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Assessing the Impact of Eco-Innovation, Economic Complexity, and Digitalization on the Circular Economy in Europe

推动欧洲循环经济：生态创新、经济复杂性与数字化的经验证据

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Abstract. Facing escalating resource depletion and environmental degradation, the transition to a circular economy (CE) has become imperative, with the European Union (EU) emerging as a leading yet uneven performer. This study examines the effects of eco-innovation, economic complexity, and digitalization on CE performance in 22 EU countries from 2010 to 2021. Employing POLS, DKSE, and MMQR estimations, alongside the Dumitrescu–Hurlin panel causality test, the analysis captures both average and heterogeneous effects across CE development levels. The results reveal that all three factors significantly promote CE advancement, with digitalization exerting the strongest influence, followed by economic complexity and eco-innovation. Notably, eco-innovation is more effective in countries with lower CE performance, while economic complexity plays a greater role in more advanced CE contexts, whereas digitalization consistently enhances CE across all levels. Causality tests indicate a unidirectional relationship from economic complexity to CE. Overall, the findings highlight the need for differentiated and context-sensitive policy frameworks that integrate digital transformation, industrial sophistication, and eco-innovative capacity to accelerate the EU's circular transition.

Keywords: Circular economy, eco-innovation, economic complexity, digitalization, European Union, sustainable development

摘要: 一在资源枯竭和环境退化日益加剧的背景下，全球经济体系正面临向循环经济（Circular Economy, CE）转型的迫切需求。作为循环经济转型的先行地区，欧洲联盟（EU）虽已制定多项政策框架，但各成员国在循环经济发展水平上仍存在显著差异。基于此，本文以2010 2021年22个欧盟成员国为样本，系统分析生态创新、经济复杂性与数字化在推动循环经济发展中的作用机制。研究采用面板普通最小二乘法（POLS）、Driscoll–Kraay稳健标准误（DKSE）以及矩估计分位数回归（MMQR）方法，以刻画平均效应及不同循环经济发展阶段下的异质性影响，并进一步运用Dumitrescu–Hurlin面板因果检验分析变量间的因果关系。研究结果表明，生态创新、经济复杂性和数字化均对循环经济发展具有显著的正向影响，其中数字化的促进作用最为突出，其次为经济复杂性和生态创新。然而，不同因素在各国的作用强度存在差异：生态创新在循环经济发展水平较低的国家中效果更为明显，而经济复杂性在循环经济发展较为成熟的国家中发挥更大作用；数字化则在各发展阶段均持续促进循环经济提升。因果检验结果显示，经济复杂性对循环经济存在单向因果关系，而生态创新与数字化未表现出独立的因果作用。研究结论表明，欧盟在推进循环经济进程中，应根据各国发展阶段实施差异化政策，将数字化转型、产业结构升级与生态创新能力建设有机结合，以加快实现资源高效利用与可持续发展目标。

关键词： 循环经济；生态创新；经济复杂性；数字化；欧洲联盟；可持续发展

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1. Introduction

The circular economy (CE) represents a regenerative economic system in which materials are repeatedly circulated through activities such as reuse, repair, recycling, and composting, thereby ensuring that resources and products remain in productive use rather than becoming waste (Ellen MacArthur Foundation, 2013). In recent years, the global transition toward CE has gained considerable momentum due to its demonstrated contribution to sustainable development (Govindan, 2023). This transition has emerged as a viable response to mounting pressures arising from resource depletion, environmental degradation, and climate change. By prioritizing resource efficiency and long-term sustainability particularly in the context of population growth and increasing material scarcity CE offers a more sustainable alternative to conventional linear economic models characterized by "take–make–dispose" practices (Barteková & Borkey, 2022; Mügge et al., 2024; Peyravi et al., 2024).

As one of the leading regions advocating the adoption of CE principles, the European Union (EU) has undertaken extensive policy and institutional initiatives to advance circularity in order to enhance environmental quality and economic competitiveness. The introduction of the European Green Deal and the Circular Economy Action Plan (CEAP) in 2015, followed by its update in 2020, reflects the EU's strong commitment to leading the global transition toward a CE. The European Green Deal constitutes a comprehensive policy framework aimed at achieving climate neutrality by 2050 through sustainable economic growth, environmental protection, and systemic transformation toward circular practices (European Commission, 2019). As a central component of this framework, the CEAP seeks to make sustainable products the norm within the EU while positioning the region as a global leader in CE implementation (European Commission, 2020). Nevertheless, despite these ambitious objectives, progress remains limited. Although the CEAP targets a recycling rate of 75% by 2035, only 11.7% of materials used within the EU originated from recycled sources in 2021 (European Environment Agency, 2023). With less than a decade remaining to achieve this target, this substantial gap underscores the urgent need for innovative strategies to close material loops and ensure timely policy attainment.

In this context, examining the roles of eco-innovation, economic complexity, and digitalization is critical for realizing the CEAP's objectives and broader EU circular economy goals. Eco-innovation, encompassing the development of environmentally friendly products, processes, and business models, plays a pivotal role in enhancing resource efficiency and reducing waste generation (Pichlak & Szromek, 2022; Peyravi et al., 2024). Empirical evidence indicates that countries embracing eco-innovative practices tend to experience lower resource consumption, reduced waste levels, and more sustainable production and consumption patterns (Le et al., 2023). In addition, economic complexity and digitalization have been identified as key structural drivers of CE transition. Economic complexity reflecting the diversity and sophistication of a nation's productive capabilities facilitates the production of high-value goods that require fewer material inputs and generate less waste (Boleti et al., 2021). Countries with higher levels of economic complexity are therefore better positioned to innovate and respond effectively to the requirements of a CE (Anwar et al., 2024).

Digitalization, defined as the integration of digital technologies to enhance productivity and efficiency, further supports CE development by optimizing resource flows, improving product traceability, and enabling circular business models. Recent advances in digital technologies, including artificial intelligence, blockchain, and the Internet of Things (IoT), have expanded opportunities to streamline processes, strengthen data-driven decision-making, and improve overall system efficiency within CE frameworks (Barteková & Borkey, 2022). The interaction among eco-innovation, economic complexity, and digitalization thus represents a potentially decisive mechanism for advancing circularity across EU member states.

Although prior studies have explored the determinants of CE and the influence of macroeconomic factors on its development (Lapatinas et al., 2021; Liu et al., 2022, 2023; Ha, 2023; Mügge et al., 2024; Peyravi et al., 2024), important research gaps remain. Much of the existing literature relies on qualitative approaches, while quantitative studies have rarely examined the interrelationships among eco-innovation, economic complexity, digitalization, and CE within an integrated empirical framework. Addressing this gap, the present study contributes novel empirical evidence by analyzing the effects of eco-innovation, economic complexity, and digitalization on CE performance in the EU over the period 2010–2021. Moreover, the study extends Schumpeterian innovation theory conceptualizing innovation as a transformative force driven by creative destruction and systemic change (Schumpeter, 1950) to the CE context, illustrating how eco-innovation, digitalization, and economic complexity can disrupt conventional resource-intensive models and facilitate a sustainable and systemic transition toward circularity. The findings are intended to inform policy design aimed at accelerating CE progress, enabling the EU to achieve its 2035 targets and serve as a global benchmark for CE advancement.

To operationalize these objectives, the study constructs a composite CE index based on four indicators: circular material use rate, gross value added in CE-related sectors, private investment in CE activities, and the municipal waste recycling rate. In addition, a digitalization index is developed using five information and communication technology (ICT) indicators, namely fixed broadband subscriptions, fixed telephone subscriptions, internet usage, mobile cellular subscriptions, and secure internet servers. The use of composite indices allows for a more comprehensive representation of CE and digitalization levels across EU countries, as reliance on single indicators may inadequately capture the multidimensional nature of circularity. The EU's emphasis on digital transformation as a strategic priority toward 2030 further reinforces the relevance of digitalization in advancing CE objectives (Usman et al., 2024). According to the European Commission (2022), substantial disparities in digitalization persist across the EU, with only 16 member states scoring above 50 out of 100 on the Digital Economy and Society Index (DESI) in 2022. Similar heterogeneity is observed in economic complexity and eco-innovation performance, with countries such as Germany, Czechia, and Austria leading in economic complexity, while Greece, Latvia, and Portugal lag behind (Atlas of Economic Complexity, 2022), and Germany and France emerging as frontrunners in environment-related technological development compared to lower-performing countries such as Lithuania and Estonia (OECD, 2023). These variations provide a valuable opportunity to assess how structural differences shape the effectiveness of CE initiatives across the EU.

To capture such heterogeneity, this study employs a set of advanced econometric techniques, including Pooled Ordinary Least Squares (POLS), Driscoll–Kraay standard errors (DKSE), and Method of Moments Quantile Regression (MMQR). While POLS estimates average relationships across the full sample, DKSE addresses cross-sectional dependence and heteroscedasticity to ensure robust inference. MMQR further enables the examination of heterogeneous effects across different quantiles of CE performance, offering deeper insights into how eco-innovation, economic complexity, and digitalization influence CE at various stages of development. Collectively, these methodological approaches allow the analysis to account for context-specific dynamics and provide a robust foundation for designing targeted policy interventions aimed at closing material loops within the EU.

2. Materials and Methods

Eco-innovation and the circular economy

The integration of eco-innovation with the circular economy (CE) has become a key pathway for advancing sustainable development and improving resource efficiency. Eco-innovation facilitates the shift from linear "take–make–dispose" systems toward circular arrangements that emphasize resource recirculation, waste minimization, and cleaner production (De Jesus & Mendonça, 2018). The literature broadly recognizes eco-innovation as a crucial enabler of closed-loop systems, as it can reduce material and energy inputs while encouraging more sustainable production and consumption patterns (Pichlak & Szromek, 2022). Achieving such systemic transformation requires firms to innovate not only technologically but also organizationally, given the complexity of implementing CE principles across heterogeneous sectors (Maldonado-Guzman et al., 2021).

Recent empirical work reinforces eco-innovation's role as a central driver of CE development, particularly in manufacturing and industrial settings. Liu et al. (2023) report that corporate social responsibility (CSR) and technological innovation efficiency significantly shape eco-innovation among manufacturing firms, thereby supporting their movement toward circular business models. This perspective is consistent with Peyravi and Jakubavicius (2022), who argue that organizational capabilities and strategic resource utilization are foundational for eco-innovation aimed at sustainability. Together, these studies imply that technological progress supported by appropriate managerial and strategic practices can help firms overcome common impediments to circularity, including high implementation costs and market uncertainty (Hinojosa, 2022). Related evidence also suggests that e-waste recycling can contribute to strengthening circularity within the EU economy (Neves et al., 2024).

Beyond enhancing product and process circularity, eco-innovation is frequently linked to broader environmental outcomes. Thakker and Bakshi (2023) show that eco-innovation may support greenhouse gas mitigation and progress toward net-zero objectives. They propose a methodological framework for ranking eco-innovations by their expected contribution to CE, enabling firms to evaluate and prioritize options with higher potential for implementation. This provides a structured approach for aligning innovation strategies with environmental performance targets. Le et al. (2023) further examine how eco-innovation interacts with cleaner production and resilience during CE transitions, suggesting that eco-innovation improves the sustainability and adaptive capacity of production systems when embedded within cleaner production practices. Such resilience is essential for firms facing simultaneous environmental pressures and economic uncertainty while seeking to maintain competitiveness. Nevertheless, despite these advantages, important challenges persist. Bao and Ha (2023) argue that although eco-innovation can strengthen circular practices in European economies, adoption and implementation vary across regions and industries. Similarly, Peyravi et al. (2024) highlight the need for greater convergence in eco-innovation practices across the EU to improve consistency, efficiency, and effectiveness in CE adoption.

At the same time, some studies emphasize the rebound effect, whereby improvements in resource efficiency unintentionally stimulate higher production or consumption levels, thereby diminishing or even reversing intended environmental gains (Figge & Thorpe, 2019; Zerbino, 2022). This issue is particularly relevant for CE policies and innovations because cost reductions or increased accessibility generated through efficiency gains may increase demand. For example, more efficient material recovery can lower input costs and, in turn, incentivize greater production by manufacturers (Castro et al., 2022). If not explicitly managed, such dynamics may weaken CE sustainability outcomes, especially when efficiency gains are incorrectly interpreted as absolute reductions in environmental impacts. Several channels may generate rebound effects, including direct and indirect motivational rebounds, income rebounds, and substitution rebounds (Bączyk et al., 2024). These mechanisms reflect how savings or efficiency gains can be reallocated toward additional economic activity. Evidence from the Dutch textile sector illustrates this concern: improvements in resource efficiency did not yield proportional environmental benefits because production volumes and consumption patterns increased (Siderius & Poldner, 2021). This example underscores the risk of overstating CE effectiveness when rebound effects are not explicitly accounted for in policy and firm-level assessments.

Economic complexity and the circular economy

The link between economic complexity and the circular economy is increasingly viewed as important for strengthening sustainability and resource-efficiency outcomes. Economic complexity reflects the sophistication of a country's productive capabilities and embedded knowledge, and it is often considered a facilitator of CE initiatives by enabling more efficient resource use and strengthening innovation capacity for sustainable practices (Hassan et al., 2023). Transitioning toward a CE requires structural change in how economies operate, including the incorporation of complex knowledge and technologies that can support sustainable growth pathways (Montiel-Hernandez et al., 2024).

Recent empirical studies identify economic complexity as a catalyst for environmental innovation within CE frameworks. Ha (2023) finds that countries with higher economic complexity tend to invest more in environmental innovation, thereby expanding their capacity to implement circular practices. Similarly, Ma et al. (2022) report a strong association between economic complexity and resource efficiency, implying that more complex economies may be better positioned to achieve sustainability-related development objectives. Beyond innovation and efficiency, economic complexity may also shape social norms and cultural orientations toward sustainability. Lapatinas et al. (2021) demonstrate that rising economic complexity is associated with stronger citizen engagement in environmental initiatives, suggesting that complex economic structures may cultivate a broader culture supportive of CE practices at both individual and organizational levels.

However, the relationship between economic complexity and environmental performance is not uniformly positive. Boleti et al. (2021) show that while economic complexity is generally linked with improved environmental outcomes, it may also be associated with adverse effects, including increased air pollution. In a related vein, Bucher et al. (2023) find that in former socialist transition economies, economic complexity may contribute to environmental improvements over time but can intensify pollution pressures in the short run. Kirikkaleli et al. (2023) further suggest that economic complexity can be leveraged to reduce environmental degradation, particularly when coupled with green technologies, implying that policymakers should promote complexity-enhancing strategies that align with sustainability objectives. Evidence from OECD countries also supports a positive association: Lee and Olasehinde-Williams (2024) empirically confirm that economic complexity improves environmental performance, highlighting the relevance of investing in knowledge-intensive sectors. At the global level, Anwar et al. (2024) emphasize that economic complexity can also exacerbate environmental degradation in lower-income settings and underline the role of renewable energy in improving environmental quality. Moreover, Albizzati et al. (2024) and Belleflamme and Ha (2024) note that recycling although central to CE may generate negative environmental externalities, reinforcing the need for careful evaluation of circular strategies and their net impacts.

Digitalization and the circular economy

Digitalization is increasingly recognized as a crucial factor in the transition toward a circular economy, as reflected by the expanding literature on the topic. Many scholars argue that digitalization can accelerate CE implementation by facilitating the movement from linear production systems to more sustainable closed-loop models (Alsaggaf, 2024; Mishra et al., 2024). Realizing this transformation typically requires a holistic approach that combines technological advancement with organizational change to operationalize circular principles effectively (Antikainen et al., 2018). Prior studies highlight multiple roles for digital technologies in enabling CE across sectors. Barteková and Borkey (2022) show that tools such as artificial intelligence and the Internet of Things can increase resource-use efficiency, reduce waste, and optimize production processes. Consistently, Liu et al. (2022) provide a comprehensive framework detailing the functions of digital technologies that are especially relevant to CE advancement. Afolabi (2023) similarly identifies digitalization as an important contributor to sustainability-oriented outcomes.

Within the European Union, the digitalization–CE relationship is particularly salient. Gil-Lamata et al. (2024) use cluster analysis to evaluate how digitalization influences circular behaviours among EU member states and find that countries exhibiting strong CE performance often share comparable levels of digital development, implying that robust digital infrastructure can be an enabling condition for successful CE implementation. Nevertheless, the practical deployment of digitalization for CE faces challenges, including data management constraints and the need for stronger coordination among stakeholders (Antikainen et al., 2018). Mügge et al. (2024) also emphasize that implementing digital twins requires continuous information flows and adaptive capabilities, even though this technology offers substantial potential for monitoring and optimizing circular practices throughout product life cycles. Aral et al. (2024) further stress that digital technology adoption differs between developed and developing economies and that local conditions must be understood to deploy digitalization effectively for circular practices. At the same time, critics argue that CE interventions such as recycling and eco-design may generate rebound effects, whereby efficiency gains are offset by increased output and consumption, limiting net environmental improvements (Lowe et al., 2024). Digitalization may also create similar dynamics if efficiency gains lower costs, stimulate demand, and ultimately increase total resource use. Distefano et al. (2024) illustrate this broader limitation by showing that although some high-income regions experience relative decoupling (GDP rising faster than resource use), absolute decoupling sufficient to meet sustainability targets remains difficult to achieve.

Another concern highlighted in the literature is the potential for greenwashing. Greenwashing refers to misleading claims in which firms portray products, services, or policies as environmentally friendly primarily to gain consumer trust and competitive advantage (Choudhury et al., 2023). In the CE–digitalization context, greenwashing can occur when organizations overstate the environmental benefits of digital initiatives while downplaying their environmental costs. Digitalization can be energy-intensive, which may conflict with CE objectives that emphasize energy efficiency and resource conservation (Fasi, 2024). While technologies such as AI, IoT, and blockchain can support transparency and efficiency, they may also entail substantial environmental burdens, including high energy consumption, e-waste generation, and additional carbon emissions. Firms may publicize recycling or tracking improvements enabled by digital tools without addressing upstream drivers such as overproduction, excessive resource extraction, or unsustainable business models. Moreover, an overreliance on recycling can itself become a vehicle for greenwashing if it shifts responsibility toward consumers rather than strengthening producer accountability for reducing material demand (Raasens & van Leeuwen, 2024). Although digital technologies can support CE goals, they may be deployed primarily for reputational benefits if not grounded in genuine environmental intent (Kushch et al., 2024). Minimizing greenwashing therefore requires transparent implementation, measurable impact assessment, and alignment with systemic changes that prioritize substantive sustainability outcomes rather than superficial technological adoption (Choudhury et al., 2023).

Research gaps and hypotheses

In response to rising concerns about resource efficiency and environmental sustainability, research increasingly seeks to identify mechanisms that can accelerate the transition toward a circular economy. Numerous studies have examined CE drivers (Lapatinas et al., 2021; Liu et al., 2023; Neves et al., 2024); however, several gaps persist. First, although prior work has considered the roles of digital orientation, eco-innovation, economic complexity, digitalization, technological progress, and renewable energy, the literature remains dominated by qualitative studies, with fewer contributions adopting quantitative designs (Pichlak & Szromek, 2022; Peyravi & Jakubavicius, 2022). Second, many studies use limited proxies for circularity and digitalization, which may not adequately represent their multidimensional scope. Third, existing research has not sufficiently examined disparities in eco-innovation, economic complexity, and digitalization across EU member states or evaluated how these differences shape CE effectiveness (Antikainen et al., 2018; Aral et al., 2024; García-Castillo et al., 2024). As a result, much evidence remains aggregated and does not capture heterogeneous effects across different stages of CE development.

This study addresses these limitations by constructing composite indices for CE and digitalization using multiple indicators, providing a more holistic measurement strategy. It also evaluates EU cross-country disparities in eco-innovation, economic complexity, and digitalization and examines their implications for CE progress by employing Method of Moments Quantile Regression (MMQR) to estimate effects across different quantiles of the CE distribution. This design explicitly incorporates heterogeneity that is often overlooked in prior studies. In addition, to engage the rebound-effect debate, the study assesses the direct effects of eco-innovation, economic complexity, and digitalization on CE outcomes and investigates how these relationships vary across levels of CE development. In doing so, the analysis contributes to understanding when these drivers support genuine resource reduction and when rebound dynamics may limit their effectiveness. On this basis, the study tests the following hypotheses:

H$_1$. *Eco-innovation significantly improves CE performance in EU countries, but its effect is heterogeneous across stages of CE development in the EU.*

H$_2$. *Economic complexity has a positive impact on CE outcomes, with heterogeneous effects across the EU.*

H$_3$. *Digitalization significantly advances CE, but the magnitude of its impact differs across EU countries.*

These hypotheses are evaluated using POLS, DKSE, and MMQR. In particular, MMQR enables quantile-specific estimation while accounting for unobserved heterogeneity in panel data, allowing the study to assess both overall effects and variation across countries at different levels of CE development. Eco-innovation, economic complexity, and digitalization are specified as the explanatory variables, while CE is treated as the dependent variable.

This study is grounded in Schumpeterian innovation theory, which conceptualizes innovation as a key engine of economic development and structural transformation, primarily through creative destruction the replacement of obsolete technologies and economic structures with newer and more efficient ones (Schumpeter, 1950; Yoguel et al., 2013). In Schumpeter's view, innovation is an evolutionary force that continuously reshapes economic systems and generates new development trajectories. The circular economy (CE) can be interpreted as such a trajectory, as it requires broad-based, system-wide innovation across sectors supported, in particular, by digitalization and economic complexity. A central proposition of Schumpeterian theory is that innovation disrupts established systems and drives economic change. Within the CE paradigm, eco-innovation represents this disruptive mechanism by introducing new products, services, and processes that reduce environmental impacts, limit waste generation, and optimize resource utilization (Usman et al., 2024). In doing so, eco-innovation challenges conventional resource-intensive models and encourages industries to adopt more sustainable practices.

Schumpeter also emphasized that innovation is shaped not only by entrepreneurs but also by the broader industrial environment and macroeconomic structures. Accordingly, economies characterized by higher productive sophistication (economic complexity) and stronger technological capability (digitalization) are more likely to adopt and diffuse innovations that facilitate CE transitions (Ha, 2023; Montiel-Hernandez et al., 2024). Building on this theoretical framing, the baseline empirical model is specified as follows:

$$CEit = \phi 0 + \phi 1 \ln (ECIN)_{it} + \phi 2 ECOM_{it} + \phi 3 DIG_{it} + \varepsilon_{it} \quad (1)$$

where CE denotes the circular economy measure, ECIN represents eco-innovation, ECOM refers to economic complexity, DIG captures digitalization, ϕ_0 is the intercept, ϕ_1–ϕ_3 are parameters, ε is the error term, and i and t index countries and time, respectively. Eco-innovation is transformed using the natural logarithm (ln) to interpret coefficients as elasticities and to align ECIN with other regressors expressed in percentage terms. The inclusion of these variables follows their theoretical and empirical relevance in prior work. Eco-innovation has repeatedly been identified as fundamental for CE transitions because it supports resource efficiency, waste minimization, and sustainable production through technological and organizational change (Pichlak & Szromek, 2022; Liu et al., 2023). Economic complexity is also linked to a country's absorptive capacity for advanced innovations, with higher complexity associated with stronger CE progress (Lapatinas et al., 2021; Ha, 2023). Finally, digitalization can facilitate CE by enhancing data transparency, coordination, and system-level optimization, particularly in advanced economies (Gil-Lamata et al., 2024; Liu et al., 2022).

To account for potential nonlinearity in the digitalization–CE relationship and to test whether higher digitalization always translates into higher circularity, the squared term of digitalization (DIG^2_{it}) is included, yielding:

$$CEit = \phi 0 + \phi 1 \ln (ECIN)_{it} + \phi 2 ECOM_{it} + \phi 3 DIG_{it} + \phi 4 DIG2_{it} + \varepsilon_{it} \quad (2)$$

Empirical analysis

The empirical strategy employs three complementary estimators: Pooled Ordinary Least Squares (POLS), Driscoll–Kraay standard errors (DKSE), and Method of Moments Quantile Regression (MMQR). POLS assumes a stable relationship among variables across the entire sample and treats observations as homogeneous, ignoring unit-specific and time-specific effects. In this study, POLS is used as a baseline benchmark. However, if unobserved heterogeneity matters, the POLS assumption may lead to biased estimates. Moreover, POLS does not address heterogeneity, cross-sectional dependence (CD), or serial correlation, which are common features of panel data.

To improve inference robustness under such conditions, DKSE is applied. DKSE produces standard errors that are robust to heteroskedasticity, autocorrelation, and cross-sectional dependence (Driscoll & Kraay, 1998). It relies on a Newey–West-type correction to the covariance matrix of the estimated coefficients and yields consistent inference even under broad forms of temporal and spatial dependence (Driscoll & Kraay, 1998). Given the interconnectedness of EU economies and the likelihood of policy spillovers, accounting for spatial dependence is essential, making DKSE particularly suitable for this analysis.

Because the key variables exhibit heterogeneity and because effects may differ across levels of CE development, the study further adopts MMQR as introduced by Machado and Silva (2019). MMQR estimates conditional quantiles of CE as a function of eco-innovation, economic complexity, and digitalization, while addressing common concerns such as endogeneity and cross-sectional heterogeneity (Usman et al., 2024). Relative to conventional quantile regression approaches, MMQR leverages moment conditions derived from the data, which can simplify estimation in complex panel structures and improve stability in large samples. Importantly, MMQR can accommodate multiple fixed effects and report location, scale, and quantile effects within a unified framework (Machado & Silva, 2019), thereby strengthening robustness and facilitating simultaneous quantile estimation.

$$Y\rho(X\tau i,t)=\sigma 1+Xi\ t', \xi +(ai +Z'i,t\gamma)Ui,t \qquad (3)$$

Where, in this paper, Yρ (is the CE index, while) Xi,t represents a vector of the predictors. The term ai +Z′i,tγ Ui,t denotes the scale coefficient, with σ1 and ξ as parameters.

Finally, the Dumitrescu–Hurlin (2012) panel causality test is used to examine causal linkages among the variables. This procedure extends the Granger causality framework to heterogeneous panel settings by allowing regression structures and causal relationships to vary across cross-sectional units (Dumitrescu & Hurlin, 2012). A major advantage of the approach is that it can be applied under both cross-sectional dependence and independence, making it appropriate for complex macroeconomic–environmental interactions across heterogeneous countries. The test evaluates the null hypothesis of no Granger causality for all panels against the alternative that causality exists for at least one unit.

As part of preliminary model validation, several diagnostic tests are performed, including correlation analysis, variance inflation factor (VIF), unit root tests, CD tests, slope heterogeneity tests, and cointegration tests. Correlation analysis summarizes the direction and strength of linear associations between variables (bounded between 0 and 1) and informs specification checks. VIF is used to assess collinearity by quantifying how much the variance of an estimated coefficient is inflated by correlation among regressors. It is computed as:

$$\text{VIFj} = \frac{1}{1-R_j^2} \qquad (4)$$

where R^2j is obtained from regressing a given predictor on the remaining predictors. VIF values exceeding 10 indicate serious multicollinearity and may require corrective measures (e.g., removing or adjusting highly correlated regressors) to improve reliability.

Because CE initiatives in one EU member state can influence others through economic integration and shared policy environments, CD is explicitly evaluated using the approach proposed by Pesaran (2004). Conditional on CD evidence, second-generation unit root tests suitable for CD are applied, namely Pesaran's (2007) CIPS and CADF tests, to assess stationarity and avoid spurious regression. Next, slope heterogeneity is tested using Pesaran and Yamagata (2008) under the null hypothesis that slopes are homogeneous; evidence of heterogeneity supports the use of MMQR. Finally, long-run equilibrium relationships among variables are examined using Pedroni's (1999) cointegration test. The overall empirical workflow is summarized in Fig. 1.

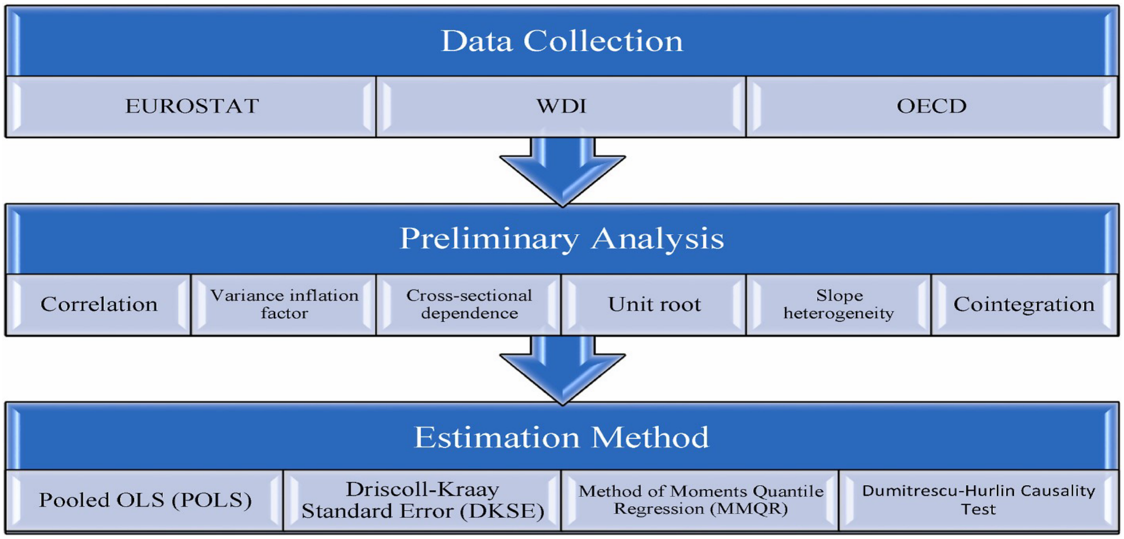

Figure. 1. Summary of methodological approach.

Data sources and variables

To analyze CE advancement in the EU, the study focuses on the effects of eco-innovation, economic complexity, and digitalization across 21 EU countries over 2010–2021, subject to data availability. The countries included are Austria, Belgium, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, the Netherlands, Poland, Portugal, the Slovak Republic, Slovenia, Spain, and Sweden.

Given the multidimensional nature of CE, relying on a single proxy would be inadequate. Following prior studies (Bao & Ha, 2023), the study operationalizes CE using four indicators: circular material use rate, gross value added related to CE sectors, private investment in CE sectors, and municipal waste recycling rate. These indicators are sourced from Eurostat and combined into a composite CE index using Principal Component Analysis (PCA). The PCA results are reported in Appendix Table 1A, and the resulting index ranges from 0 (low CE) to 1 (high CE), reflecting the CE level for each country in the sample.

The country-level outcomes are visualized in Fig. 2, indicating that EU member states are at distinct stages of CE transition. This pattern is consistent with Mazur-Wierzbicka (2021), which identifies Germany, Austria, Belgium, and the Netherlands as leading CE performers, while Greece, the Slovak Republic, Estonia, and Latvia are among the lowest-ranked countries based on CE indicators.

Digitalization is similarly treated as a multidimensional construct. A composite digitalization index is developed from ICT indicators fixed broadband subscriptions, fixed telephone subscriptions, individuals using the internet, mobile cellular subscriptions, and secure internet servers and is constructed using PCA. ICT data are drawn from the World Development Indicators (WDI) database. The digitalization index ranges from 0 (low) to 1 (high), highlighting substantial cross-country heterogeneity in digital development across the EU.

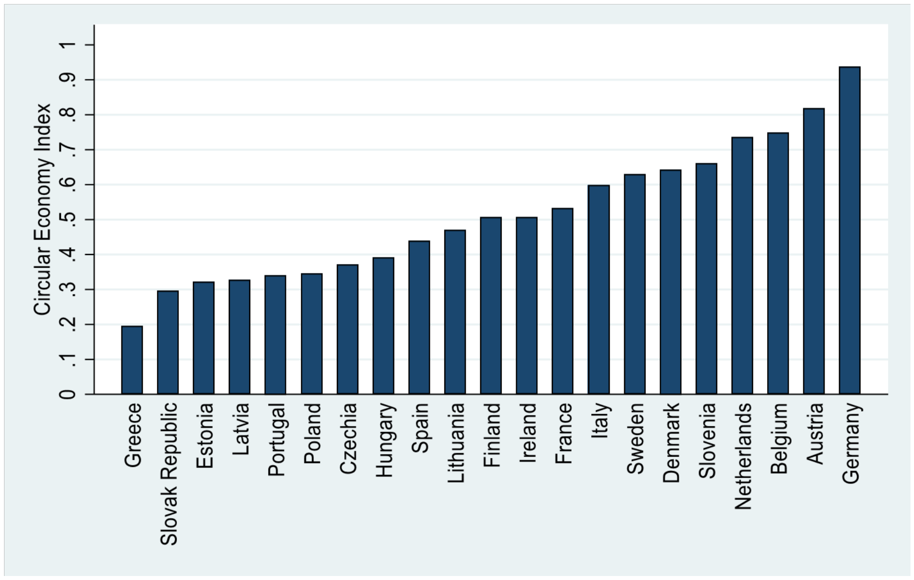

Figure 2. CE index distribution

Table 1. Variable measurement and summary statistics.

Variables	**Measurement**	**Source**	**Obs**	**Mean**	**Std. Dev.**	**Min**	**Max**
Circular Economy	Circular Economy Index	Author	252	0.515	0.219	0	1
Circular material use	Circular material use rate (%)	Eurostat	252	9.533	6.393	1.2	29
Gross value added in CE sectors	Gross value added in circular economy sectors (% of GDP)	Eurostat	252	1.781	0.794	0.5	6.4
Private investment in CE sectors	Private investment in circular economy sectors (% of GDP)	Eurostat	252	0.661	0.353	0.1	1.7
Recycling rate	Recycling rate of municipal waste (%)	Eurostat	252	38.569	14.331	4.9	70.3
Eco-innovation	Development of Environment-related technologies	OECD	252	458.492	987.672	0.500	5200.48
Economic complexity	Economic Complexity (EC) Index	Atlas of EC	252	1.255	0.473	0.020	2.310
Digitalization	Digitalization Index	Author	252	0.656	0.194	0	1
Fixed broadband subscriptions	Fixed broadband subscriptions (per 100 people)	WDI	252	6373230.6	8522826.3	347883	36880564
Fixed telephone subscriptions	Fixed telephone subscriptions (per 100 people)	WDI	252	8137208.7	12404716	192088	52900000

Variables	Measurement	Source	Obs	Mean	Std. Dev.	Min	Max
Internet penetration	Individuals using the Internet (% of the population)	WDI	252	80.154	10.561	44.4	98.866
Mobile cellular subscriptions	Mobile cellular subscriptions (per 100 people)	WDI	252	23897548	28951490	1652809	1.097
Secure internet servers	Secure Internet servers (per 1 million people)	WDI	252	284661.66	822157.77	477	8109646

Eco-innovation is proxied by the development of environment-related technologies, with data obtained from the Organisation for Economic Cooperation and Development (OECD) database. This source provides comprehensive patent-based indicators of innovation in environmental technologies, allowing for an assessment of innovative performance at both the country and firm levels. Data on economic complexity are drawn from the Atlas of Economic Complexity developed by the Harvard Growth Lab. This dataset captures the diversity and sophistication of a country's export structure and reflects its underlying productive knowledge and capabilities by examining the range and complexity of exported products (Atlas of Economic Complexity, 2022).

Table 1 summarizes the variables, data sources, and descriptive statistics. The mean value of the CE index (51.5%) indicates that, on average, EU member states have achieved slightly above-moderate progress toward circular economy practices, suggesting a gradual shift toward circularity. However, substantial variation exists across countries. The minimum and maximum values of eco-innovation reveal a clear distinction between innovation leaders and follower countries within the EU. Similar disparities are observed for eco-innovation and digitalization, highlighting differences between highly advanced and digitally intensive economies and those with less sophisticated productive structures. This uneven development implies that while some EU countries are at the forefront of sustainability-oriented innovation and digital transformation, others continue to lag behind. Such heterogeneity is likely to influence the pace and effectiveness of CE advancement across the region.

Figure 3 provides a visual representation of the temporal trends in the main variables for each sampled country, further illustrating cross-country differences in CE performance, eco-innovation, economic complexity, and digitalization over the study period.

3. Result & Discussion

Diagnostic test results

Figure 4 presents the correlation matrix describing the relationships among the circular economy (CE), eco-innovation, economic complexity, and digitalization. The associated scatter plots indicate upward-sloping patterns between CE and each of the three explanatory variables, suggesting positive correlations overall, albeit with varying strengths. In particular, CE exhibits a strong positive association with eco-innovation, implying that countries with higher levels of eco-innovative activity tend to demonstrate more advanced engagement in circular economy practices. By contrast, economic complexity and digitalization display moderate positive correlations with CE, indicating that countries characterized by more sophisticated and diversified production structures, as well as stronger digital capabilities, are generally more likely to exhibit higher levels of circularity.

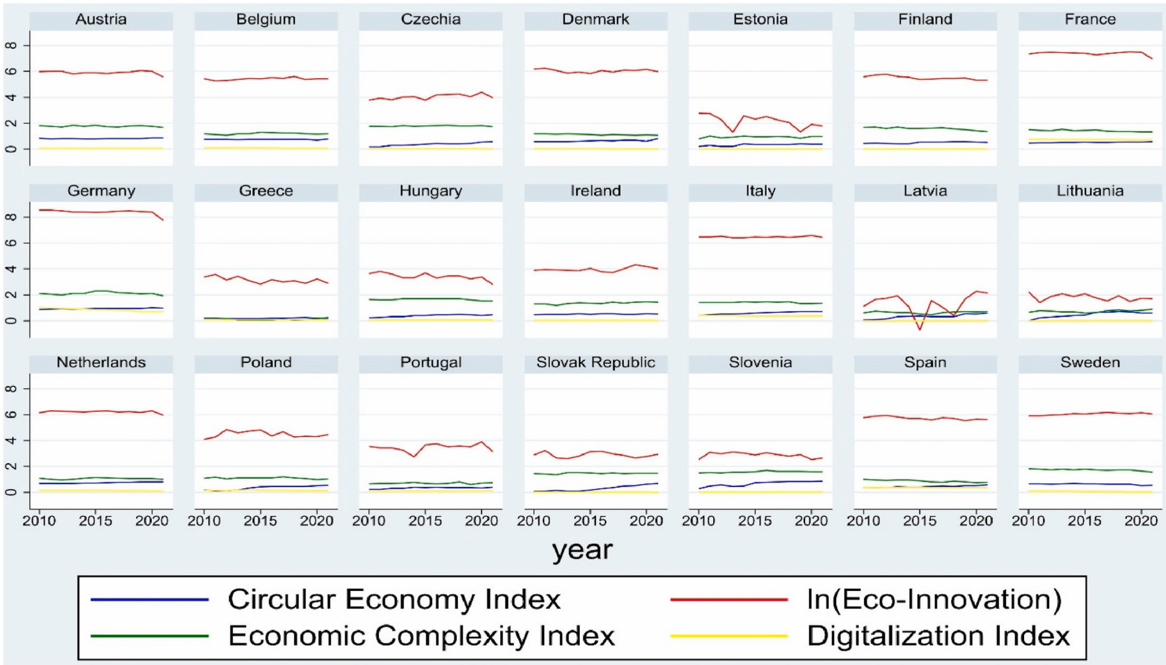

Figure 3. Trend of key variables.

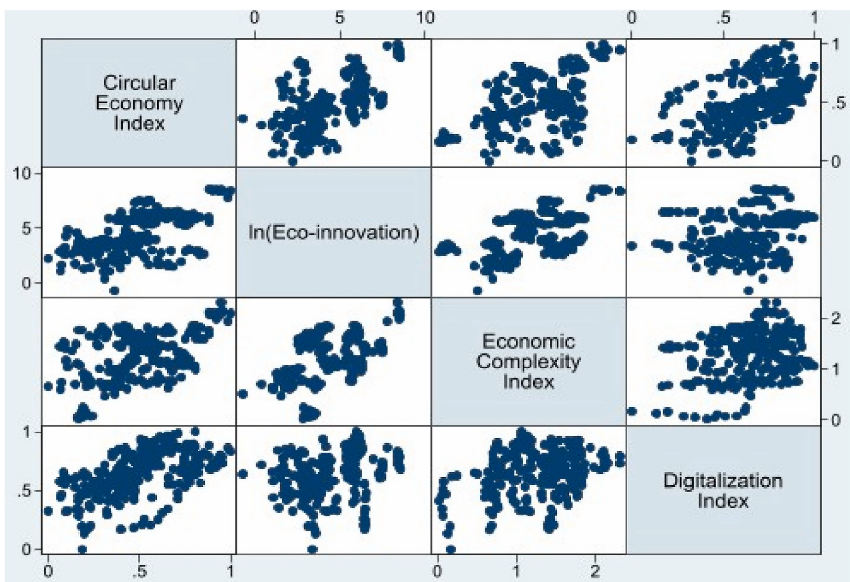

Figure 4. Correlation matrix.

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

Table 2 .Results of variance inflation factor, unit root, and CD tests.

Variable	**VIF**	**1/VIF**	**CIPS (Level)**	**CIPS (1st Diff.)**	**CADF (Level)**	**CADF (1st Diff.)**	**CD Test (Pesaran, 2004)**
CE	–	–	−2.405***	−3.151***	−0.254	−2.369***	26.370***
ln(Eco-innovation)	1.391	0.719	−2.010	−3.447***	0.332	−3.811***	3.940***
Economic complexity	1.399	0.715	−1.799	−3.388***	−1.603	−4.319***	4.280***
Digitalization	1.123	0.890	−2.998**	−4.075***	−2.834***	−5.585***	22.480***

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

Table 2 reports the results of the variance inflation factor (VIF), unit root, and cross-sectional dependence (CD) tests. The VIF values and their inverses are shown in the second and third columns, the unit root test outcomes are reported in columns four to seven, and the CD test results appear in the final column. The VIF statistics are used to detect potential multicollinearity, which could otherwise bias coefficient estimates and undermine reliability. The reported values indicate that multicollinearity is not a concern, as all VIFs and their inverses fall well below the commonly accepted thresholds of 10 and 5, respectively. Consequently, including CE, eco-innovation, economic complexity, and digitalization jointly in the empirical model is unlikely to distort estimation results.

The CD test results lead to rejection of the null hypothesis of cross-sectional independence (CD ~ N(0,1)), suggesting that shocks or changes in CE, eco-innovation, economic complexity, and digitalization in one EU country may spill over to others. In light of this dependence, second-generation unit root tests that explicitly account for CD namely the CIPS and CADF tests are employed instead of conventional approaches. The outcomes from these tests are broadly consistent: eco-innovation and economic complexity are non-stationary at levels, whereas digitalization exhibits level stationarity. However, mixed evidence emerges for CE, which appears level-stationary under the CIPS test but only stationary in first differences under the CADF test. This combination of results points to the potential existence of long-run relationships among the variables.

Table 3. Slope heterogeneity and cointegration test results.

Statistic	Slope Homogeneity	Pedroni Cointegration	
Delta	7.297***	Gt Modified Phillips-Perron t	4.151***
Adj. Delta	9.554***	Phillips-Perron t	− 1.165
		Augmented Dickey-Fuller t	− 1.891**

Table 3 presents the findings from the slope heterogeneity and cointegration analyses. The slope heterogeneity test assesses whether the estimated coefficients for eco-innovation, economic complexity, and digitalization are uniform across EU member states. The statistically significant delta and adjusted delta statistics lead to rejection of the null hypothesis of slope homogeneity, confirming the presence of cross-country heterogeneity. This implies that the effects of eco-innovation, economic complexity, and digitalization on CE differ across EU countries. Despite economic integration and policy coordination within the EU, member states therefore display distinct structural and developmental dynamics that shape CE outcomes in different ways. Such heterogeneity justifies the application of the MMQR approach, which is well suited to capturing distributional and country-specific effects.

Finally, the Pedroni cointegration test which accommodates both cross-sectional dependence and heterogeneity provides strong evidence of cointegration among CE, eco-innovation, economic complexity, and digitalization. This result indicates that the variables share a stable long-run equilibrium relationship across EU countries, reinforcing the relevance of a long-term analytical perspective in assessing CE dynamics.

Main estimation

The empirical relationship between eco-innovation, economic complexity, and digitalization and the circular economy (CE) is examined using the Pooled Ordinary Least Squares (POLS) and Driscoll–Kraay standard error (DKSE) estimators. Each explanatory variable is initially evaluated separately before being jointly included in a unified specification. This stepwise approach allows for an assessment of estimate robustness and helps determine whether the results are sensitive to alternative model specifications. The estimation outcomes are reported in Table 4, where POLS results are presented in columns (1)–(5) and DKSE results in columns (6)–(10).

Table 4. Results of POLS and DKSE estimation.

Variables	**(1) POLS**	**(2) POLS**	**(3) POLS**	**(4) POLS**	**(5) POLS**	**(6) DKSE**	**(7) DKSE**	**(8) DKSE**	**(9) DKSE**	**(10) DKSE**
ln(Eco-innovation)	0.045*** (0.014)			0.028**(0.013)	0.026*** (0.013)	0.070*** (0.008)			0.046*** (0.008)	0.045***(0.008)
Economic complexity		0.195*** (0.061)		0.117**(0.053)	0.123**(0.053)		0.239*** (0.008)		0.095*** (0.028)	0.097***(0.027)
Digitalization			0.630*** (0.047)	0.627*** (0.046)	0.420**(0.174)			0.621*** (0.034)	0.428*** (0.043)	0.352***(0.090)
Digitalization²					0.185(0.149)					0.064(0.079)
Constant	0.306*** (0.073)	0.270**(0.084)	0.101**(0.048)	−0.171**(0.081)	−0.120(0.092)	0.191**(0.067)	0.215*** (0.037)	0.107*** (0.029)	−0.095**(0.037)	−0.075* (0.038)
Number of obs.	252	252	252	252	252	252	252	252	252	252
Overall R-squared	0.365	0.266	0.302	0.518	0.517	0.365	0.266	0.302	0.551	0.551
Chi-square	9.967	10.214	180.646	200.371	201.92	78.74	800.78	333.45	869.46	624.98
Prob > χ^2	0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Standard errors are reported in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

The higher coefficient of determination observed in the multivariate models relative to the bivariate specifications indicates that the combined inclusion of eco-innovation, economic complexity, and digitalization explains a greater share of the variation in CE. This finding suggests that the joint effects of these factors are more influential in shaping CE outcomes than when each determinant is considered in isolation.

The results consistently show that eco-innovation exerts a statistically significant and positive effect on CE development in the EU. Specifically, the POLS estimates indicate that a 1% increase in eco-innovation is associated with an improvement in CE of approximately 0.03%–0.05%, while the DKSE estimates suggest a slightly larger effect, ranging from about 0.05% to 0.07%. Taken together, these results demonstrate that eco-innovation plays a substantive role in promoting circularity, implying that broader adoption of eco-innovative practices can significantly strengthen CE performance across EU member states. This effect is consistent with the role of eco-innovation in enabling closed-loop systems that reduce waste through recycling, reuse, and material recovery at the end of product life cycles core principles of the CE framework (Maldonado-Guzman et al., 2021; Pichlak & Szromek, 2022; Thakker & Bakshi, 2023). Eco-innovation also supports the design of more durable, repairable, and upgradeable products, thereby extending product lifespans and reducing demand for virgin materials, manufacturing inputs, and waste generation.

These dynamics are particularly evident in countries such as Austria, Belgium, Denmark, Germany, Slovenia, and the Netherlands, where advances in recycling technologies have improved the recovery of metals, plastics, and electronic components from end-of-life products (European Environment Agency, 2023). Germany's waste-to-energy (WtE) facilities provide a prominent example of how advanced technologies can convert municipal waste into usable energy while simultaneously recovering valuable materials. Municipal solid waste incineration plants, refuse-derived fuel facilities, and hazardous waste incineration plants increasingly rely on sophisticated incineration technologies to transform waste streams into energy outputs (Weber et al., 2020). These findings are consistent with García-Castillo et al. (2024), who argue that eco-innovation facilitates the emergence of new business models that prioritize maximizing the use of existing products rather than expanding production of new goods.

In a similar vein, economic complexity is found to have a positive and statistically significant impact on CE. The POLS estimates indicate that a 1% increase in economic complexity is associated with a CE improvement of approximately 0.12%–0.20%, while the DKSE estimates place the effect between about 0.10% and 0.24%. The consistency of these estimates across methodologies underscores the importance of economic complexity in supporting CE advancement in the EU. Higher levels of economic complexity appear to promote more efficient resource utilization and foster sustainable production and consumption patterns, which are closely aligned with CE principles. This result supports earlier evidence suggesting that economic complexity enhances innovation capacity, facilitates knowledge diffusion, and encourages the development of advanced, resource-efficient industries that underpin circular transitions (Lapatinas et al., 2021; Hassan et al., 2023).

Finally, the findings identify digitalization as a key driver of CE progress. Among the explanatory variables, digitalization exhibits the largest and most consistently significant positive effect on CE, highlighting its central role in enabling circular practices and reinforcing the importance of digital transformation in accelerating the EU's transition toward a circular economy.

Table 5. Results of MMQR estimation

Variables	**Location**	**Scale**	**Q = 0.25**	**Q = 0.50**	**Q = 0.75**
ln(Eco-innovation)	0.046***(0.006)	−0.012***(0.003)	0.056***(0.006)	0.047***(0.006)	0.035***(0.007)
Economic complexity	0.095***(0.023)	−0.070***(0.013)	0.036(0.023)	0.087***(0.024)	0.166***(0.028)
Digitalization	0.428***(0.047)	−0.035(0.026)	0.458***(0.048)	0.432***(0.047)	0.395***(0.057)
Constant	0.095***(0.033)	−0.108***(0.018)	−0.187***(0.034)	−0.107***(0.034)	0.006(0.041)
ln(Eco-innovation)	0.045***(0.007)	−0.010***(0.004)	0.053***(0.006)	0.046***(0.007)	0.036***(0.008)
Economic complexity	0.097***(0.025)	−0.064***(0.015)	0.044*(0.024)	0.089***(0.025)	0.155***(0.032)
Digitalization	0.352***(0.190)	−0.221***(0.111)	0.168(0.183)	0.325*(0.188)	0.555***(0.244)
$Digitalization^2$	0.064(0.162)	−0.212**(0.095)	0.240(0.154)	0.090(0.160)	0.131(0.207)
Constant	−0.075(0.056)	0.038(0.033)	−0.107**(0.054)	−0.080(0.055)	0.004(0.072)

Standard errors are reported in parentheses.
*** p < 0.01, ** p < 0.05, * p < 0.10.

Consistent with earlier results, digitalization emerges as the most influential driver of CE advancement. On average, a 1% increase in digitalization leads to an approximate 0.43% improvement in CE across the distribution. Notably, the effect of digitalization is strongest at the lower end of the CE distribution: at the 25th percentile, a 1% increase in digitalization is associated with a 0.46% increase in CE, compared to a 0.43% increase at the median and a 0.40% increase at the 75th percentile. These findings suggest that digitalization can substantially enhance CE performance in the EU by improving resource-use efficiency, optimizing production and consumption processes, increasing supply-chain transparency, and facilitating the emergence of innovative circular business models (Barteková & Borkey, 2022; Usman et al., 2024). Importantly, the consistently positive effects across quantiles indicate that digital transformation is a critical lever for advancing CE regardless of a country's existing level of circularity.

By contrast, the squared digitalization term displays a negative scale coefficient and an insignificant positive effect across quantiles, implying that although the impact of digitalization may increase at a diminishing or stable rate, the overall relationship between digitalization and CE remains approximately linear within the observed range. Overall, the MMQR results closely mirror those obtained from the POLS and DKSE estimations, underscoring the robustness and consistency of the empirical findings and reinforcing their suitability for informing policy decisions. Taken together, the results provide empirical support for accepting the hypotheses formulated earlier in the study.

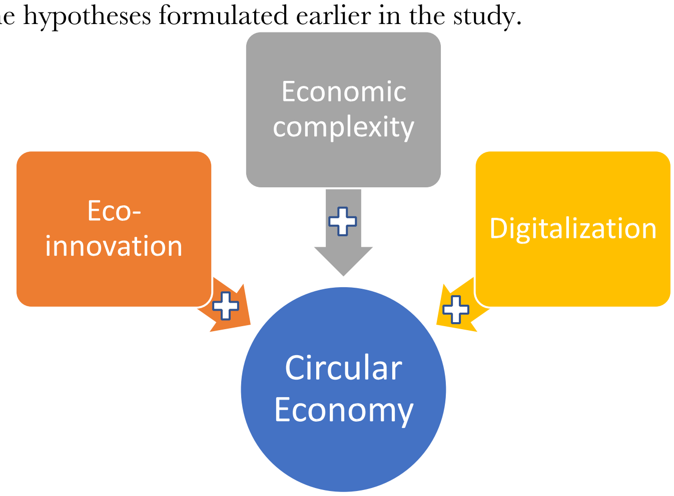

Figure 5. Summary of empirical results across estimation methods

The results of the Dumitrescu–Hurlin panel Granger causality test, reported in Table 6, shed further light on the dynamic relationships between CE and the key explanatory variables. The findings reveal a bidirectional causal relationship between eco-innovation and CE, although the reverse causality running from CE to eco-innovation is stronger and more statistically significant. This suggests that as circular principles become increasingly embedded within economic systems, they may stimulate additional innovation efforts aimed at closing material loops and reducing environmental impacts. In addition, the analysis identifies a unidirectional causal relationship from economic complexity to CE, with borderline statistical significance, indicating that economies with more diversified and knowledge-intensive production structures are better positioned to adopt and sustain circular strategies. Most notably, the results indicate a strong bidirectional causality between digitalization and CE, with both directions exhibiting high statistical significance. This mutual causality points to a reinforcing and dynamic interaction, whereby digital technologies facilitate the scaling up of circular practices, while the expansion of CE activities, in turn, creates further demand for digital solutions.

Table 6. Dumitrescu–Hurlin causality test

Null Hypothesis	Z-bar	Prob.
Eco-innovation does not Granger-cause CE	1.899*	0.058
CE does not Granger-cause eco-innovation	3.192***	0.001
Economic complexity does not Granger-cause CE	1.924*	0.054
CE does not Granger-cause economic complexity	1.401	0.161
Digitalization does not Granger-cause CE	6.553***	0.000
CE does not Granger-cause digitalization	4.474***	0.000

*** $p < 0.01$, * $p < 0.10$.

4. Conclusions

The European Union (EU) is widely regarded as a global frontrunner in advancing the circular economy (CE), yet progress toward full circularity has remained relatively slow. Motivated by the objective of supporting the EU in achieving the targets of the Circular Economy Action Plan (CEAP) by, or no later than, 2035, this study provides new empirical insights into the roles of eco-innovation, economic complexity, and digitalization in promoting CE. By extending Schumpeterian innovation theory to the CE context, the study emphasizes that innovation should not only stimulate economic growth but also enhance resource efficiency, reduce waste, and enable systemic sustainability. Using POLS, DKSE, and MMQR estimators on panel data from 22 EU countries over the period 2010–2021, the findings identify eco-innovation, economic complexity, and digitalization as key drivers of CE across the EU. Although all three factors exert positive effects, their impacts are heterogeneous across CE levels. Eco-innovation plays a stronger role at lower stages of CE development, economic complexity becomes more influential in advanced circular economies, and digitalization consistently promotes CE improvement across all performance levels, emerging as the most influential driver overall. These results underscore the importance of adopting context-specific strategies to promote CE, particularly in countries with relatively low levels of circularity.

The findings have important policy implications for accelerating CE transitions in the EU, where institutional, economic, and socio-political heterogeneity limits the effectiveness of uniform policy approaches. EU-wide strategic coordination should therefore be complemented by differentiated national and regional implementation pathways. Policies that strengthen digital infrastructure and the diffusion of digital technologies are essential for improving resource tracking, production efficiency, and supply-chain transparency, although less developed economies may first require foundational investments in digital skills, connectivity, and SME support. At the same time, fostering economic complexity through industrial diversification, education, and innovation ecosystems can enhance countries' capacity to adopt circular practices, particularly in more advanced economies. Increased investment in eco-innovation through R&D funding, technology transfer, green entrepreneurship, and public–private partnerships is especially critical for countries at earlier stages of CE adoption, while advanced performers should focus on scaling successful innovations, improving recycling technologies, and strengthening regulatory frameworks that reward circular business models. Despite these contributions, this study has limitations. It focuses on 22 EU countries and three main CE drivers over the 2010–2021 period. Future research could expand the analysis to all EU member states, incorporate additional variables such as green finance or policy instruments, and conduct sector-specific investigations to capture industry-level dynamics. Further work could also examine the roles of consumer behavior, cultural attitudes, social resistance, and multinational corporations in shaping CE adoption, as well as test whether the relationships identified in this study hold in other regions, including North America, Asia, and emerging economies.

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