (UNE), which reflects labor-market inclusion and the job-creation potential of CE activities in repair, recycling, and green technologies (H5; ILO, 2018; Bai et al., 2022). Life expectancy (LE) and secondary education enrolment (EDU) serve as additional social and human-capital controls, capturing health improvements from reduced pollution (SDG 3) and the role of awareness and innovation capacity in facilitating sustainability transitions (SDG 4; Kostakis and Tsagarakis, 2022).

Population density (POP) is included as a standard control for urbanization effects, accounting for both scale economies in infrastructure and potential concentration of environmental pressures (Liddle, 2014).

Fig. 2 shows the map of the decadal average of log-transformed population density (persons per km²) for the 18 EU countries included in the analysis. Darker shades indicate higher population density. The map reveals substantial spatial heterogeneity: Benelux countries (Netherlands, Belgium, Luxembourg) and Germany exhibit the highest densities, while Nordic countries (Finland, Sweden) and Baltic states (Latvia, Lithuania) show substantially lower densities. This spatial variation justifies the inclusion of population density as a control variable in the econometric specifications, as these structural differences may influence waste management infrastructure, collection logistics,

Average Population Density Across 18 EU Countries

Decadal Average (2010–2019) – Log-Transformed Values



Average Population Density (log-transformed, 2010–2019)

1.6 (Low) 2.0 (Medium) 2.4 (High)

Data: Eurostat / World Development Indicators. Darker colors indicate higher density.

Fig. 2. Average population density across 18 EU countries (2010–2019).

and the feasibility of circular economy initiatives independent of policy choices.

To systematically assess circular economy impacts across sustainability dimensions, four panel data models are specified corresponding

to different analytical objectives. Each model is estimated with country and year fixed effects to control for time-invariant country characteristics and common temporal shocks.

Model 1: Drivers of Circular Economy Adoption

This model examines factors influencing circular economy adoption, treating circular material use as an outcome shaped by economic, environmental, and policy variables. The specification tests H6 regarding the relationship between waste generation and circularity, while controlling for energy transition and economic development:

$$\ln(CE_{it}) = \alpha_i + \beta_1 \ln(EG_{it}) + \beta_2 \ln(CO2_{it}) + \beta_3 \ln(POP_{it}) + \beta_4 \ln(MW_{it}) + \beta_5 \ln(RE_{it}) + \beta_6 \ln(RETR_{it}) + \lambda_t + \mu_i + \varepsilon_{it}$$

Model 2: Environmental Sustainability

This model evaluates how circular economy adoption and related drivers influence environmental outcomes, directly testing H1, H2 and H3:

$$\ln(CO2_{it}) = \alpha_i + \beta_1 \ln(CE_{it}) + \beta_2 \ln(EG_{it}) + \beta_3 \ln(LE_{it}) + \beta_4 \ln(RE_{it}) + \beta_5 \ln(EDU_{it}) + \beta_6 \ln(RETR_{it}) + \lambda_t + \mu_i + \varepsilon_{it}$$

Model 3: Economic Sustainability

This model assesses whether circular economy adoption contributes to economic prosperity, testing H4 while controlling for labor market conditions, health, education, and demographic factors:

$$\ln(EG_{it}) = \alpha_i + \beta_1 \ln(CO2_{it}) + \beta_2 \ln(UNE_{it}) + \beta_3 \ln(CE_{it}) + \beta_4 \ln(LE_{it}) + \beta_5 \ln(MW_{it}) + \beta_6 \ln(RETR_{it}) + \beta_7 \ln(EDU_{it}) + \beta_8 \ln(POP_{it}) + \lambda_t + \mu_i + \varepsilon_{it}$$

Model 4: Social Sustainability

This model examines labor market effects of circular economy transitions, capturing social inclusion outcomes and testing H5:

$$\ln(UNE_{it}) = \alpha_i + \beta_1 \ln(EG_{it}) + \beta_2 \ln(CO2_{it}) + \beta_3 \ln(CE_{it}) + \beta_4 \ln(MW_{it}) + \beta_5 \ln(RETR_{it}) + \lambda_t + \mu_i + \varepsilon_{it}$$

Where:

i denotes country

t denotes year

μ_i represents country-specific fixed effects

λ_t represents year-specific fixed effects

ε_{it} is the idiosyncratic error term

All models include country fixed effects (μ_i) to control for time-invariant unobserved heterogeneity, including geographic, institutional, and cultural factors that may influence both circular economy adoption and sustainability outcomes. Year fixed effects (λ_t) account for common temporal shocks such as EU policy changes, business cycle fluctuations, and technological shifts affecting all countries simultaneously. To confirm the appropriateness of fixed effects relative to random effects, we conducted the Hausman (1978) specification test for each model. The test compares coefficients estimated under both approaches; under the null hypothesis that random effects are consistent and efficient, the difference should be unsystematic. As reported in Table 5, Hausman test statistics reject the null for all models ($p < 0.01$), confirming that fixed effects are the preferred specification.

5. Descriptive statistics and correlation analysis

5.1. Descriptive statistics

Table 3 presents descriptive statistics for all variables after logarithmic transformation, providing an overview of the distributional properties of the 180 country-year observations (18 countries $\times$ 10 years).

The sample reveals substantial heterogeneity in circular economy adoption (CE), with log-values ranging from 0.079 to 1.477 (mean 0.925, SD 0.296). Negative skewness (−0.525) indicates that most observations cluster toward higher circularity, with a tail of laggard countries. CO₂ emissions (mean log 4.781) exhibit moderate dispersion (SD 0.561) and near-symmetry, while GDP per capita (EG) shows lower variation (SD 0.271), reflecting relative economic convergence within the EU. Unemployment (UNE) averages 0.865 (moderate SD 0.173), consistent with post-crisis recovery patterns. Control variables display expected features: life expectancy (LE) and education (EDU) have very low dispersion (SD 0.015 and 0.065), indicating EU-wide convergence in health and human capital; population density (POP) varies markedly (SD 0.376), distinguishing dense Western states from sparse Nordic/Baltic ones; renewable shares (RE, RETR) show wide ranges, capturing differential energy transitions; municipal waste (MW) exhibits high dispersion (SD 0.560), signaling diverse consumption and waste regimes. Jarque-Bera tests confirm non-normality in several series, justifying logarithmic transformation and fixed-effects robustness.

5.2. Correlation analysis

Table 4 presents pairwise correlation coefficients among all variables. Coefficients significant at the 5% level are denoted with an asterisk.

The correlation matrix reveals complex interrelationships that inform hypothesis testing while highlighting the necessity of moving beyond bivariate analysis to fixed-effects estimation. The discussion is organized around the three sustainability dimensions established in the theoretical framework.

In the environmental dimension, the strong positive correlation between CE and CO₂ emissions ($r = 0.538^*$) appears counterintuitive to H1 but is readily explained by cross-sectional confounding: more industrialized, higher-emitting countries tend to have greater institutional capacity and resources for circular material recovery. This pattern highlights why within-country time variation is essential to isolate genuine decoupling effects. Municipal waste (MW) correlates almost perfectly with CO₂ ($r = 0.954^*$), suggesting that linear consumption patterns and fossil-fuel dependence co-vary strongly across countries, raising potential multicollinearity concerns that variance inflation factors will monitor. Renewable energy indicators behave more consistently with expectations: RE shows a modest positive link to CE ($r = 0.074$, ns) but negative to emissions ($r = -0.203^*$), while RETR exhibits a clearer negative association with CO₂ ($r = -0.339^*$), provisionally supporting H2 and H3, yet correlates negatively with CE ($r = -0.319^*$), hinting at policy silos between material circularity and transport decarbonization.

Economically, CE correlates positively with GDP per capita ($r = 0.296^*$), aligning with H4 and EMT's proposition that environmental modernization can coexist with prosperity. The exceptionally strong GDP–LE link ($r = 0.830^*$) reflects the income–health gradient, while EDU associates positively with EG ($r = 0.363^*$) as human-capital theory predicts. Notably, the near-zero GDP–CO₂ correlation ($r = 0.064$, ns) offers tentative cross-sectional support for decoupling, though this must be tested rigorously in multivariate models.

Socially, the negative CE–UNE association ($r = -0.361^*$) provides initial backing for H5, consistent with CE's potential to generate jobs in circular sectors. UNE also correlates negatively with EG ($r = -0.291^*$) and LE ($r = -0.276^*$), illustrating interconnected

Table 3

Descriptive statistics.

Statistic	CE	CO ₂	EG	UNE	RE	MW	POP	RETR	LE	EDU
Mean	0.925	4.781	4.484	0.865	0.786	3.628	2.028	1.227	1.901	2.046
Median	0.937	4.667	4.586	0.871	0.811	3.632	2.065	1.184	1.908	2.025
Maximum	1.477	5.890	5.035	1.289	1.481	4.717	2.712	1.723	1.925	2.215
Minimum	0.079	3.852	4.032	0.303	−0.006	2.525	1.247	0.566	1.865	1.957
Std. Dev.	0.296	0.561	0.271	0.173	0.250	0.560	0.376	0.281	0.015	0.065
Skewness	−0.525	0.204	−0.052	−0.256	−0.252	0.233	−0.394	−0.086	−0.877	1.159
Kurtosis	3.274	2.153	2.037	3.249	4.991	2.535	2.665	2.315	2.442	3.438
Jarque-Bera	8.848*	6.629*	7.030*	2.426	31.646*	3.248	5.508	3.741	25.416*	41.741*
Observations	180	180	180	180	180	180	180	180	180	180

Note: All variables are log-transformed.

* Indicates rejection of normality at $p < 0.05$.**Table 4**

Pairwise correlation matrix.

Variables	(1) CE	(2) CO ₂	(3) EG	(4) UNE	(5) RE	(6) MW	(7) POP	(8) RETR	(9) LE	(10) EDU
(1) CE	1.000									
(2) CO ₂	0.538*	1.000								
(3) EG	0.296*	0.064	1.000							
(4) UNE	−0.361*	−0.202*	−0.291*	1.000						
(5) RE	0.074	0.203*	0.208*	−0.184*	1.000					
(6) MW	0.470*	0.954*	0.067	−0.137	0.268*	1.000				
(7) POP	0.603*	0.470*	0.201*	−0.317*	−0.159*	0.363*	1.000			
(8) RETR	−0.319*	−0.339*	−0.124	0.073	0.312*	−0.167*	−0.748*	1.000		
(9) LE	0.492*	0.388*	0.830*	−0.276*	0.300*	0.383*	0.286*	−0.134	1.000	
(10) EDU	0.026	−0.088	0.363*	−0.028	0.221*	−0.050	−0.103	0.109	0.316*	1.000

* Indicates significance at $p < 0.05$.

prosperity–health–inclusion dynamics. RETR shows no meaningful link to UNE ($r = 0.073$, ns), suggesting transport transitions had limited net labor-market effects during the period.

Cross-cutting patterns reinforce the need for panel estimation: the positive CE–CO₂ link illustrates how cross-country differences can mask within-country dynamics; the MW–CO₂ near-collinearity signals specification risks; and the weak RE–CE and negative RETR–CE associations suggest that energy and material transitions remain insufficiently integrated in practice. These bivariate signals, while informative, are prone to confounding and cannot establish directionality, motivating the fixed-effects regressions that follow to test the hypotheses under more robust identification.

6. Regression results and discussion

This section presents fixed-effects panel regression results for the four empirical models. The discussion integrates theoretical interpretation, hypothesis evaluation, and comparison with prior literature throughout, organized around the three sustainability dimensions established in the theoretical framework.

6.1. Model specification and diagnostic tests

Table 5 presents fixed-effects regression results. The Hausman specification test rejects random effects for all models ($p < 0.01$), confirming fixed effects as the appropriate estimator for isolating within-country relationships. Country fixed effects control for time-invariant unobserved heterogeneity (geography, institutions, culture); year fixed effects account for common temporal shocks (EU policy changes, business cycles).

6.2. Environmental dimension

Model 2 tests H1–H3 with CO₂ emissions as the dependent variable. Circular economy adoption (CE) significantly reduces emissions: a 1% increase in circular material use corresponds to a 0.048% decrease in

Table 5

Fixed-effects regression results.

Variables	Model 1 (CE)	Model 2 (CO ₂)	Model 3 (EG)	Model 4 (UNE)
CE		−0.048*** (0.002)	0.008 (0.472)	−0.097** (0.022)
CO ₂	−0.853*** (0.006)		0.268*** (0.000)	−0.060 (0.713)
EG	0.806*** (0.001)	0.504*** (0.000)		−3.021*** (0.000)
UNE			−0.181*** (0.000)	
RE	−0.157*** (0.001)	−0.017* (0.055)		
MW	0.315 (0.154)		−0.082** (0.017)	−0.728*** (0.000)
POP	−2.580** (0.011)		−0.290* (0.055)	
RETR	−0.138 (0.335)	−0.104*** (0.000)	0.091*** (0.000)	0.217*** (0.001)
LE		−6.425*** (0.000)	3.589*** (0.000)	
EDU		−0.292*** (0.000)	0.158*** (0.000)	
Specification	FE	FE	FE	FE
Hausman (p-value)	27.777 (0.000)	22.881 (0.001)	39.260 (0.000)	376.433 (0.000)
Observations	180	180	180	180
Number of groups	18	18	18	18

Notes: p-values in parentheses.

*** $p < 0.01$,** $p < 0.05$,* $p < 0.1$.

CO₂ ($p = 0.002$), supporting H1. Substituting secondary materials for virgin resources reduces energy-intensive extraction and processing emissions, validating the environmental logic of circular transitions (Kirchherr et al., 2017; Korhonen et al., 2018). This finding aligns with recent panel evidence from G-20 economies where packaging-waste

circularity yields long-run emission reductions [Liu and Zhang \(2026\)](#) and with European evidence demonstrating circular economy practices significantly reduce emissions intensity ([Hailemariam and Erdiaw-Kwasie, 2023](#)).

Renewable energy variables exhibit expected negative relationships. Renewable energy share (RE) reduces emissions ($\beta = -0.017$, $p = 0.055$), marginally supporting H2. Renewables in transport (RETR) shows stronger effects ($\beta = -0.104$, $p < 0.001$), confirming H3 and suggesting targeted decarbonization of high-emission sectors yields greater marginal benefits than economy-wide energy transitions. This finding resonates with [Knäble et al. \(2022\)](#), who found that different circular economy dimensions affect sustainability outcomes through distinct channels, with energy-related measures showing particularly strong environmental effects.

Education (EDU) significantly reduces emissions ($\beta = -0.292$, $p < 0.001$), consistent with human capital facilitating sustainable behaviors and green policy adoption ([Kostakis and Tsagarakis, 2022](#)), reinforcing SDG 4's emphasis on education for sustainable development. Life expectancy (LE) shows a large negative coefficient ($\beta = -6.425$, $p < 0.001$), likely reflecting correlation between health outcomes, institutional quality, and environmental performance rather than direct causation, a relationship noted in Ecological Modernization Theory's emphasis on institutional capacity ([Jänicke, 2008](#); [Spaargaren and Mol, 2020](#)).

Economic growth positively associates with emissions ($\beta = 0.504$, $p < 0.001$), revealing persistent tension between economic expansion and environmental pressure. This finding, alongside the insignificant bivariate GDP-CO₂ correlation in [Section 5.2](#), demonstrates that within-country growth trajectories increase emissions even when cross-sectional comparisons suggest decoupling. This nuance supports Ecological Modernization Theory's emphasis that decoupling requires active policy steering rather than occurring automatically through growth ([Jänicke, 2008](#)). The contrasting results for H1 (supported) and growth-emissions (positive) illustrate green growth versus post-growth debates: proponents argue technological innovation progressively decouples emissions from growth ([Chen et al., 2018](#); [Dong et al., 2022](#)), while post-growth scholars contend absolute decoupling remains elusive ([Bauwens, 2021](#); [D'Alisa and Kallis, 2020](#)). Our findings suggest circular economy adoption contributes to decoupling but does not fully neutralize growth's emissions impulse, supporting both perspectives while emphasizing complementary policies.

6.3. Economic dimension

Model 3 tests H4 with GDP per capita as dependent variable. Circular material use (CE) shows a positive but insignificant coefficient ($\beta = 0.008$, $p = 0.472$), failing to support H4.

Several studies document positive circular economy-growth associations. [Radičević et al. \(2024\)](#) find resource productivity and recycling rates positively influence GDP across 27 EU countries. [Chen and Pao \(2022\)](#) report causal links between circular economy performance and economic growth in EU-25. [Jakubelskas and Skvarciany \(2025\)](#) confirm circular material use positively affects GDP per capita. The absence of significant direct effects in our specification may reflect: (1) fixed-effects estimator isolating within-country variation over a short decade, whereas benefits may materialize over longer horizons; (2) relationships conditional on technological readiness or institutional quality ([Nikou et al., 2025](#)); or (3) circular material use capturing only one circularity dimension, whereas broader indicators might reveal stronger effects ([Knäble et al., 2022](#)). [Radičević et al. \(2024\)](#) use of pooled OLS exploits cross-sectional variation that our fixed-effects specification purges, suggesting growth benefits may operate primarily through cross-country differences in circular capacity rather than within-country changes. Both findings are informative: circular economies are richer, but becoming more circular does not guarantee short-term growth acceleration.

Control variables perform as expected and provide important contextual insights. Life expectancy (LE) strongly associates with GDP ($\beta = 3.589$, $p < 0.001$), reflecting bidirectional health-prosperity relationships central to SDG 3. Education (EDU) positively influences growth ($\beta = 0.158$, $p < 0.001$), consistent with human capital theory. Unemployment (UNE) negatively affects GDP ($\beta = -0.181$, $p < 0.001$), confirming macroeconomic costs of labor underutilization.

Municipal waste (MW) negatively associates with GDP ($\beta = -0.082$, $p = 0.017$), indicating linear waste patterns impose economic costs: materials flowing to disposal rather than recovery represent lost value ([Korhonen et al., 2018](#)). Population density (POP) shows marginally significant negative association ($\beta = -0.290$, $p = 0.055$), suggesting densely populated areas may face congestion costs offsetting scale economies. Renewables in transport (RETR) positively affects GDP ($\beta = 0.091$, $p < 0.001$), indicating transport decarbonization investments stimulate economic activity through infrastructure development and innovation, supporting the "double dividend" hypothesis ([Porter and van der Linde, 1995](#); [Ahmad et al., 2021](#)). [Bouattour et al. \(2025\)](#) similarly demonstrate that green technological innovation, renewable energy, and circular economy jointly contribute to green growth, with innovation playing a mediating role between circularity and economic performance.

6.4. Social dimension

Model 4 tests H5 with unemployment as dependent variable. Results strongly support the hypothesis: a 1% increase in circular material use associates with 0.097% unemployment reduction ($p = 0.022$). This validates circular transitions' labor-market logic: recycling, repair, remanufacturing, and waste management are labor-intensive, generating employment across skill levels ([Bai et al., 2022](#); [Walker et al., 2021](#)). The magnitude aligns with evidence that circular economy employment has grown across EU countries, with repair and recycling contributing to job creation even during downturns ([Multani et al., 2025](#)). This finding extends Ecological Modernization Theory's traditional environmental-economic focus to incorporate social dimensions, responding to calls for inclusive sustainability frameworks ([Bai et al., 2022](#)).

Municipal waste (MW) shows strong negative association with unemployment ($\beta = -0.728$, $p < 0.001$), higher waste generation paradoxically associates with lower unemployment. This likely reflects economic activity accompanying consumption: material throughput correlates with both waste generation and employment in production, retail, and logistics. The policy implication is not celebrating waste but transforming waste management into employment-generating circular infrastructure. The employment effects documented here align with [Nikou et al. \(2025\)](#), who find employment reforms and job creation accelerate circular transitions, suggesting bidirectional causality between labor markets and circularity.

Economic growth (EG) exhibits expected strong negative relationship ($\beta = -3.021$, $p < 0.001$), confirming Okun's Law and growth's centrality for labor market performance (SDG 8). Renewables in transport (RETR) shows positive coefficient ($\beta = 0.217$, $p = 0.001$), indicating transport decarbonization associates with higher unemployment, possibly reflecting transitional labor displacement as conventional transport restructures, even as new green jobs emerge ([ILO, 2018](#); [Antikainen et al., 2018](#)).

CO₂ emissions show no significant relationship with unemployment ($\beta = -0.060$, $p = 0.713$), suggesting environmental performance and labor market outcomes are not directly coupled in the short run, consistent with "jobs versus environment" framing being largely false dichotomy at macro level.

6.5. Drivers of circular economy adoption

Model 1 examines factors influencing circular material use.

Economic growth (EG) emerges as the strongest driver: a 1% GDP increase associates with 0.806% circular material use increase ($p = 0.001$), confirming that circular transitions require investment capacity, consistent with Ecological Modernization Theory (Jänicke, 2008).

CO₂ emissions show a strong negative coefficient ($\beta = -0.853$, $p = 0.006$), indicating emission-intensive economies have lower circular material use. This reinforces that material and energy transitions should be pursued jointly (Bouattour et al., 2025).

Renewable energy share (RE) positively influences circular adoption ($\beta = 0.157$, $p = 0.001$), supporting that energy and material transitions are synergistic; this aligns with ecological modernization theory. However, the insignificant renewables in transport (RETR) coefficient and its negative correlation with CE (Section 5.2) suggest policy silos between transport decarbonization and material circularity.

Population density (POP) exhibits a strong negative association ($\beta = -2.580$, $p = 0.011$), indicating densely populated areas face structural barriers: space constraints, complex logistics, competing land uses, that require targeted interventions (Liddle, 2014).

Municipal waste (MW) shows a positive but insignificant coefficient ($\beta = 0.315$, $p = 0.154$), providing weak support for H6. This may reflect waste's dual role as both linearity indicator and circular feedstock, suggesting policies must address reduction and recovery simultaneously.

7. Implications

The empirical findings carry significant implications, grounded in Ecological Modernization Theory and the results presented in Section 6.

This study advances the literature by providing empirical evidence on how circular economy transitions simultaneously affect environmental, economic, and social outcomes, a multidimensional assessment previously lacking (Chary et al., 2023; Knäble et al., 2022). The findings contribute to Ecological Modernization Theory in three important respects.

First, the significant negative relationship between circular material use and CO₂ emissions ($\beta = -0.048$, $p = 0.002$) validates EMT's core premise that environmental innovation can reduce ecological pressures without requiring economic contraction (Jänicke, 2008; Spaargaren and Mol, 2020). However, the modest elasticity relative to the positive growth-emissions coefficient ($\beta = 0.504$, $p < 0.001$) suggests that circular economy alone cannot fully offset emissions from continued economic expansion, supporting critiques that technological optimism must be tempered with attention to scale effects (Korhonen et al., 2018; Bauwens, 2021).

Second, the employment benefits of circular adoption ($\beta = -0.097$, $p = 0.022$) extend EMT's traditional environmental-economic focus to incorporate social sustainability, responding to calls for more inclusive frameworks (Bai et al., 2022; Walker et al., 2021). The strong labor-market effects of waste management ($\beta = -0.728$, $p < 0.001$) indicate that circular transitions can contribute to SDG 8 alongside environmental objectives, a synergy underemphasized in EMT's early formulations prioritizing industrial competitiveness (Murphy and Gouldson, 2000).

Third, the finding that renewables in transport reduce emissions ($\beta = -0.104$, $p < 0.001$) while associating with higher unemployment ($\beta = 0.217$, $p = 0.001$) reveals trade-offs within modernization processes, supporting recent EMT scholarship emphasizing that environmental transitions create both winners and losers, requiring just transition policies (Gouldson and Murphy, 2000; ILO, 2018). The partial independence of energy and material transitions, evidenced by the insignificant RETR coefficient in Model 1, suggests decarbonization and circularity are pursued by different policy communities, challenging the integrated vision of ecological modernization and pointing to the need for policy coordination.

By testing all three sustainability dimensions within a unified framework, the results reveal that circular economy delivers

environmental and social benefits more consistently than automatic economic gains, a pattern corroborated by recent multi-country evidence (Knäble et al., 2022; Radivojević et al., 2024). This finding challenges uncritical "win-win" rhetoric and supports more nuanced discourse recognizing that circular transitions require deliberate steering to realize their full potential.

The negative coefficient on population density ($\beta = -2.580$, $p = 0.011$) contributes to emerging literature on spatial dimensions of circular transitions (Liddle, 2014). Densely populated areas face structural barriers, space constraints, complex logistics, competing land uses, that require place-based policy approaches. Methodologically, the contrast between bivariate correlations (CE-CO₂ $r = 0.538$) and fixed-effects coefficients ($\beta = -0.048$) demonstrates the critical importance of isolating temporal variation from cross-sectional heterogeneity, confirming the necessity of fixed-effects estimation when unobserved country characteristics correlate with both circular adoption and sustainability outcomes.

Finally, the geopolitical dimension introduced by the Russian war on Ukraine adds urgency to circular economy research (European Environment Agency, 2022). The finding that circular adoption reduces emissions while generating employment suggests circular economy can contribute to both environmental objectives and strategic autonomy, enhancing resource security and reducing dependence on volatile import markets (Rodríguez-Antón et al., 2022).

8. Conclusion

This study has investigated the relationship between circular economy transitions and sustainable development outcomes across 18 European Union countries over the decade 2010–2019. Anchored in Ecological Modernization Theory and employing fixed-effects panel estimation, the analysis has generated robust empirical evidence on how circular material use, renewable energy adoption, waste management, and socio-economic conditions jointly influence environmental, economic, and social sustainability.

8.1. Summary of key findings

The research confirms that circular economy transitions play a significant role in advancing environmental sustainability. A 1% increase in circular material use corresponds to a 0.048% reduction in CO₂ emissions ($p = 0.002$), validating H1 and demonstrating that substituting secondary materials for virgin resources reduces the energy-intensive extraction and processing that generate emissions. Renewable energy adoption reinforces these environmental benefits, with renewables in transport showing particularly strong effects ($\beta = -0.104$, $p < 0.001$), supporting H3 and highlighting the importance of sectoral decarbonization strategies. Education emerges as a significant contributor to emission reductions ($\beta = -0.292$, $p < 0.001$), underscoring the role of human capital in facilitating sustainability transitions.

Economically, the findings present a more nuanced picture. Economic growth strongly drives circular adoption ($\beta = 0.806$, $p = 0.001$), indicating that circular transitions require investment capacity that prosperous economies can provide. However, circular material use does not significantly affect GDP per capita (H4 not supported), suggesting that the economic benefits of circularity may materialize over longer time horizons, operate through indirect channels, or require complementary conditions such as technological readiness or institutional quality. Municipal waste negatively associates with GDP ($\beta = -0.082$, $p = 0.017$), confirming that linear waste patterns impose economic costs through lost material value.

Socially, circular economy transitions contribute positively to labor market outcomes. A 1% increase in circular material use associates with 0.097% unemployment reduction ($p = 0.022$), supporting H5 and validating the labor-market logic of circular transitions. Waste management exhibits particularly strong employment effects ($\beta = -0.728$, p

< 0.001), indicating that recycling, repair, and recovery activities generate accessible jobs across skill levels. However, renewables in transport show a positive association with unemployment ($\beta = 0.217$, $p = 0.001$), suggesting that transport decarbonization may create transitional labor displacement even as it delivers environmental benefits.

The pattern of findings, strong environmental and social benefits alongside mixed economic evidence, suggests that circular economy delivers on its sustainability promises in some dimensions more consistently than others. This nuanced conclusion challenges uncritical "win-win" rhetoric while affirming that circular transitions, when appropriately supported by policy, can contribute meaningfully to multiple SDGs.

8.2. Policy recommendations

Based on the empirical findings, the following policy recommendations are proposed to harness the full potential of circular economy transitions while addressing identified trade-offs and constraints.

First, integrate circular economy into industrial and innovation policy. The strong relationship between economic growth and circular adoption ($\beta = 0.806$) indicates that circular transitions require investment capacity. Policymakers should embed circular economy objectives within broader industrial strategies, ensuring that funding mechanisms, including the Just Transition Fund, Recovery and Resilience Facility, and Horizon Europe, allocate resources for circular infrastructure, technological upgrading, and institutional capacity building. This integration would advance SDG 9 while supporting circular transitions.

Second, pursue coordinated energy and material transitions. The partial independence of renewable energy and circular material use revealed by this study suggests missed synergies. Policymakers should create coordination mechanisms across energy, transport, environment, and industry ministries to ensure that decarbonization and circularity strategies are mutually reinforcing. Joint roadmaps, integrated impact assessments, and cross-sectoral targets could capture synergies that single-domain policies miss.

Third, implement just transition measures alongside environmental regulations. The positive RETR-unemployment relationship ($\beta = 0.217$) signals that transport decarbonization may displace workers, even as circular activities create employment elsewhere. Policymakers should accompany environmental regulations with retraining programs, income support, and regional diversification strategies that ensure equitable outcomes aligned with SDG 8 and SDG 10. Social dialogue involving unions, employers, and communities should inform transition planning at all governance levels.

Fourth, invest in waste management infrastructure for employment and environment. The strong unemployment reduction associated with municipal waste management ($\beta = -0.728$) indicates that waste systems can be leveraged for job creation. Investment in recycling facilities, materials recovery operations, and composting infrastructure should be prioritized not merely as environmental measures but as employment strategies advancing SDG 8.5.

Fifth, address spatial barriers to circularity in dense urban areas. The negative population density coefficient ($\beta = -2.580$) indicates that densely populated areas face structural challenges requiring targeted interventions. Urban planning should integrate circular infrastructure, allocating space for recycling facilities, repair cafes, and material recovery centers, while optimizing collection logistics for high-density environments. Decentralized solutions including community composting and local repair networks can complement centralized systems while engaging citizens in circular transitions (SDG 11).

Sixth, invest in sustainability education at all levels. Education's significant contribution to emission reductions ($\beta = -0.292$) supports integrating sustainability into school curricula, vocational training, and university programs (SDG 4.7). Public awareness

campaigns promoting circular behaviors, repair, reuse, recycling, can complement formal education while building social acceptance for circular economy policies.

Seventh, enhance resource security through circular economy. The geopolitical context highlighted by the Russian war on Ukraine adds urgency to circular economy as strategic policy. Circular adoption reduces emissions while generating employment and can simultaneously reduce dependence on imported raw materials. Policies enhancing circularity should be framed as contributing to both climate objectives and strategic autonomy, potentially building broader political support for ambitious action.

Eighth, strengthen monitoring and evaluation frameworks. The methodological insights from this study, particularly the contrast between cross-sectional and fixed-effects results, underscore the importance of rigorous evaluation. Policymakers should invest in data collection and analysis that enables within-country, over-time assessment of circular economy impacts (SDG 17.18). Such evidence-based approaches can inform adaptive policy design and ensure interventions are tailored to context.

In conclusion, this study demonstrates that circular economy transitions offer genuine potential for advancing sustainable development across environmental, economic, and social dimensions. However, realizing this potential requires deliberate policy design, strategic investment, and attention to distributional consequences. The pattern of findings, environmental and social benefits more readily observed than automatic economic gains, reinforces the need for public policy to steer markets toward circular outcomes rather than assuming spontaneous business case emergence. With appropriate frameworks, investments, and coordination, circular economy can contribute meaningfully to EU climate neutrality, resource security, and inclusive prosperity, while serving as a model for sustainable development globally.

9. Limitations and future research directions

The study is subject to several limitations inherent in its design. First, the focus on 18 EU countries with relatively advanced CE frameworks limits generalizability to less mature economies or non-EU contexts where institutional and infrastructural conditions differ markedly. Second, the 2010–2019 panel, while chosen for data consistency, excludes post-2019 developments, including COVID-19 disruptions, the acceleration of the European Green Deal, and the energy-security imperatives following the Russian invasion of Ukraine. These events likely altered CE trajectories and should be examined in updated datasets. Third, reliance on circular material use rate as the primary CE proxy captures only one dimension of circularity; broader indicators (repair, sharing, product longevity) might reveal additional economic and social effects. Finally, the short time horizon may mask lagged benefits, particularly for growth and innovation payoffs that often materialize gradually.

Future research should address these constraints and extend the analysis in several directions. Longer panels incorporating post-2020 data would allow assessment of recent policy shocks and Green Deal impacts. Comparative studies across EU sub-regions could explore how institutional maturity, historical development paths, and cultural factors moderate CE outcomes, particularly in Central and Eastern Europe where infrastructure and adoption barriers remain pronounced (Apostu et al., 2023). Incorporating e-waste recycling and critical-mineral recovery would strengthen insights into resource security and pollution reduction (SDG 12.4). Examination of digital technologies (AI sorting, blockchain traceability) and behavioral interventions (community-led initiatives) could illuminate demand-side drivers of circularity. Finally, deeper investigation of policy coherence across governance levels would identify best practices for harmonizing national and EU-wide CE strategies, ensuring accountability and equitable implementation (SDG 17).

CRedit authorship contribution statement

Judit Oláh: Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Mohammad Bin Amin:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Mehedi Hasan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Investigation, Data curation, Conceptualization. **Md. Saddam Hossain:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Investigation, Data curation, Conceptualization. **Md. Atikur Rahaman:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Funding acquisition.

Declaration of competing interest

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

Acknowledgments

This research was supported by the University of Debrecen Program for Scientific Publication.

References

- Ahmad, M., Jan, I., Jabeen, G., Alvarado, R., 2021. Does energy-industry investment drive economic performance in regional China: implications for sustainable development. *Sustain. Prod. Consum.* 27, 176–192. <https://doi.org/10.1016/j.spc.2020.10.033>.
- Ali, K., Jianguo, D., Kirikkaleli, D., Oláh, J., Bakhsh, S., 2023. Do environmental taxes, environmental innovation, and energy resources matter for environmental sustainability: evidence of five sustainable economies. *Heliyon*. 9 (11). <https://doi.org/10.1016/j.heliyon.2023.e21577>.
- Alola, A.A., Bekun, F.V., Sarkodie, S.A., 2019. Dynamic impact of trade policy, economic growth, fertility rate, renewable and non-renewable energy consumption on ecological footprint in Europe. *Sci. Total Environ.* 685, 702–709. <https://doi.org/10.1016/j.scitotenv.2019.05.139>.
- Antikainen, M., Uusitalo, T., Kivikyto-Reponen, P., 2018. Digitalisation as an enabler of circular economy. *Procedia CIRP*. 73, 45–49. <https://doi.org/10.1016/j.procir.2018.04.027>.
- Apostu, S.A., Gigauri, I., Panait, M., Martín-Cervantes, P.A., 2023. Is Europe on the way to sustainable development? Compatibility of green environment, economic growth and circular economy issues. *Int. J. Environ. Res. Public Health* 20 (2), 1078. <https://doi.org/10.3390/ijerph20021078>.
- Arellano, M., 2005. *Panel Data Econometrics*. Oxford Univ. Press, Oxford Online Resource.
- Bai, C., Orzes, G., Sarkis, J., 2022. Exploring the impact of industry 4.0 technologies on social sustainability through a circular economy approach. *Ind. Mark. Manag.* 101, 176–190. <https://doi.org/10.1016/j.indmarman.2021.12.004>.
- Baltagi, B.H., 2008. *Econometric Analysis of Panel Data*, 4. John Wiley & sons, Chichester, pp. 135–145.
- Bauwens, T., 2021. Are the circular economy and economic growth compatible? A case for post-growth circularity. *Resour. Conserv. Recycl.* 175, 105852. <https://doi.org/10.1016/j.resconrec.2021.105852>.
- Berger, G., Flynn, A., Hines, F., Johns, R., 2001. Ecological modernization as a basis for environmental policy: current environmental discourse and policy and the implications on environmental supply chain management. *Innovation: the Eur. J. Soc. Sci. Res.* 14 (1), 55–72. <https://doi.org/10.1080/13511610125074>.
- Bianchi, M., Cordella, M., 2023. Does circular economy mitigate the extraction of natural resources? Empirical evidence based on analysis of 28 European economies over the past decade. *Ecol. Econ.* 203, 107607. <https://doi.org/10.1016/j.ecolecon.2022.107607>.
- Bouattour, A., Gharbi, S., Kalai, M., Helali, K., 2025. Relationships between green technological innovation, renewable energy, circular economy, and green growth. *J. Innov. Knowl.* 10 (4), 100748. <https://doi.org/10.1016/j.jik.2025.100748>.
- Buttel, F.H., 2000. Ecological modernization as social theory. *Geoforum*. 31 (1), 57–65. [https://doi.org/10.1016/S0016-7185\(99\)00044-5](https://doi.org/10.1016/S0016-7185(99)00044-5).
- Byaro, M., Nkonoki, J., Mafwolo, G., 2023. Exploring the nexus between natural resource depletion, renewable energy use, and environmental degradation in sub-Saharan Africa. *Environ. Sci. Pollut. Res.* 30 (8), 19931–19945. <https://doi.org/10.1007/s11356-022-23104-7>.
- Castro-Lopez, A., Entrialgo, M., Liao, C.T., Santos-Vijande, M.L., 2025. Towards circular economy through innovation: the role of entrepreneurial orientation and human resource management. *Int. Entrep. Manag. J.* 21 (1), 36. <https://doi.org/10.1007/s11365-024-01032-x>.
- Chary, K., van Riel, A.J., Muscat, A., Wilfart, A., Harchaoui, S., Verdegem, M., Wiegertjes, G.F., 2023. Transforming sustainable aquaculture by applying circularity principles. *Rev. Aquac.* <https://doi.org/10.1111/raq.12860>.
- Chen, C.-C., Pao, H.-T., 2022. The causal link between circular economy and economic growth in EU-25. *Environ. Sci. Pollut. Res.* 29 (50), 76352–76364. <https://doi.org/10.1007/s11356-022-21010-6>.
- Chen, J., Wang, P., Cui, L., Huang, S., Song, M., 2018. Decomposition and decoupling analysis of CO₂ emissions in OECD. *Appl. Energy* 231, 937–950. <https://doi.org/10.1016/j.apenergy.2018.09.179>.
- Chen, Z., Chen, S., Liu, C., Nguyen, L.T., Hasan, A., 2020. The effects of circular economy on economic growth: a quasi-natural experiment in China. *J. Clean. Prod.* 271, 122558. <https://doi.org/10.1016/j.jclepro.2020.122558>.
- Cudjoe, D., Wang, H., Zhu, B., 2021. Assessment of the potential energy and environmental benefits of solid waste recycling in China. *J. Env. Manage.* 295, 113072. <https://doi.org/10.1016/j.jenvman.2021.113072>.
- D'Alisa, G., Kallis, G., 2020. Degrowth and the state. *Ecol. Econ.* 169, 106486. <https://doi.org/10.1016/j.ecolecon.2019.106486>.
- Dantas, T.E.T., de-Souza, E.D., Destro, I.R., Hammes, G., Rodriguez, C.M.T., Soares, S.R., 2021. How the combination of Circular economy and industry 4.0 can contribute towards achieving the Sustainable Development Goals. *Sustain. Prod. Consum.* 26, 213–227. <https://doi.org/10.1016/j.spc.2020.10.005>.
- Dong, F., Li, Y., Gao, Y., Zhu, J., Qin, C., Zhang, X., 2022. Energy transition and carbon neutrality: exploring the non-linear impact of renewable energy development on carbon emission efficiency in developed countries. *Resour. Conserv. Recycl.* 177, 106002. <https://doi.org/10.1016/j.resconrec.2021.106002>.
- Ellen MacArthur Foundation (EMF), 2015. *Delivering the Circular Economy: A Toolkit for Policymakers*. Ellen MacArthur Foundation, pp. 1–177, 263.
- European Environment Agency (EEA), 2022. Circular economy in Europe: a policy brief on the role of circular economy in addressing geopolitical challenges. <https://www.eea.europa.eu/publications/circular-economy-in-europe>.
- European Environment Agency., 2022. Transport and Environment Report 2021. Publications Office of the European Union. <https://www.eea.europa.eu/publication/s/transport-and-environment-report-2021>.
- Fisher, D.R., Freudenburg, W.R., 2001. Ecological modernization and its critics: assessing the past and looking toward the future. *Soc. Nat. Resour.* 14 (8), 701–709. <https://doi.org/10.1080/08941920119315>.
- Gallego-Nicholls, J.F., Ortigosa-Blanch, A., Sánchez-García, J., Rivera-Lirio, J.M., 2025. Sustainable development goals and corporate sustainability reporting: a bibliometric analysis. *ESIC Mark.* 56 (1), e345. <https://doi.org/10.7200/esicm.56.345>.
- Gandolfo, A., Lupi, L., 2021. Circular economy, the transition of an incumbent focal firm: how to successfully reconcile environmental and economic sustainability? *Bus. Strategy Environ.* 30 (7), 3297–3308. <https://doi.org/10.1002/bse.2803>.
- García-Sánchez, I.-M., Piñeiro-Chousa, J.R., Aibar-Guzmán, C., Aibar-Guzmán, B., 2024. Environmental products and sustainability awards: the intangible benefits of sustainability strategies. *ESIC Mark.* 55 (1), e353. <https://doi.org/10.7200/esicm.55.353>.
- Geissdoerfer, M., Savaget, P., Bocken, N.M., Hultink, E.J., 2017. The Circular Economy—A new sustainability paradigm? *J. Clean. Prod.* 143, 757–768. <https://doi.org/10.1016/j.jclepro.2016.12.048>.
- Georgescu, L.P., Fortea, C., Antohi, V.M., Balsalobre-Lorente, D., Zlati, M.L., Barbuta-Misu, N., 2025. Economic, technological and environmental drivers of the circular economy in the European Union: a panel data analysis. *Environ. Sci. Eur.* 37 (1), 76. <https://doi.org/10.1186/s12302-025-01119-4>.
- Giampietro, M., 2019. On the circular bioeconomy and decoupling: implications for sustainable growth. *Ecol. Econ.* 162, 143–156. <https://doi.org/10.1016/j.ecolecon.2019.05.001>.
- Hailemariam, A., Erdiaw-Kwasie, M.O., 2023. Towards a circular economy: implications for emission reduction and environmental sustainability. *Bus. Strategy Environ.* 32 (4), 1951–1965. <https://doi.org/10.1002/bse.3229>.
- Hausman, J.A., 1978. Specification tests in econometrics. *Econometrica* 46 (6), 1251. <https://doi.org/10.2307/1913827>.
- Huber, J., 2008. Pioneer countries and the global diffusion of environmental innovations: theses from the viewpoint of ecological modernisation theory. *Glob. Environ. Change* 18 (3), 360–367. <https://doi.org/10.1016/j.gloenvcha.2008.03.004>.
- International Labour Organization, 2018. *World Employment and Social Outlook 2018: Greening with Jobs*. ILO. <https://www.ilo.org/publications/world-employment-and-social-outlook-2018-greening-jobs>.
- Jänicke, M., 2008. Ecological modernisation: new perspectives. *J. Clean. Prod.* 16 (5), 557–565. <https://doi.org/10.1016/j.jclepro.2007.02.011>.
- Jakubelskas, U., Skvarciany, V., 2025. Evaluation of circular economy indicators seeking sustainable development goals. *E+M Econ. Manag.* 28 (3), 17–31. <https://doi.org/10.15240/tul/001/2025-5-018>.
- Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. *Resour. Conserv. Recycl.* 127, 221–232. <https://doi.org/10.1016/j.resconrec.2017.09.005>.
- Knäble, D., de Quevedo Puente, E., Pérez-Cornejo, C., Baumgärtler, T., 2022. The impact of the circular economy on sustainable development: a European panel data approach. *Sustain. Prod. Consum.* 34, 233–243. <https://doi.org/10.1016/j.spc.2022.09.016>.
- Korhonen, J., Honkasalo, A., Seppälä, J., 2018. Circular economy: the concept and its limitations. *Ecol. Econ.* 143, 37–46. <https://doi.org/10.1016/j.ecolecon.2017.06.041>.

- Kostakis, I., Tsarakakis, K.P., 2022. Social and economic determinants of materials recycling and circularity in Europe. *Ann. Reg. Sci.* 68 (2), 263–281. <https://doi.org/10.1007/s00168-021-01074-x>.
- Kuo, L., Chang, B.G., 2021. The affecting factors of circular economy information and its impact on corporate economic sustainability-evidence from China. *Sustain. Prod. Consum.* 27, 986–997. <https://doi.org/10.1016/j.spc.2021.02.014>.
- Liao, C., Parkhurst, G., Parker, C.J., 2025. Future flight's dynamic capabilities and circular economy opportunities. *Sustain. Technol. Entrep.*, 100114 <https://doi.org/10.1016/j.stae.2025.100114>.
- Liddle, B., 2014. Impact of population, age structure, and urbanization on carbon emissions/energy consumption: evidence from macro-level, cross-country analyses. *Popul. Env.* 35 (3), 286–304. <https://doi.org/10.1007/s11111-013-0198-4>.
- Liu, M., Zhang, X., 2026. Waste not, emit not: how circular economy strategies shape climate and growth outcomes in G-20 nations? *J. Clean. Prod.* 540, 147415. <https://doi.org/10.1016/j.jclepro.2025.147415>.
- Masood, T., Israr, A., Zubair, M., Qazi, U.W., 2023. Assessing challenges to sustainability and resilience of energy supply chain in Pakistan: a developing economy from Triple Bottom Line and UN SDGs' perspective. *Int. J. Sustain. Energy* 42 (1), 268–288. <https://doi.org/10.1080/14786451.2023.2189489>.
- Mazzoni, L., Sedita, S.R., 2025. Unpacking the drivers of the socio-environmental sustainability of new ventures: insights from innovative digital start-ups in Italy. *Int. Entrep. Manag. J.* 21, 16. <https://doi.org/10.1007/s11365-024-01019-8>.
- Mpofu, F.Y., 2022. Industry 4.0 in Financial services: mobile money taxes, revenue mobilisation, financial inclusion, and the realisation of sustainable development goals (SDGs) in Africa. *Sustainability* 14 (14). <https://doi.org/10.3390/su14148667>.
- Multani, M., Borms, L., Bachus, K., 2025. Circular economy as a driver of sustainable growth: quantitative analysis of the role of recycling and secondary raw materials in the EU. *Sustainability* 17 (11), 5181. <https://doi.org/10.3390/su17115181>.
- Murphy, J., Gouldson, A., 2000. Environmental policy and industrial innovation: integrating environment and economy through ecological modernisation. *Geoforum* 31 (1), 33–44.
- Nikou, V., Sardanou, E., 2025. Building a circular economy of belonging: an econometric approach. *Waste Manag. Res.: J. Sustain. Circ. Econ.* 43 (12), 2068–2074. <https://doi.org/10.1177/0734242X251350544>.
- Pearce, D.W., Turner, R.K., 1989. *Economics of Natural Resources and the Environment*. Harvester Wheatsheaf, New York, London.
- Porter, M.E., van der Linde, C., 1995. Toward a new conception of the environment-competitiveness relationship. *J. Econ. Perspect.* 9 (4), 97–118. <https://doi.org/10.1257/jep.9.4.97>.
- Preston, B.J., 2024. The right to a clean, healthy and sustainable environment: how to make it operational and effective. *J. Energy Nat. Resour. Law* 42 (1), 27–49. <https://doi.org/10.1080/02646811.2023.2165310>.
- Radivojević, V., Radenović, T., Dimovski, J., 2024. The role of circular economy in driving economic growth: evidence from EU countries. *Sage Open* 14 (4), 21582440241240624. <https://doi.org/10.1177/21582440241240624>.
- Rodríguez-Antón, J.M., Rubio-Andrada, L., Celemin-Pedroche, M.S., et al., 2022. From the circular economy to the sustainable development goals in the European Union: an empirical comparison. *Int. Env. Agreem.* 22, 67–95. <https://doi.org/10.1007/s10784-021-09553-4>.
- Sanz-Torró, V., Calafat-Marzal, C., Guaita-Martinez, J.M., Vega, V., 2025. Assessment of European countries' national circular economy policies. *J. Env., Manage* 373, 123835. <https://doi.org/10.1016/j.jenvman.2024.123835>.
- Sanz-Torró, V., Calafat-Marzal, C., Guaita-Martinez, J.M., Martí, L., 2025. An integrated approach to resource efficiency, green markets and support measures in SMEs. *Int. Entrep. Manag. J.* 21 (1), 84. <https://doi.org/10.1007/s11365-025-01098-1>.
- Shi, R., Gao, P., Su, X., Zhang, X., Yang, X., 2024. Synergizing natural resources and sustainable development: a study of industrial structure, and green innovation in Chinese region. *Resour. Policy* 88, 104451. <https://doi.org/10.1016/j.resourpol.2023.104451>.
- Sodhi, M.S., Tang, C.S., 2024. Seeking and exploiting synergies among the UN Sustainability Development Goals: research opportunities for operations management. *Prod. Oper. Manag.* <https://doi.org/10.1177/10591478241235004>.
- Spaargaren, G., Mol, A.P., 2020. Sociology, environment, and modernity: ecological modernization as a theory of social change. *The Ecological Modernisation Reader*. Routledge, pp. 56–79. <https://doi.org/10.1080/08941929209380797>.
- Sun, Y., Wu, Y., Lin, S., 2024. Global perspective of sustainable development: the role of mineral resources, technological advancement and renewable investments. *Resour. Policy* 90, 104640. <https://doi.org/10.1016/j.resourpol.2024.104640>.
- Walker, A.M., Opferkuch, K., Lindgreen, E.R., Simboli, A., Vermeulen, W.J., Raggi, A., 2021. Assessing the social sustainability of circular economy practices: industry perspectives from Italy and the Netherlands. *Sustain. Production Consump.* 27, 831–844. <https://doi.org/10.1016/j.spc.2021.01.030>.
- WCED, 1987. *Our Common Future*. Oxford University Press, Oxford, U.K.
- Wooldridge, J.M., 2010. *Econometric Analysis of Cross Section and Panel Data*, 2nd ed. MIT Press.