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ARTICLE

Economic and technological determinants of circularity: Panel data evidence from EU-27 member states

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ABSTRACT

To address growing resource constraints and the environmental problems of linear production and consumption, the transition to a circular economy has become a global priority for sustainability. The study examines whether resource productivity, fixed broadband subscriptions, research and development (R&D) expenditure, and employment in circular economy sectors are associated with the circular material use rate in the EU-27. The study estimated a fixed-effects panel model with country-clustered robust standard errors for 27 EU member states over 2014–2023 (270 observations). Resource productivity and fixed broadband subscriptions were positively and significantly associated with circularity, while R&D expenditure and employment in circular economy sectors were not statistically significant. The results suggest that resource-use efficiency and digital connectivity are associated with higher circularity, while the effects of R&D and circular-sector employment may depend on factors not captured in the model. The findings point to the relevance of resource efficiency and digital infrastructure for circularity policy.

INTRODUCTION

The circular economy (CE) has emerged as a model for sustainable development that replaces the linear approach with a regenerative system built on recycling, reuse, and waste reduction (Kirchherr et al., 2023). Conceptually, CE links economic, environmental, and technological dimensions across production and consumption and seeks to decouple material use from economic growth. The growing threats of resource scarcity, climate change, and pollution have made the circular economy a leading model for addressing them while balancing economic, social, and environmental aims (Hoang et al. 2026). Bag et al. (2022) argue that CE is not merely a green solution but also a catalyst for sustainable growth through lower dependence on primary resources.

The CE approach, which aims to optimise resource use, minimise waste, and foster economic resilience, aligns with the priorities of the European Union (EU) (Churikanova and Tykhoplav 2025). The shift to a circular economy is expected to create jobs and support economic progress (Robaina et al. 2020). The Ellen MacArthur Foundation (2013) reported that a circular economy could raise Europe's annual resource productivity growth by up to 3 percentage points. A growing CE could create jobs by reducing the structural mismatch in high-unemployment regions of Europe (Mitchell and James 2015). Implementing circular practices in the EU could create up to 3 million jobs by 2030 (Mitchell and James 2015).

CE research has accelerated exponentially across global bibliometric databases over the past two decades (Goyal et al. 2020; Fafalios and Tsagarakis 2026). Bibliometric and metadata evaluations establish that the European Union leads international scientific output, representing approximately 58% of global circularity publications due to concentrated policy frameworks like the Circular Economy Action Plan (Garcilazo-Lopez et al. 2026; Türkeli et al. 2018). Empirical analysis has advanced in recent years, yet important gaps persist. For example, Kostakis and Tsagarakis (2022) examined economic drivers (resource productivity, entrepreneurship) and environmental drivers (recycling infrastructure) without fully integrating technological ones such as digitalisation and innovation capacity. Georgescu et al. (2025) highlighted the importance of infrastructure and technological advancements in supporting circularity, but their

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KEYWORDS

circular economy, panel data, resource productivity, circularity rate

model omits digital connectivity and labour enablers. The present study differs by extending their model specification to include circular sector employment, operationalising the technological indicator through fixed broadband subscriptions, and applying the fixed effects estimation approach to control for unobserved, time-invariant heterogeneity across panel units.

This gap motivates the present study, which uses panel data to examine how economic and technological factors are related to the circular material use rate across the EU-27. The study makes two contributions to the current field of study. First, it links CE to economic performance and to indicator of digital connectivity and circular sector employment within one framework. Second, it applies a fixed effects estimation approach to country-level panel data in estimating relationships from changes within each country over time while accounting for persistent country-specific characteristics. The findings may help policymakers design effective and efficient interventions that support sustainable growth.

Section 2 reviews the literature on the economic and technological determinants of circularity. Section 3 describes the data, variables, and estimation methods. Section 4 presents and discusses the results. Section 5 summarises the findings, discusses policy implications and limitations, and suggests directions for future research.

LITERATURE REVIEW

This study draws on endogenous growth theory, which holds that long-run economic performance depends mainly on knowledge creation, innovation, technological progress, and human capital rather than on the accumulation of physical inputs alone (Romer 1990; Lucas 1988). Within this framework, technological infrastructure, research activity, and skilled labour are treated as productive assets that enhance the efficiency with which economies transform resources into value. This perspective allows circularity to be treated as an economic outcome as well as an environmental objective. Resource productivity, a central explanatory variable here, measures how much output an economy generates per unit of material input, which fits the endogenous-growth view that technology and knowledge enable more efficient production (Aghion and Howitt 1990). Likewise, R&D spending and digital infrastructure help knowledge spread across industries and promote innovation in resource management, production, and monitoring (Li et al. 2024; Cainelli et al. 2020). On this view, economies that have integrated innovation, digitalisation, and human capital into production can decouple value creation from material consumption and may therefore have higher circular material use (Kostakis and Tsagarakis 2022).

Innovation systems theory adds that skills, institutions, technological capacity, and knowledge diffusion interact to shape structural change (Freeman, 1987; Lundvall, 1992; Nelson, 1993). Innovation arises from networks of people, infrastructure, and capabilities rather than in isolation. Nations with more advanced innovation systems are better placed to adopt circular business models, improve material-recovery technologies, and apply eco-design (Sehnem et al. 2021; Fogarassy and Finger 2020). The operational and human-capital side of the system is represented here by employment in circular economy sectors. This indicates how far circular activities are embedded in the real economy through specialised activities and skilled labour.
Digital connectivity can also improve coordination and knowledge exchange along value chains, allowing material flows to be tracked in real time and circular processes to be scaled up (Liu et al. 2023). Because circular performance depends on how well national innovation systems support technological adaptation, knowledge diffusion, and labour participation in resource-efficient activities, innovation systems theory offers an explanation for differences between countries. Taken together, these theories suggest that circularity is a structural feature of developed, knowledge-based, innovative economies.

Recent empirical research on the drivers of circular-economy performance increasingly focuses on technological and economic factors in European countries. These studies use various panel-data methods to relate circular material use to infrastructure, efficiency, and innovation. Economic efficiency, especially resource productivity, has been a major focus of empirical research as a facilitator of circularity. In a panel of 26 EU countries for the 2000-2016 period, Robaina et al. (2020) found that environmental tax revenues and industry share were negatively associated with resource productivity across the growth groups, whereas population density and services-sector share were positively associated. The results for other factors varied by group: R&D was positively associated with resource productivity in the low- and medium-growth groups but negatively associated in the high-growth group; recycling was negative in the low-growth group and positive in the medium- and high-growth groups; and renewable energy was negative in the low- and medium-growth groups but positive in the high-growth group. This heterogeneity suggests that the associations between these factors and resource productivity differ with countries' resource productivity-growth profiles. The broader model of Georgescu et al. (2025) for the EU-27 also identified resource productivity as the most robust determinant of circularity and interpreted it as a structural expression of knowledge-intensive, innovation-driven growth rather than only an environmental indicator.

It is also increasingly recognised that technological infrastructure, especially digital connectivity, facilitates circular behaviour. Using macro-level panel data, Platon et al. (2022) found that high-speed internet coverage is associated with better circularity outcomes, which they link to technologies such as remote flow monitoring, digital marketplaces for secondary materials, and real-time tracking. Galdeano-Gómez and García-Fernández (2024), who built a composite CE indicator and related digital infrastructure to circular performance across EU economies, report similar findings. Both studies treat digitalisation as a core capability that supports the scaling of circular business models, coordination across value chains, and the diffusion of innovation.

R&D spending is another factor frequently examined in empirical work. In longitudinal panel data, Kostakis and Tsagarakis (2022) found that economies with sustained R&D investment have noticeably higher circular material use rates. The authors attribute this to greater absorptive capacity, which lets firms adopt advanced recycling technology, take part in eco-design, and move to circular product-service system (Zheng et al. 2019). Similarly, Bianchi and Cordella (2023) use data from 28 European economies to show that R&D investment is associated with lower material extraction through waste valorisation and substitution. These studies suggest that innovation systems are relevant for the CE transition, especially in developed economies, where incremental innovation may be more feasible than radical change.

In the CE literature, labour-market participation has emerged as a further, less studied dimension alongside economic efficiency and innovation. Llorente-González and Vence (2020) demonstrated through structural analysis of EU circular activities that scaling material recovery requires continuous engagement of the workforce owing to the labour-intensive nature of repair, reuse and

recycling activities. This focus on labour is similarly highlighted by Padilla-Rivera et al. (2020) and Luthra et al. (2022), who emphasised on the importance of human capital and skill development in building the organisational capacity required to operationalise circular practices. Mihai et al. (2018) also argue that the social pillar of the CE model, namely job creation and vocational training in circular industries, is crucial, particularly alongside inclusive policies.

More recent studies use integrated econometric models, whereas earlier work often concentrated on single variables or descriptive correlations. For example, Trica et al. (2019) used panel regression for the EU-28 to build and test a CE sustainability index that combined technological, environmental, and economic indicators. Fortea et al. (2026) extended the study by modelling the two-way dynamics between CE innovation and macroeconomic performance with a panel vector autoregression (PVAR). These system-level approaches reflect a growing recognition that CE outcomes are embedded in wider institutional and structural settings.

Although prior studies have examined economic, technological, and environmental determinants of circular material use, the studies reviewed here provide limited evidence on the association of digital connectivity indicator and employment in circular-economy sectors with circular material use when considered alongside resource productivity and R&D in an EU-27 model specification. To address this gap, this study estimates one model in which resource productivity, fixed broadband subscriptions, R&D expenditure, and employment in circular economy sectors are entered together as determinants of the circular material use rate in 27 EU member states from 2019 to 2023. The model also uses fixed effects model estimation with cluster-robust standard errors which are robust to heteroskedasticity and serial correlation issues. By combining efficiency, innovation, digitalisation, and human capital in one model, the study contributes to understanding the structural correlates of circular economy outcomes in the EU.

DATA AND METHODOLOGY

Data and Description of Variables

The study uses a balanced panel of the 27 EU member states (Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden) for 2014-2023, giving 270 country-year observations.

The focus on EU countries reflects data availability: harmonised, comparable circular-economy and macroeconomic indicators are published systematically by Eurostat and World Bank's World Development Indicator for EU member states. The period is limited by data availability: employment in the circular economy sectors is available from 2014 and the latest complete year at the time of analysis was 2023. The sample is treated as a single panel, without stratification by region or income. Table 1 below defines the variables and sources.

Table 1: Measurement of Variables

Variable	Indicator	Measurement	Data Source
Dependent variable	Circularity rate	Circular material use rate: recycled materials fed back into the economy as a share of total material use (domestic material consumption plus recycled material), %	Eurostat
Independent variables	Resource productivity	Gross Domestic Product (GDP) divided by domestic material consumption (DMC), where DMC is the total amount of materials directly used by an economy; unit: EUR per kg, chain-linked volumes	Eurostat
	Technological infrastructure	Fixed broadband subscriptions, per 100 people	World Development Indicators
	R&D expenditure	Gross domestic expenditure on R&D (GERD), all sectors of performance, % of GDP	Eurostat
	Employment in the circular economy sectors	Number of persons employed in three circular-economy sectors (recycling; repair and reuse; rental and leasing)	Eurostat
Control variable	GDP per capita	GDP per capita, current US$	World Development Indicators

The dependent variable, circularity, is measured by the circular material use rate (%): the share of material inputs that are recovered and returned to the economy relative to total material use. The circular material use rate is the standard EU indicator of how far an economy has moved toward circularity, because it tracks how far recycled materials replace primary raw materials (Georgescu et al. 2025; Knable et al. 2022); it does not capture reuse, repair, or lifetime extension. The independent variables are the economic and technological drivers identified in the literature: resource productivity, fixed broadband subscriptions, R&D expenditure, and employment in circular economy sectors. Resource productivity measures how effectively material resources are converted into output and reflects an economy's capacity to improve its environmental and economic performance by using raw materials more efficiently (Mushafiq and Prusak 2023; Robaina et al. 2020). Technological infrastructure, which supports more efficient production and circular business models, is measured by fixed broadband

subscriptions (Bressanelli et al. 2018). Innovation capacity is proxied by R&D expenditure, consistent with the literature on the role of technological innovation in circular practices and sustainable production (Cainelli et al. 2020). Employment in circular economy sectors is included as a proxy for the labour dimension of circularity and for how far circular activities are embedded in national economies. The control variable used in this study is GDP per capita, which is measured in current US dollars.

Model Specification

To examine the association between economic and technological factors and the circular material use rate, we adapt the model of Georgescu et al. (2025) as follows:

$$\ln CIR_{it} = \beta_0 + \beta_1 \ln REP_{it} + \beta_2 \ln FBB_{it} + \beta_3 \ln RND_{it} + \beta_4 \ln EMP_{it} + \beta_5 \ln GDPPC_{it} + \mu_{it}$$

where i indexes countries and t years, CIR is the circular material use rate, REP is resource productivity, FBB is fixed broadband subscriptions, RND is R&D expenditure, EMP is employment in circular economy sectors, GDPPC is GDP per capita; β_0-β_5 are parameters, and μ_{it} is the error term. All variables are in natural logarithms, which makes the coefficients elasticities and reduces the skewness of the variables. Percentage variables (the circularity rate, R&D expenditure and employment in circular economy sectors) were logged in their original percentage units. In this log-log specification, each coefficient is an elasticity: the percentage change in the circularity rate associated with a 1% increase in the corresponding explanatory variable.

Econometric Methodology

The analysis uses a static panel regression. Common panel methods include pooled OLS, fixed effects (FE), random effects (RE), feasible generalised least squares (FGLS), and panel-corrected standard errors (PCSE) (Garg et al. 2025; Ha 2024). Using a panel FE model to assess the determinants of circularity in EU-27 member countries for the years 2014 to 2023 is methodologically sound and commonly applied in European macroeconomic literature (Khan and Osińska 2022; Bianchi and Cordella 2023). The application of the FE model is justified in this study as the sample represents a predetermined group of countries, rather than a random selection from a wider population, so the fixed-effects specification is necessary to address the presence of time-invariant individual effects within the panel (Khan and Osińska 2022; Sabău-Popa et al. 2022). EU economies exhibit structural, geographical, historical, and institutional heterogeneity that governs recycling infrastructure and material consumption patterns (Dincă et al. 2022; Mura and Donath 2023). The FE estimation method employs specific intercepts for each cross-section and eliminates endogeneity associated with omitted time-invariant country-specific characteristics such as administrative culture, geographical endowments, and persistent regulatory frameworks that would likely correlate with macro-level indicators such as GDP per capita, resource productivity, digital infrastructure, and R&D expenditure (Khan and Osińska 2022; Sabău-Popa et al. 2022; Kilinc-Ata and Dolmatov 2022).

Furthermore, across panel empirical investigations examining circular economy metrics, European environmental indicators, and digital penetration, standard specification procedures (such as the Hausman test and information criteria) frequently favour the fixed-effects model to ensure consistent, unbiased within-unit parameter estimates in the presence of unobserved panel heterogeneity (Dincă et al. 2022; Aydınbaş and Erdinç 2023; Khan and Osińska 2022; Mura and Donath 2023; Korica et al. 2020).

Before estimating the fixed effects model, several model-selection and diagnostic tests were conducted. The Breusch-Pagan Lagrange Multiplier (BPLM) test assessed for the presence of individual random effects. The null hypothesis is that the variance of the individual effects is zero (pooled OLS is adequate), against the alternative that individual effects are present. Rejection of the null hypothesis justifies proceeding to a panel estimator (Cheng and Kamaruddin 2024; Nwakuya and Ijomah 2021). Conditional on rejecting poolability, the Hausman test selects between fixed and random effects by comparing the two coefficient vectors (Sani et al. 2023). The null hypothesis is that the appropriate model is random effects, which suggests that there is no correlation between the unobserved individual effect and the explanatory variables; the alternative is that such correlation exists (Sani et al. 2023). Rejection of the null hypothesis indicates that the random-effects estimator is inconsistent, and the fixed-effects model should be used for subsequent inference (Sani et al. 2023; Nwakuya and Ijomah 2021; Cheng and Kamaruddin 2024). Multicollinearity was assessed with variance inflation factors (VIFs), with values above 5 taken as a sign of serious collinearity (Montgomery et al. 2001). The modified Wald and Wooldridge tests were then applied to assess groupwise heteroskedasticity and first-order serial correlation, respectively. Rejection of their null hypotheses indicates that conventional error assumptions may not hold, supporting the use of standard errors robust to heteroskedasticity and serial correlation (Drukker 2003; Cheng and Kamaruddin 2024).

RESULTS AND DISCUSSION

Table 2 gives descriptive statistics for the raw (untransformed) variables.

Table 2: Descriptive statistics

Variable	Obs.	Mean	Std. Dev.	Min	Max
CIR (%)	270	9.23	6.51	1.30	32.00
REP (EUR/kg)	270	1.86	1.14	0.30	5.90
FBB (per 100 people)	270	33.40	6.70	18.91	48.67
RND (% of GDP)	270	1.66	0.88	0.38	3.64
EMP (% of population)	270	1.14	0.50	0.52	3.98
GDPPC (current US$)	270	36063.88	24250.88	7269.03	134965.80

The dependent variable, the circular material use rate (CIR), has a mean of 9.23% and ranges from 1.30% to 32.00%, indicating substantial variation in circularity across the panel. Resource productivity (REP) averages EUR 1.86 per kilogram, with values ranging from EUR 0.30 to EUR 5.90 per kilogram. Fixed broadband subscriptions (FBB) average 33.40 per 100 people and range from 18.91 to 48.67, showing variation in digital connectivity. Research and development expenditure (RND) averages 1.66% of GDP, with a standard deviation of 0.88 percentage points and a range of 0.38% to 3.64%. Employment in circular-economy sectors (EMP) averages 1.14% of the

population and ranges from 0.52% to 3.98%. GDP per capita (GDPPC) averages US$36,063.88, with values ranging from US$7,269.03 to US$134,965.80, reflecting considerable differences in income levels across the panel.

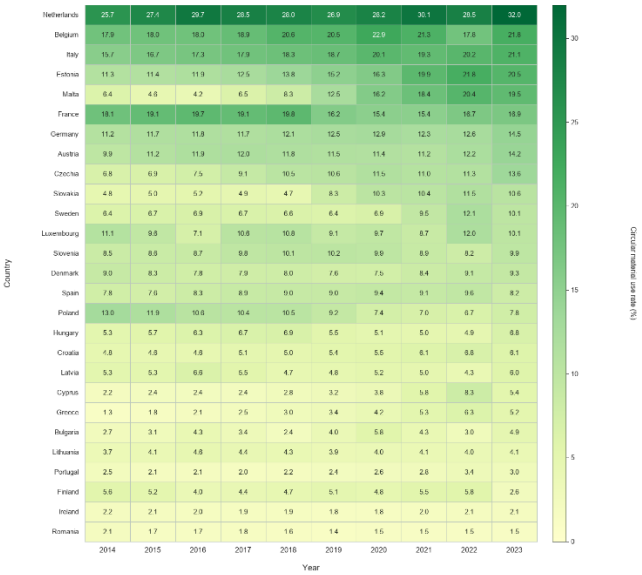


Figure 1: Circular material use rate (%) in the 27 EU member states, 2014-2023.

Figure 1 is a heatmap of circular material use rates for the 27 EU economies from 2019 to 2023. The heatmap organises countries vertically and years horizontally, utilising colour density to illustrate circularity levels. Circularity differs greatly across the 27 economies (Figure 1). The Netherlands records the highest rate in every year, rising from 25.7% in 2014 to 32.0% in 2023. Malta and Estonia show the largest increases, from 6.4% to 19.5% (+13.1 percentage points) and from 11.3% to 20.5% (+9.2), respectively. Italy also rises overall, from 15.7% to 21.1%. Germany increases more modestly, from 11.2% to 14.5%, while France fluctuates between 15.4% and 19.8% and ends at 16.9%. Ireland and Romania remain at the bottom of the distribution, with rates of 1.8–2.2% and 1.4–2.1%, respectively. These low rates may reflect different structural constraints: Ireland's domestic material extraction is dominated by biomass and non-metallic minerals (Central Statistics Office 2023), which are less suited to recycling, while Romania has had low recycling rates, high reliance on landfilling, and a need to improve separate collection and waste treatment (European Commission 2023).

Table 3 reports the estimates of the static panel regression of circularity on the economic and technological variables for the EU-27. The Breusch-Pagan LM and Hausman tests both reject their respective null hypotheses, indicating the presence of panel effects and supporting fixed effects over random effects. The mean VIF (2.33) is well below 5, suggesting no serious multicollinearity. The modified Wald and Wooldridge tests all reject their null hypotheses ($p < 0.05$), indicating presence of heteroskedasticity and serial correlation. In response to these diagnostics, the fixed-effects model is estimated with clustered robust standard errors.

Table 2: Panel data regression estimates

Variables	Fixed Effects	Random Effects
REP	1.1128**	0.8792***
	(0.4134)	(0.2371)
FBB	0.6600**	0.7409***
	(0.2717)	(0.2886)
RND	0.2232	0.2746
	(0.2608)	(0.2099)
EMP	0.0971	0.1644
	(0.1063)	(0.1181)
GDPPC	-0.2392	-0.3072*
	(0.1985)	(0.1814)
Constant	1.5863	2.0800
	(1.7488)	(1.6796)
No. of observations	270	
No. of countries	27	
BP LM Test	787.42***	
Hausman Test	14.67**	
Variance Inflation Factor	2.33	
Modified Wald test	46548.34***	
Wooldridge test	24.45***	

Notes: Values in parentheses are clustered-robust standard errors, whereby ***, ** and * indicate significance at 1%, 5% and 10% level, respectively.

The estimates show that resource productivity (REP) and fixed broadband subscriptions (FBB) are positively and significantly associated with circularity across the sampled countries. This suggests that circularity is more consistently associated with resource-use efficiency and digital connectivity than with aggregate R&D expenditure or circular-sector employment in this model.

Resource productivity has the largest estimated coefficient (1.1128), indicating the strongest association with circularity among the variables. A 10% increase in resource productivity is associated with an approximately 11.13% higher circularity rate. Resource productivity captures how much economic value is obtained from a given amount of material. Higher productivity means less material is used and less waste is produced, which may raise the share of recycled material in total use. This is consistent with the circular-economy aim of decoupling GDP growth from resource use through efficiency and sustainable resource management (McDowall et al. 2017), although the decoupling literature is critical of how far this can go (Bithas and Kalimeris 2018; Korhonen et al. 2018). Resource productivity may also indicate the structure of an economy; if so, its coefficient partly reflects other characteristics of high-productivity economies. High-productivity economies tend to have more advanced production technology, better materials management, and stronger institutions (Ghisellini et al. 2016). These characteristics make circular strategies such as eco-design, industrial symbiosis, and closed-loop production easier to implement, since they depend on keeping material losses low

along the value chain (Ghisellini et al. 2016). Resource productivity is thus both a measure of efficiency and an indicator of how far circular principles are built into production and consumption.

Fixed broadband subscriptions (FBB) are positively and significantly correlated with circularity. The coefficient estimate indicates that a 10% increase in resource productivity is associated with about a 6.6% increase in circularity. At the macro level, the result suggests that technological infrastructure may help an effective transition to a circular economy. Economies with better technological infrastructure may find it easier to introduce circular solutions in their sectors or regions, while those with limited access may face structural barriers. This is in line with the literature that presents digitalisation as an enabler of circular economy through greater transparency, innovation, and system-level efficiency (Xing et al. 2025; Chauhan et al. 2022). Enabling technologies include Internet of Things (IoT) sensors, big data analysis, and blockchain-based solutions that allow real-time tracking of material flows, better sorting and quality control of secondary materials, and increased transparency in recycling and remanufacturing (Carlos et al. 2024; Ingemarsdotter et al. 2019; Reuter 2016). These capabilities can reduce the technological and informational barriers to reuse and help scale closed-loop supply chains. Thus, the outcome is consistent with a role for technology in scaling up circular projects.

The results show no evidence of a significant association between R&D expenditure and circularity. This means that substantial spending on research and development does not necessarily translate into measurable changes in circularity. Circular innovations may require time to evolve from idea to prototype and then to be applied in production, therefore delaying their impact on the national circularity rates (Vuță 2018; Tantau 2018). In addition, circularity is dependent on the capacity to collect and absorb secondary materials, which is influenced by waste management infrastructure, resource productivity, and domestic consumption patterns (Tantau 2018; Bodislav 2025). This result corresponds to the evidence that broad innovation expenditures are not highly correlated with national circularity rates in the short term (Tantau 2018; Lehmann 2022). There is also no significant association between employment in circular economy sectors and circularity. Although workers are needed for activities such as recycling, remanufacturing and circular design, employment could be a result of the expansion in circular activities, not a driver of it. This is in line with findings suggesting that the relationship between circular economy development and employment can be bidirectional (Nikou 2025; Erdiaw-Kwasie 2024).

As a robustness check, the fixed-effects (FE) estimates were compared with the random-effects (RE) estimates. Resource productivity (REP) and fixed broadband subscriptions (FBB) are positive and statistically significant in both specifications, with coefficients of 1.1128 and 0.8792 for REP, and 0.6600 and 0.7409 for FBB, respectively. R&D expenditure (RND) and employment in circular-economy sectors (EMP) remain positive but statistically insignificant under both estimators. GDP per capita (GDPPC) is negative in both models but statistically significant only under RE, indicating that its statistical significance is sensitive to the specification. The consistency of the REP and FBB results supports the robustness of their positive associations with circularity. However, the significant Hausman statistic (14.67**) favours FE over RE, so the FE estimates remain the primary results.

CONCLUSION AND RECOMMENDATIONS

This study examined the association between economic and technological variables and circularity in the EU-27 using a static panel regression with fixed effect model for the period 2014-2023. The findings add to the circular-economy literature by showing that resource productivity and fixed broadband subscriptions are positively and significantly associated with circularity. These associations are consistent with the view that efficient resource use and technological infrastructure go together with higher circularity.

In practical terms, the results suggest that circular-economy policy should consider industrial and digital measures together. First, resource productivity is the variable most strongly associated with circularity. Policies that promote material efficiency, such as eco-design, industrial symbiosis, and resource-efficient production, can help bring more secondary material into production chains. Instruments such as Extended Producer Responsibility (EPR) schemes, landfill taxes, recycled-content requirements, and the Ecodesign for Sustainable Products Regulation (ESPR) can further encourage producers to reduce waste, improve durability, and use more secondary material (OECD 2024, 2016).

The positive association with fixed broadband subscriptions suggests that investment in digital infrastructure could form part of circular-economy strategy. Wider access, together with digital solutions for material traceability, supply-chain coordination, and circular marketplaces, can improve transparency and efficiency. In particular, the digital product passport, a key regulatory element (Regulation (EU) 2024/1781) of the EU Circular Economy Action Plan, should remain a policy priority for resource circularity, lower emissions, and stronger supply-chain governance.

The insignificant link between R&D expenditure and circularity found in this study indicates that R&D expenditure does not guarantee circularity by itself. This does not mean R&D is not important; rather, the influence of R&D relies on the type of innovation, national conditions and the time needed to put technological innovations into practical use. For instance, circular materials are linked to recycling and secondary material patents (Kasztelan et al. 2025; Fortea et al. 2026) and the relationship between innovation and circularity varies among EU member states. The evidence that government spending on R&D activities does not lead to improved municipal recycling rates would suggest that the efficacy of such investments depends on how the support is delivered (Arthur et al. 2023). These findings support considering targeted support for eco-innovation alongside measures associated with circularity in this analysis, such as resource productivity and private investment. Evaluation may also need to account for the time lag between research, adoption, and implementation of environmentally beneficial technologies (Georgescu et al. 2022).

Employment in circular-economy sectors is not statistically significantly associated with circularity in this analysis. This suggests that employment growth may accompany the circular transition but should not be assumed to raise material circularity on its own. Studies report that circular-economy development and employment can be related in both directions, while estimates of the overall employment effect remain small or uncertain (Nikou and Sardianou 2025; Nademi and Kalmarzi 2025; Wiebe et al. 2019; Laubinger et al. 2020). Circular-economy measures may nevertheless bring labour-market benefits, including a shift towards services and increased

opportunities for some worker groups (Wiebe et al. 2019). Policy to improve circularity could therefore focus on material-flow factors, including resource use and recycling, while monitoring employment as a related social outcome (Bodislav et al. 2025; Erdiaw-Kwasie et al. 2024).

This study has several limitations. The panel covers 27 EU countries over ten years (2014-2023), but this time span may not capture the delayed effects of long-term circular-economy policies and innovation. Future studies should extend the panel, for example, back to 2010, when the circular material use series begins, to provide more accurate measurement and analysis of the policy effects. Although the static fixed-effects model estimation approach used in this study accounts for time-invariant country characteristics, the findings should be interpreted as correlational and may be affected by time-varying unobserved variables, reverse causality, or dynamic adjustment. Country fixed effects also do not, by themselves, account for cross-sectional dependence arising from common shocks across the countries. Future studies could use instrumental-variable estimation, dynamic panel models, or structural equation modelling to examine causality and the interplay of factors. The inclusion of other variables such as governance quality, green finance, and social innovation would clarify the institutional and socioeconomic conditions behind circularity.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

CONTRIBUTIONS OF INDIVIDUAL AUTHORS

Debbra T. Nipo: Conceptualisation, Formal analysis, Writing – original draft. Saizal Pinjaman: Data curation, Methodology. Sing Y. Wong: Data curation, Methodology. Jaratin Lily: Writing – review and editing. Awangku H. B. Pengiran Bagul: Conceptualisation, Writing – review and editing.

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