

Do digital small and medium-sized enterprises drive green economic growth in the European Union?

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ABSTRACT

Objective: The article aims to investigate whether digitalisation among small and medium-sized enterprises (SMEs) contributes to green economic growth (GEG) across European Union countries, focusing on environmental performance outcomes.

Research Design & Methods: Using panel data from 25 European Union countries for the period 2010-2023, we applied fixed-effects, moderation, and panel threshold regression models. Digitalisation was proxied by the share of enterprises with e-commerce turnover above 1%, while GEG was measured via adjusted net savings. The analysis controlled for energy intensity and globalisation, and tests interactions with trade openness and R&D investment.

Findings: The results revealed a robust, positive, and statistically significant relationship between SME digitalisation and GEG. Higher trade openness (interaction coefficient = 0.148) and R&D intensity (interaction coefficient = 0.058) amplified the impact.

Implications & Recommendations: Policymakers should treat SME digitalisation as both an innovation and an environmental strategy. Support should focus on scaling digital capabilities in traditional sectors, improving access to R&D resources, and fostering enabling conditions like trade integration and green startup support. Investments in digital infrastructure, skills training, ESG metrics, and regional innovation hubs are essential for realising the synergistic benefits of the green-digital transition.

Contribution & Value Added: This study shows that SME digitalisation is an important driver of environmental performance, but its impact depends on wider institutional and structural conditions. By combining fixed-effects, moderation, and threshold models, the study offers original evidence of a nonlinear digitalization-sustainability relationship, demonstrating that environmental gains intensify once SMEs reach higher levels of digital maturity. The study further identifies trade openness and R&D intensity as mechanisms that amplify these effects, contributing theoretically by clarifying how structural contexts shape the translation of digital capabilities into green economic outcomes.

Article type: research article

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INTRODUCTION

Green economic growth (GEG) and digital transformation are increasingly promoted as twin imperatives within the European Union's long-term development agenda (European Commission, 2025). Grounded in frameworks such as the European Green Deal and the Digital Decade 2030, the EU envisions a future in which technological innovation catalyses low-carbon economic activity, enhances resource efficiency, and fosters social inclusion. This dual transition is frequently framed as synergistic and self-reinforcing,

supported by the belief that digitalisation will accelerate green innovation and sustainability outcomes (Clegg & Casnici, 2023; Han & Zhang, 2022; Gobniece & Titko, 2024; Szczepańska-Woszczyzna & Muras, 2023; Thirakulwanich *et al.*, 2025). However, despite strong policy narratives linking digital transformation to sustainability, the empirical evidence remains inconsistent, particularly regarding whether SME-level digitalisation translates into measurable improvements in environmental performance. Existing research tends to focus either on macro-level digital economy indicators or on firm-level innovation outcomes, leaving the specific environmental implications of digital SMEs insufficiently examined. Moreover, SMEs, which constitute more than 99% of all EU businesses, are positioned as key drivers of both green and digital transitions (Abbas *et al.*, 2024; European Commission, 2025; Titko *et al.*, 2023a; Szczepańska-Woszczyzna *et al.*, 2022). However, the assumption that digitalisation seamlessly drives GEG through SME innovation may overlook significant structural and contextual challenges. Recent studies highlight SMEs' limited absorptive capacity to integrate advanced digital and green technologies due to resource constraints, knowledge gaps, and institutional fragmentation (Putri *et al.*, 2025; Nie *et al.*, 2025; Gross-Golacka *et al.*, 2024). Furthermore, the role of cultural (Dacko-Pikiewicz, 2019b), educational (Korzeniowska & Sułkowski, 2020; Szczepańska-Woszczyzna & Gatnar, 2022), and policy ecosystems in enabling these transitions is often underestimated. Titko *et al.* (2023b) and Verina *et al.* (2021) emphasised the importance of cultivating staff digital competencies and sustainability literacy to enhance transformation outcomes. However, institutional inertia and fragmented support systems continue to hinder the scaling of best practices across regions and sectors (Yang *et al.*, 2024; Obadire *et al.*, 2025). Despite the growing literature on digitalisation and sustainability, existing studies do not provide a clear empirical assessment of whether SME-level digitalisation improves environmental performance in a comparable, cross-country context. Prior work either examines digitalisation at the macroeconomic level or focuses on innovation outcomes rather than measurable green economic growth. Moreover, the conditional nature of this relationship, particularly the roles of trade openness, R&D intensity, and possible nonlinear effects, remains largely unexplored.

This gap prevents a full theoretical understanding of how and under which structural conditions digitalisation contributes to green outcomes. These unresolved issues justify the need for additional investigation. Although policy narratives assume that digitalisation naturally accelerates green transformation, empirical evidence remains inconsistent. It remains unclear whether SMEs, given their resource constraints, technological heterogeneity, and uneven access to innovation ecosystems, generate environmental gains from digitalisation, and whether such gains depend on broader institutional conditions. Clarifying these relationships is essential for advancing theory and guiding effective policy interventions.

Thus, while the convergence of digital and green transitions offers transformative potential, realising this vision will require more than technological adoption. It demands systemic change supported by coordinated innovation ecosystems, inclusive financing mechanisms, critical education, and robust SME support structures, particularly in areas such as circularity, energy efficiency, and carbon-neutral logistics (Pacheco *et al.*, 2024; Klingenberg & Kochanowski, 2015). Proponents argue that SMEs are particularly well suited to drive sustainability-oriented change because of their organisational agility, local embeddedness, and capacity for business model innovation (Dacko-Pikiewicz, 2019a; Quintás *et al.*, 2018; Arsawan *et al.*, 2024). Scholars consider digital technologies, especially those supporting e-commerce, IoT-enabled monitoring, blockchain for traceability, and AI for optimisation, to be critical enablers in green transition (Shao *et al.*, 2024; Ullah *et al.*, 2021; Kwilinski, 2023b). Moreover, policy narratives increasingly position digital SMEs, particularly those operating through e-commerce channels, as the cornerstone of Europe's digitally driven GEG strategy. These firms are expected to connect sustainable producers with conscious consumers, reduce emissions through smart logistics, and lead to innovation in green services (Mustafa *et al.*, 2022; Kwilinski, 2023a).

Considering studies (Lee & Kim, 2025; Maesaroh *et al.*, 2024; Hasbullah *et al.*, 2024), this vision involves several implicit tensions and oversimplification risks. Firstly, digitalisation is not inherently green. The growing deployment of digital infrastructures, including data centres, cloud computing, and AI, requires significant energy and material inputs and, in some cases, contributes to the environmental burden rather than alleviating it. Without alignment between digital tools and sustainability objectives, SMEs risk engaging in 'digital for digital's sake' rather than genuine ecological transformation (Li, 2024; lux *et*

al., 2023). Secondly, despite the promise of digital inclusion, uneven access to digital technologies and skills continues to marginalise many SMEs, especially in rural areas, low-income regions, or transition economies, thus exacerbating the digital divide and potentially reinforcing economic disparities (Bassi & Guidolin, 2021; Najmaei & Sadeghinejad, 2023; Pojani *et al.*, 2025). While the EU's Digital Decade emphasises the integration of SMEs into e-commerce ecosystems, the concentration of digital markets among a few dominant platforms raises concerns about market access, algorithmic discrimination, and value capture (Cherednichenko *et al.*, 2023; Zatonatska *et al.*, 2025; Zhuang, 2024). Furthermore, SMEs operating within these systems may struggle to retain autonomy, data ownership, and fair market share, which thus limits their ability to reinvest in green innovation. The presumed convergence between digital and green agendas also overlooks institutional fragmentation across EU member states, where regulatory inconsistencies, financing gaps, and bureaucratic burdens frequently impede SME participation in sustainability schemes. Moreover, empirical evidence on the environmental effectiveness of digitalisation in SMEs remains mixed. While some studies (Alfadul & AlKubaisy, 2024; Wit *et al.*, 2021; Yi, 2014; Zsolnai, 2002) affirm positive relationships between digital capability and environmental performance, others (Haq & Huo, 2023) caution that digitalisation alone does not guarantee meaningful decarbonisation or circularity unless deliberate sustainability strategies, appropriate metrics, and policy incentives accompany it (Wani *et al.*, 2024). For instance, greenwashing risks persist in the absence of standardised reporting and robust environmental accountability frameworks.

Accordingly, we addressed the following analytical problem: under what institutional and structural conditions does SME digitalisation generate measurable environmental benefits in EU economies? The objective was to quantify the impact of SME digitalisation on green economic growth, to test the moderating roles of trade openness and R&D intensity, and to evaluate whether these effects exhibit nonlinear threshold behaviour.

Given the strategic importance of SMEs in the EU's green and digital transition agendas and the growing reliance on digitalisation as a driver of sustainability, the study aimed to empirically identify whether and under which structural conditions SME digitalisation contributes to GEG in EU countries. Specifically, we examined the direct effect of SME digitalisation on environmental performance, the moderating roles of trade openness and R&D intensity, and the presence of nonlinear threshold effects. This study contributes to theoretical development by addressing a key limitation in the existing literature: the implicit assumption that digitalisation uniformly and linearly enhances environmental performance. Prior studies have provided important insights into how digital capabilities stimulate innovation and productivity. However, they have not established whether these mechanisms translate into green economic outcomes at the level of SMEs, nor under what institutional configurations such translation becomes feasible. The present study advances this line of inquiry by conceptualising SME digitalisation as a process whose environmental effectiveness depends on complementary structural conditions. Specifically, we examined the roles of trade openness and R&D intensity as enabling environments that shape the diffusion, scaling, and environmental orientation of digitally supported practices. This approach aligns with recent theoretical perspectives emphasising that digital technologies generate sustainability benefits only when embedded within supportive innovation and market ecosystems. Methodologically, the integration of fixed-effects, moderation, and threshold regression techniques enables the identification of context-dependent and nonlinear relationships that remain undetected in conventional linear empirical designs. Consequently, the study delineates the boundary conditions under which digitalisation contributes to green economic growth, thereby refining existing theoretical interpretations of the digitalisation-sustainability nexus in entrepreneurship and innovation research.

The article has the following structure: literature review analyses relevant literature on GEG, SME digitalisation, and their interlinkages, leading to the formulation of the research hypothesis. The research methodology section describes the methodological approach, including data sources, variable construction, and econometric techniques. The results and discussion section explores the empirical results and interprets the findings within existing theories and policy frameworks. Finally, conclusions summarise the main results, drawing policy implications, and outlining limitations and future research directions.

LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

Green economic growth (GEG) represents a synergistic development pathway that simultaneously pursues environmental sustainability, economic resilience, and social inclusion. Central to this transformation are structural and institutional determinants, notably the strategic role of small and medium-sized enterprises (SMEs), the acceleration of digital transformation, the emergence of innovative start-ups, and the facilitation of trade openness. Furthermore, SMEs are critical enablers of green economic (GE) transformation because of their adaptive capacity, innovation potential, and sectoral diversity. Feng *et al.* (2025a) highlight that SMEs across Mediterranean economies significantly contribute to GEG by adopting lean-green practices and implementing sustainable business strategies. When equipped with green human resource management (Aldaas *et al.*, 2022) and eco-efficient production models (Ahsan, 2024), these enterprises achieve both environmental improvements and operational efficiency.

The integration of circular economy principles into SMEs' operations further accelerates sustainable transformation. Ho *et al.* (2024) confirmed that circularity-infused green practices bolster productivity and business resilience. Moreover, Le and Ferasso (2022) provide empirical evidence from the food manufacturing sector, highlighting that green investments directly enhance SMEs' sustainable performance.

Previous studies (Dzwigol *et al.*, 2024; Ozturk *et al.*, 2024) have shown that digitalisation acts as a catalyst for GEG by streamlining operations, reducing environmental footprints, enhancing resource efficiency, and unlocking new market opportunities through innovative technologies. It enables real-time monitoring of emissions, energy use, and supply chain processes, thereby empowering enterprises to make more informed and sustainable decisions. Islam *et al.* (2023) underscore the dual transition of Indonesian SMEs toward both digital and GE, emphasising the complementarity of digitalisation and sustainability. Their findings suggest that digital transformation is not merely a technological upgrade but also a strategic shift that reshapes business models towards environmental responsibility. Waqar *et al.* (2025) revealed that the fintech revolution facilitates circular economy practices and green innovation among SMEs by improving financial access, enabling more efficient resource allocation, and incentivising sustainable investments. Digital financial tools, such as blockchain, mobile payments, and digital credit scoring, contribute to building more transparent and inclusive green business ecosystems (Kwilinski, 2025).

The integration of digital solutions into manufacturing helps reduce waste and optimise production cycles, further enhancing SMEs' contribution to GE objectives. Huang *et al.* (2025) confirmed that through industrial intelligence and e-commerce, the digital economy significantly drives green transitions, especially when aligned with industrial policy and innovation support mechanisms. These transformations contribute not only to operational efficiency but also to the broader goals of carbon neutrality and sustainable consumption. In particular, e-commerce constitutes a powerful enabler of green business models that bridge local production with global markets while minimising the need for physical infrastructure and intermediaries. Caiyi *et al.* (2022) demonstrated that although the rapid expansion of e-commerce can exacerbate environmental pressures via increased packaging waste and transportation emissions, strategic governance, logistics innovation, and digital eco-certification can mitigate these effects and foster greener consumer behaviour. Zatonatska *et al.* (2024) and Kiselicki *et al.* (2022) further proved that e-commerce platforms create significant revenue opportunities for SMEs in developing and transition economies, especially when combined with digital marketing strategies and eco-oriented product positioning. In these contexts, digital platforms not only lower entry barriers to international markets but also support the adoption of traceable and transparent supply chains, which are crucial for meeting environmental, social, and governance (ESG) standards (Titko *et al.*, 2021; Williams, 2022).

Innovations in green logistics, such as route optimisation, real-time inventory management, and carbon tracking tools, contribute to decarbonising e-commerce operations. Zhou *et al.* (2023) and Liu (2023) emphasise that integrating e-commerce with green supply chain strategies enhances SMEs' ability to meet sustainability goals while remaining competitive.

Owing to their agility and disruptive innovation capabilities, start-ups are key agents of ecological modernisation. Sehnem *et al.* (2022) reported that start-ups that embed circularity in their

business models tend to outperform traditional enterprises in terms of sustainability indicators. The entrepreneurial ecosystem plays a vital role here: support structures, such as green subsidies and incubation environments, bolster the resilience and scalability of sustainable start-ups (Dragomir *et al.*, 2023; Shang, 2025). Sector-specific evidence, such as in tourism (Arteaga Estrella *et al.*, 2018), green logistics (Masudin *et al.*, 2025), and ecotourism (Chen, 2019), demonstrates that start-ups are pioneering green practices across diverse contexts. Sokil *et al.* (2022) emphasise that start-ups in post-transition economies such as Ukraine exhibit significant potential for GEG, particularly when policy frameworks support long-term sustainability.

Trade openness supports GEG by enhancing the diffusion of environmentally friendly technologies, fostering competition, and broadening access to sustainable inputs. Bıçakcıoğlu *et al.* (2020) and Bıçakcıoğlu-Peynirci and Tanyeri (2022) empirically confirmed that green business strategies positively influence export performance, especially when firms align with global environmental standards. Increased integration into international markets incentivises green certifications, ecoinnovation, and sustainable value chain participation (Chen, 2019; Liu, 2023). However, institutional mechanisms that mitigate environmental leakage and reinforce compliance with green regulations must complement openness to trade (Nie *et al.*, 2025). Thus, the convergence of trade liberalisation and environmental protection policies becomes imperative for inclusive GEG.

Investment in R&D supports the transition to low-carbon and circular economies by generating knowledge that enhances resource efficiency, reduces environmental impact, and fosters green competitiveness. Fernando *et al.* (2019) highlight that environmental innovation, rooted in R&D, directly improves sustainable business performance, whereas Golden *et al.* (2021) underscore the role of green chemistry in creating market opportunities aligned with ecological goals. Public initiatives such as the North Carolina Green Business Fund (Hall & Link, 2015) and cleantech clusters (Davies, 2013) illustrate how targeted R&D investments can amplify regional GEG through spillovers and technological diffusion. In emerging economies, R&D also empowers SMEs to overcome infrastructure and policy gaps. Alkandi (2025) shows that green R&D enhances business outcomes when it is embedded in corporate social responsibility strategies. Maulidi (2025) and Singh *et al.* (2016) confirm that R&D-driven green product innovation increases cost efficiency and market performance, particularly among SMEs. Furthermore, R&D supports circular economy transitions in high-impact industries such as construction, textiles, and manufacturing (Gyimah *et al.*, 2025; Habtemaryam *et al.*, 2025) while improving firms' resilience and adaptability to sustainability challenges (Chalyi *et al.*, 2020). Chatzistamoulou and Tyllianakis (2022) noted that well-informed SMEs, often those investing in research, are more likely to follow GEG pathways.

Although prior research recognises the link between digitalisation and sustainability, there is a lack of focused, integrative analysis on how SME-level digital transformation specifically contributes to GE outcomes. Most existing studies treat digitalisation and GEG as parallel priorities but do not thoroughly examine their interaction within the SME sector. Addressing this gap is essential for evidence-based policy design, particularly within the EU and emerging markets, where SMEs dominate the economic landscape. Prior studies suggest several mechanisms through which SME digitalisation affects environmental performance. Digital tools improve energy efficiency through real-time monitoring, support waste reduction via data-driven optimisation, and enhance transparency in supply chains (Shao *et al.*, 2024; Kwilinski, 2023b). Moreover, SMEs that adopt digital solutions often streamline logistics, reduce resource intensity, and accelerate green innovation. Nevertheless, the evidence remains mixed, and the environmental benefits may depend on the firms' absorptive capacity and access to complementary resources. These insights support the expectation that SME digitalisation is positively associated with environmental performance. Thus, we developed the following research hypothesis 1:

H1: The digitalisation of SMES enhances GEG.

Internationalisation-related theories further suggest that trade openness amplifies the environmental returns to digitalisation. Open economies benefit from greater exposure to advanced technologies, sustainability standards, and competitive pressures that incentivise digital innovation with green outcomes (Philbin *et al.*, 2022; Ozturk *et al.*, 2024). Empirical studies show that firms in highly integrated markets adopt cleaner production, improve energy efficiency, and apply environmental man-

agement tools more rapidly than those in closed economies. Therefore, SMEs operating in more open trade environments are likely to achieve stronger environmental gains from digitalisation:

H2: Trade openness positively moderates the relationship between SMES digitalisation and GEG.

Innovation capability theory suggests that R&D enhances firms' ability to translate digital capabilities into environmental improvements. Countries with higher R&D intensity possess stronger knowledge infrastructures, greater absorptive capacity, and more developed technological ecosystems, which enable SMEs to leverage digital tools for eco-efficiency and green innovation (Yang & Liu, 2024; Cobbinah *et al.*, 2025). Thus, the environmental impact of SME digitalisation should be stronger in economies with robust R&D investment:

H3: R&D investment positively moderates the relationship between SME's digitalisation and GEG.

Figure 1 shows the study's theoretical framework.

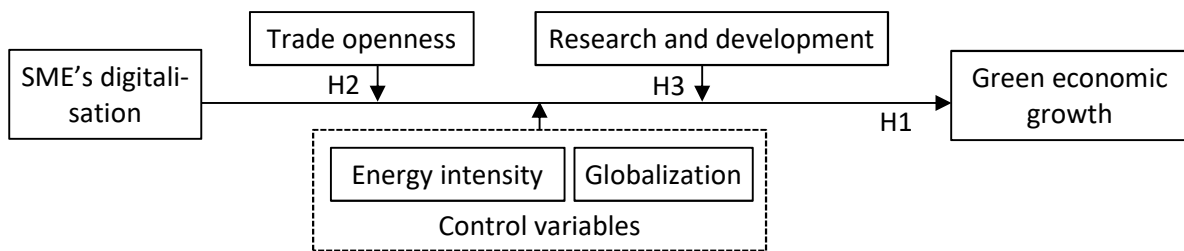


Figure 1. The theoretical framework of the study

Source: own elaboration.

RESEARCH METHODOLOGY

To test the hypotheses, in the empirical analysis, we relied on three complementary econometric models: a benchmark fixed-effects specification, a moderation model with interaction terms, and a panel threshold model. The baseline fixed-effects panel regression examined the average effect of digital SMEs on GEG across European countries over time. The model controlled for unobserved heterogeneity at the country and year levels:

$$GEG_{it} = \alpha + \beta_1 DigitalSMEs_{it} + \beta_2 Controls_{it} + \mu_i + \lambda_i + \epsilon_{it} \quad (1)$$

in which:

GEG - GEG indicator for country *i* in year *t*;

DigitalSMEs - measure of digital small and medium-sized enterprises in country *i* in year *t*;

Controls - vector of control variables;

μ_i - country fixed effects, capturing time-invariant heterogeneity across countries;

λ_i - time fixed effects, capturing year-specific shocks and trends;

ϵ_{it} - error term.

We measured the explained variable (GEG) by adjusted net savings, including particulate emission damage (as a percentage of the GNI), obtained from the World Bank's World Development Indicators. This indicator reflects the integration of environmental externalities into national accounts, in line with the EU Green Deal and the broader sustainability agenda. Wani *et al.* (2024) employed adjusted savings to analyse the impact of green technology, energy, foreign direct investment (FDI), and globalisation in G7 economies (Wani *et al.*, 2024). Khan *et al.* (2023) investigated the interaction effects of green innovation, energy efficiency, and FDI on GEG in OECD countries via related sustainability indicators. Sohag *et al.* (2019) examined the relationships among GEG, cleaner energy, and militarisation in Turkey and operationalised GEG through adjusted or environmentally corrected economic measures.

In line with the literature review, we recognised SME digitalisation as a multidimensional organisational capability, which integrates several interrelated dimensions: technological infrastructure and connectivity, enabling access to digital platforms and cloud-based services; process automation and integration of internal operations; data-driven decision-making and analytics-supported managerial

routines; and digitally enabled business models that reshape firms' value creation logic in markets (Ozturk *et al.*, 2024; Waqar *et al.*, 2025; Yang & Liu, 2024). These components jointly determine SMEs' ability to transition from basic digital adoption to advanced digital maturity, which is associated with stronger sustainability-oriented innovations, resource efficiency gains, and environmentally beneficial outcomes (Islam *et al.*, 2023; Cobbinah *et al.*, 2025).

However, empirical operationalisation of this comprehensive construct remains challenging due to heterogeneity of data coverage, differing survey methodologies, and temporal inconsistencies in measurement across countries (Philbin *et al.*, 2022; Chatzistamoulou & Tyllianakis, 2022; Haq & Huo, 2023). Cross-country comparable indicators that reflect advanced forms of digital transformation (cloud computing, ERP integration, industrial automation, AI-driven operations) are only partially available for SMEs, and typically for shorter time windows or limited sets of sectors. This constraint restricts their use in long-horizon econometric designs, especially when the focus extends to environmental outcomes that require robust panel identification. To ensure methodological consistency across 25 EU countries over 2010–2023, we therefore adopted an entry-level, behaviour-revealing proxy of digital adoption: the share of SMEs with e-commerce sales accounting for at least 1% of turnover (Eurostat, 2024). This indicator captures the commercialisation dimension of digitalisation, a fundamental step in SMEs' digital transition according to the EU's Digital Intensity framework and Digital Decade Policy Programme 2030, which prioritise the diffusion of basic digital competencies among SMEs as a minimum progress benchmark (European Commission, 2021; 2025). Importantly, engagement in e-commerce is not merely a technical adjustment but entails a broader organisational transformation. It reflects firms' ability to adopt digitally supported marketing practices, maintain online customer interfaces, integrate order management and distribution systems, synchronise logistics, and handle digital payment and data-processing arrangements (Kiselicki *et al.*, 2022; Mustafa *et al.*, 2022; Shao *et al.*, 2024). Such infrastructural and operational capabilities constitute critical preconditions for deeper digital upgrading, facilitating the diffusion of circular-oriented innovations, the optimisation of energy and material use, emission-reducing logistics strategies, and sustainable customer engagement, mechanisms empirically linked to improved environmental performance of SMEs (Huang *et al.*, 2025; Zhou *et al.*, 2023; Nie *et al.*, 2025). Accordingly, we should regard this indicator as a lower-bound operationalisation of SME digitalisation, signalling threshold digital readiness that enables firms to participate in digital markets, interface with global supply chains, and internalise efficiency-enhancing routines.

In this study, we selected energy intensity (*EI*) and the overall globalisation index (*GLO*) as control variables. Higher energy intensity (measured as total primary energy supply per unit of GDP (toe per 1 000 USD at PPP) implies lower efficiency in the use of energy resources, which directly contributes to higher greenhouse gas emissions and environmental degradation (IEA, 2023). Empirical research consistently documents a negative association between energy intensity and indicators of environmental performance and sustainable economic growth (Baloch *et al.*, 2020; Shokoohi *et al.*, 2022; Dzwigol *et al.*, 2024). In the context of this study, we expected digital SMEs to improve their environmental outcomes partly through gains in resource use efficiency. However, baseline differences in energy intensity across countries reflect structural characteristics of production and consumption that independently affect environmental outcomes. Countries with energy-intensive industrial sectors tend to exhibit worse environmental performance regardless of the level of digitalisation (IEA, 2023). The overall globalisation index, developed by Dreher (2006) and updated by Gygli *et al.* (2019), aggregates the economic, social, and political dimensions of globalisation to measure the extent of international integration. Globalisation influences environmental performance through several documented mechanisms. On the one hand, it facilitates the transfer of cleaner technologies, best practices, and sustainability standards across borders, improving environmental outcomes. On the other hand, increased trade and production associated with globalisation can exacerbate resource consumption and pollution in the absence of adequate regulations (Shahbaz *et al.*, 2015). Globalisation creates incentives to adopt digital technologies to access international markets, comply with global standards, and compete effectively (Skare & Soriano, 2021; Elfaki & Ahmed, 2024).

To investigate whether the association between environmental performance and digitalisation among SMEs depends on broader structural and institutional conditions, the analysis incorporates interaction terms between digitalisation and two moderating variables: trade openness (trade as a percentage of GDP) and research and development (R&D) expenditure (as a percentage of GDP).

$$GEG_{it} = \alpha + \beta_1 DigitalSMEs_{it} + \beta_2 Controls_{it} + \beta_3 Controls_{it} + \beta_3 (DigitalSMEs_{it} \times Moderator_{it}) + \mu_i + \lambda_i + \epsilon_{it} \quad (2)$$

in which:

$Moderator_{it}$ - moderating variable;

$(DigitalSMEs_{it} \times Moderator_{it})$ - an interaction term indicating whether the impact of digital SMEs on GEG depends on the moderator;

International trade facilitates the diffusion of advanced technologies and environmental standards, thereby increasing the capacity of digital SMEs to contribute to sustainable development (Philbin *et al.*, 2022; Ozturk *et al.*, 2024). Higher trade intensity has been associated with stronger linkages between technological innovation and environmental outcomes because of exposure to global competition and access to cleaner technologies (Wang *et al.*, 2021). Similarly, R&D expenditure captures national investment in innovation and knowledge creation, which conditions SMEs' ability to leverage digital tools for environmental improvement. Prior studies identify R&D intensity as a critical enabling factor for translating digitalisation into green outcomes by fostering the development and adoption of sustainable technologies (Yang & Liu, 2024; Cobbinah *et al.*, 2025). Countries with higher R&D spending tend to exhibit stronger synergies between digitalisation and environmental performance because of greater absorptive capacity and technological capabilities.

To examine potential nonlinear effects, we estimated a panel threshold model (Hansen, 1999). This model tests whether the effect of digital SMEs on GEG changes when the moderating variable exceeds an estimated threshold:

$$GEG_{it} = \begin{cases} \alpha_1 + \beta_1 DigitalSMEs_{it} + \epsilon_{it}, & \text{if } q_{it} \leq \gamma \\ \alpha_2 + \beta_2 DigitalSMEs_{it} + \epsilon_{it}, & \text{if } q_{it} > \gamma \end{cases} \quad (3)$$

in which:

q_{it} - threshold variable;

γ - estimated threshold value separating the two regimes.

We based the empirical analysis on a panel dataset comprising European Union member states over the 2010-2023 period. We excluded Malta and Cyprus from the sample because of data limitations. Table 1 summarises descriptive statistics for the variables used in models (1)-(3).

Table 1. Descriptive statistics of variables

Stats	GEG	DigitalSMEs	Startup	TO	RD	EI	GLO
Mean	9.472764	16.93234	123.9626	126.4206	1.719255	3.565331	82.50955
SD	5.543195	7.639241	246.2969	63.44917	0.8783699	1.142731	3.953934
Min	-11.35125	3.07	0	50.92252	0.38208	0.97	71.00684
Max	21.79603	37.66	1724.768	412.1772	3.70532	7.1	90.6544
VIF		1.44	1.44	1.20	2.77	1.25	3.00

Source: own study.

Table 1 presents the VIF statistics, which indicate no substantial multicollinearity among the regressors, with all values remaining below 3.0. This suggests that correlations among the explanatory variables are not sufficiently high to distort coefficient estimates or their inference.

RESULTS AND DISCUSSION

Table 2 reveals the results of the baseline fixed-effects panel regressions examining the effect of digital SMEs on GEG in European Union countries. Across all three model specifications, the coefficient of *DigitalSMEs* remained positive and statistically significant at the 5% level, suggesting that greater digitalisation among SMEs was associated with improved GEG.

The R-squared values remained high across all the models (approximately 0.87). Both country and year fixed effects were included in all the models to control for unobserved heterogeneity.

Table 2. Baseline regression outputs

Variables	Model 1	Model 2	Model 3
<i>DigitalSMEs</i>	0.0857** (0.0394)	0.0942** (0.0426)	0.0938** (0.0427)
<i>EI</i>		-0.6966*** (0.1843)	-0.6916*** (0.1877)
<i>GLO</i>			0.1572 (1.0802)
Constant	2.8044*** (0.1071)	2.7702*** (0.1167)	2.7709*** (0.1169)
Observations	350	350	350
R-squared	0.8676	0.8684	0.8684
Individual FE	YES	YES	YES
Year FE	YES	YES	YES

Note: standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Source: own study.

To verify the robustness of the baseline findings, we estimated alternative model specifications and reported them in Table 3. Model (4) includes the lagged dependent variable to address potential dynamic effects and persistence in environmental performance over time. The coefficient of *DigitalSMEs* remained positive and statistically significant at the 5% level (0.0995), confirming the positive association between digitalisation in SMEs and GEG. This stability indicates that the observed association was not sensitive to the relaxation of the strict exogeneity assumption, mitigating concerns that short-run endogeneity may bias the estimates.

Table 3. Alternative model specifications for robustness

Variables	Model 4	Model 5	Model 6	Model 7
<i>DigitalSMEs_{t-1}</i>	0.0995** (0.0429)			
<i>Startup</i>		0.0322*** (0.0101)	0.0220** (0.0106)	0.0221** (0.0106)
<i>EI</i>			-0.5053*** (0.1880)	-0.4951*** (0.1902)
<i>GLO</i>				0.4096 (1.0623)
Constant	2.7670*** (0.1158)	2.9290*** (0.0347)	2.9578*** (0.0369)	2.9563*** (0.0372)
Observations	325	350	350	350
R-squared	0.8635	0.8662	0.8618	0.8658
Individual FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

Note: standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Source: own study.

The persistence of this relationship in a dynamic specification suggests that the environmental benefits of digitalisation are not short-lived but accumulate over time. This aligns with evidence showing that digital adoption generates learning effects, organisational restructuring, and gradual efficiency gains that materialise only after repeated use (Thirakulwanich *et al.*, 2025). The stability of the coefficient across models also indicates that the effect was not driven by a single-year anomaly but reflected a structural association between SME digitalisation and green economic dynamics. Models (5)-(7) tested the robustness of the results by replacing the dependent variable with an alternative measure:

venture capital investments in start-ups and early-stage firms (*Startup*). By focusing on venture capital investments in startups and early-stage enterprises, the measure reflected the allocation of financial resources toward new, potentially environmentally friendly technologies and business models that support the transition to a greener economy (Mrkajic *et al.*, 2019; Rizzitello *et al.*, 2025). *Startup* remained positive and statistically significant at the 1% or 5% level, with coefficients ranging from 0.0322 to 0.022. This suggests that higher levels of start-up activity are associated with improved environmental performance, which is consistent with the baseline findings.

Table 4 presents the results of the moderating effect regressions, which aimed at examining whether trade openness and R&D investment influence the strength of the relationship between SME digitalisation and GEG.

Table 4. Moderating effect regression results

Variables	Model 8	Model 9	Model 10	Model 11
<i>DigitalSMEs</i>	0.0849** (0.0417)	0.06027* (0.0415)	0.0757* (0.0426)	0.0781* (0.0429)
<i>TO</i>	0.5629*** (0.1367)			
<i>TO × Digital</i>		0.1482*** (0.0450)		
<i>RD</i>			0.1950*** (0.0649)	
<i>RD × Digital</i>				0.0575** (0.0237)
<i>EI</i>	-0.6985*** (0.1826)	-0.7179*** (0.1847)	-0.6712*** (0.1852)	-0.6944*** (0.1861)
<i>GLO</i>	-0.0675 (1.0526)	-0.1979 (1.0675)	0.4316 (1.0693)	0.3180 (1.0731)
Constant	0.1226 (0.6531)	2.7469*** (0.1152)	2.7400*** (0.1158)	2.7404*** (0.1166)
Observations	350	350	350	350
R-squared	0.8758	0.8733	0.8725	0.8711
Individual FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

Note: standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Source: own study.

The value of DigitalSMEs was consistently positive and statistically significant across all four models, with coefficients ranging from 0.0603 to 0.0849. This confirmed the hypothesis (H1) that higher levels of digitalisation among SMEs are associated with improved GEG in EU countries. In Model 9, the interaction effect between trade openness and digitalisation was positive and highly significant (0.1482). This finding suggests that in countries with greater trade openness, the positive impact of digital SMEs on GEG is amplified (H2). We may interpret the result as evidence that access to international markets enables digital SMEs to adopt and scale green technologies more effectively, enhancing their environmental contribution. Model 11 includes an interaction between R&D expenditure and digitalisation, which also has a significant positive effect (0.0575). This finding indicates that in countries with higher levels of investment in R&D, digital SMEs are better positioned to translate their technological capabilities into green outcomes (H3). Thus, innovation-friendly environments enhance the effectiveness of digital transformation in supporting environmental goals. Across all the models, environmental intensity had a negative and statistically significant effect. This means that higher pollution levels reduce the potential for GEG. Moreover, the globalisation index was not statistically significant in any of the models, suggesting that, unlike targeted trade openness, general global integration does not strongly influence the green performance of digital SMEs.

Table 5 extends this analysis by introducing threshold regression models to explore potential nonlinearities in the digitalisation-GEG relationship. The results demonstrate that the positive impact of digital SMEs becomes significantly stronger once a certain threshold level of digital adoption is reached.

Table 5. Results of threshold regression analysis

Variables	Model 12	Model 13
<i>DigitalSMEs</i> ($q_{it} \leq \eta$)	0.1769*** (0.0650)	0.2076*** (0.0636)
<i>DigitalSMEs</i> ($q_{it} > \eta$)	0.1409*** (0.0394)	0.1615*** (0.0382)
<i>TO</i>	0.3548*** (0.1095)	
<i>RD</i>		0.1724** (0.0668)
<i>EI</i>	-0.4128** (0.1810)	-0.4723*** (0.1806)
<i>GLO</i>	0.0761 (1.0077)	0.6415 (1.0157)
Constant	0.9629** (0.4822)	2.5169*** (0.0995)
Observations	350	350
R-squared	0.1489	0.1380

Note: standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Source: own study.

In Models (12) and (13), the coefficient for *DigitalSMEs* increased to 0.1769 and 0.2076, respectively, suggesting that the relationship is not strictly linear and that countries with more digitally mature SME sectors exhibit disproportionately greater environmental benefits. The threshold results indicate that the environmental benefits of SME digitalisation accelerate only once economies surpass a minimum level of structural readiness. Below this threshold, digital uptake may be insufficient to overcome technological and organisational constraints, resulting in weaker or insignificant green outcomes. Scholars have identified similar nonlinear patterns in studies of digital maturity and eco-innovation, which show that environmental returns emerge only after firms accumulate sufficient technological capabilities and supportive institutional conditions (Yang & Liu, 2024). Therefore, the identified threshold corresponds to a point at which digital capabilities begin to interact synergistically with national innovation systems, enabling SMEs to leverage digital tools for substantive environmental gains. Moreover, the interaction terms in Table 7 also remained positive and significant. Both trade openness and R&D investment continue to enhance the environmental impact of digital SMEs, which supports H2 and H3. The stronger effects observed in open economies are consistent with theories of technological diffusion, which argue that exposure to international markets accelerates the adoption of digital and green innovations (Philbin *et al.*, 2022). Furthermore, SMEs engaged in or operating within open trade environments benefit from access to foreign technologies, external knowledge flows, and competitive pressures that reward environmentally efficient practices. By contrast, the moderating role of R&D intensity reflects the importance of national absorptive capacity: economies with higher R&D investment provide more supportive innovation ecosystems, enabling SMEs to translate digital tools into meaningful environmental improvements (Cobbinah *et al.*, 2025). These distinct mechanisms explain why the strength of the digitalisation effect varies across contexts.

The *RD* and SME digitalisation interaction term in Model 13 was 0.1724, whereas the *TO* and *DigitalSMEs* terms were 0.1615. These results reinforce the conclusion that supportive policy environments, characterised by open markets and strong innovation systems, are critical for realising the full green potential of digital SMEs. The threshold effects highlight the importance of building comprehensive policy frameworks that not only support digital transformation but also foster innovation ecosystems and global integration to achieve sustainable economic development.

The results show that SME digitalisation contributes positively to green economic growth, but the magnitude and significance of this effect depend strongly on broader institutional and structural conditions. The moderation and threshold findings highlight the nonlinearity of the digitalisation-environment nexus and demonstrate that digital technologies generate meaningful environmental benefits only when combined with enabling factors such as openness and innovation capacity. These results reinforce existing theoretical expectations while extending empirical knowledge on the contextual nature of digital-led green transitions.

CONCLUSIONS

The study empirically examined the impact of digitalisation among SMEs, including high-tech startups, on GEG across 25 EU countries over the 2010-2023 period. The findings consistently show that digitalised SMEs have a statistically significant and positive effect on GE performance, measured by adjusted net savings (mean = 6.41%) as a proxy for GEG. Beyond the average positive effect, the study demonstrates that the environmental gains from SME digitalisation are strongly conditioned by broader structural factors. Both trade openness and R&D intensity significantly amplify the green impact of digital adoption, while the threshold analysis confirms that these benefits materialise only once economies surpass a minimum level of institutional and technological readiness.

In the baseline regression models, the coefficient for SME digitalisation, measured by the percentage of enterprises with e-commerce turnover of at least 1%, ranged from 0.0603 to 0.0849, which were statistically significant at the 10% or 5% level. In the robustness models, the coefficient remained stable at 0.0995, confirming the reliability of the results. Interaction models further revealed that this positive effect was significantly strengthened by trade openness (interaction term = 0.1482) and R&D investment (interaction term = 0.0575), indicating that SMEs embedded in open and innovation-intensive economies are better positioned to generate green outcomes. Threshold regression analysis confirms the presence of nonlinear effects. Specifically, once digitalisation among SMEs exceeds a certain threshold, its positive impact on GEG intensifies, rising to 0.2076 in high-digitalisation regimes. This suggests that the green benefits of SME digitalisation are not merely linear but accelerate beyond the tipping point of digital maturity.

These results corroborate the theoretical arguments of Islam *et al.* (2023) and the empirical findings of Wani *et al.* (2024) and Khan *et al.* (2023), who show that technology adoption and innovation facilitate the decoupling of economic growth from environmental degradation by enabling cleaner production processes, improved resource efficiency, and the diffusion of green innovations. Therefore, policymakers should treat SME digitalisation not only as a competitiveness agenda but also as a core environmental strategy. Investment in digital infrastructure, subsidies for e-commerce adoption, and digital skills training should be targeted, especially for SMEs operating in traditional and high-emission sectors (Islam *et al.*, 2023; Huang *et al.*, 2025; Waqar *et al.*, 2025). Public-private partnerships and regional digital hubs can play a role in accelerating this transformation.

This study extends prior work by demonstrating that the positive impact of SME digitalisation on environmental performance is contingent on institutional and structural conditions, particularly the levels of trade openness and R&D investment. The significant interaction effects identified here align with those of Chen (2019) and Maulidi (2025), who document that open trade regimes and strong innovation ecosystems enhance firms' capacity to adopt and deploy sustainable technologies effectively. Specifically, the finding that trade openness amplifies the environmental benefits of digital SMEs suggests that international market access facilitates knowledge spillovers and incentivises firms to meet higher environmental standards, which is consistent with the 'pollution halo' hypothesis (Duan & Jiang, 2021). Therefore, trade policies should integrate sustainability benchmarks, such as those requiring green certifications, digital traceability, and compliance with environmental standards, as part of trade facilitation for SMEs (Bıçakcıoğlu *et al.*, 2020; Chen, 2019; Zhou *et al.*, 2023). Bilateral and multilateral trade agreements should support digital platforms that promote green product visibility in international markets. Similarly, the positive moderating effect of R&D intensity supports the view that absorptive capacity and innovation infrastructure are critical for translating digital investments

into measurable green outcomes (Sehnm *et al.*, 2022; Shang, 2025; Dragomir *et al.*, 2023). Governments should expand innovation grants, tax reliefs, and cofinancing schemes for SMEs to develop eco-innovations, especially in terms of clean tech, energy efficiency, a circular economy, and green logistics (Fernando *et al.*, 2019; Maulidi, 2025; Golden *et al.*, 2021). National and EU-level R&D frameworks should also emphasise support for low-carbon digital technologies.

The threshold effects observed in the study suggest that SMEs below a certain digital maturity level may not yet benefit from the green gains of digital transformation. Targeted interventions, particularly in lagging regions, rural economies, and transition countries, are essential to avoid regional digital-environmental inequality (Putri *et al.*, 2025; Gross-Golacka *et al.*, 2024; Obadire *et al.*, 2025). This includes increasing access to high-speed internet, local business digitalisation support centres, and training programs.

While digital tools can reduce emissions and enhance efficiency, there is also a risk of digital greenwashing without proper metrics. Authorities should incentivise SMEs to adopt transparent ESG indicators, use lifecycle assessment tools, and report digitally enabled environmental improvements (Lux *et al.*, 2023; Alfadul & AlKubaisy, 2024). Digital platforms such as blockchain can also serve to track green claims across supply chains (Zhou *et al.*, 2023; Liu, 2023).

Realising the synergy between digitalisation and GEG requires not only isolated programs but also coordinated institutional frameworks. This includes collaboration across digital, environmental, trade, and innovation ministries. Building institutional capacity at the regional and local levels to support SME transitions is critical (Nie *et al.*, 2025; Yang *et al.*, 2024; Klingenberg & Kochanowski, 2015).

Building on these findings, the study offers several targeted policy recommendations that directly reflect the moderation and threshold patterns identified in the empirical analysis:

- The empirical results clearly demonstrate that the environmental impact of SME digitalisation depends on broader structural factors. Thus, policymakers should avoid uniform, one-size-fits-all approaches and instead design interventions that reflect the distinct trajectories of countries with low versus high institutional and technological readiness. Recognising these asymmetries is essential for ensuring that digitalisation policies translate into measurable sustainability gains.
- In countries operating below the threshold levels of trade openness or R&D intensity, digital tools alone are insufficient to generate environmental improvements. Policy efforts should prioritise expanding innovation capacity, strengthening national research infrastructure, and reducing barriers to global market integration. These measures create the necessary absorptive capacity for SMEs to effectively deploy digital technologies in ways that enhance resource efficiency and environmental performance.
- For countries that already exceed the threshold conditions, the policy focus should shift toward deepening the technological sophistication of SMEs. This includes supporting investments in advanced digital infrastructures, data-intensive technologies, artificial intelligence, and digitally enabled green innovations. Such interventions can accelerate the non-linear gains identified in the empirical analysis and reinforce the role of digitalisation as a catalyst for green economic transformation.
- Given the identified moderating role of structural variables, policymakers should cultivate complementary ecosystem elements, such as digital skills development, broadband expansion, innovation networks, and knowledge-transfer platforms, that magnify the environmental benefits of SME digital adoption. These ecosystem components help ensure that digitalisation is embedded in a supportive institutional context rather than functioning as an isolated technological upgrade.
- In their design, digitalisation incentives should promote environmentally beneficial practices rather than solely commercial digital adoption. Policy instruments could include targeted subsidies for digital green technologies, regulation that encourages resource-efficient digital solutions, and performance-based incentives that reward SMEs for integrating digital tools into sustainability-oriented business models.

While this study offers valuable insights into the relationship between SME digitalisation and GEG in the EU, readers should acknowledge several limitations. The operationalisation of digitalisation relies on a narrow indicator capturing only the share of SMEs engaged in online sales, which does not fully reflect the multidimensional nature of digital transformation. The use of aggregate

SME-level data prevents the analysis of heterogeneity across micro-firms, medium-sized enterprises, and technology-intensive startups. The absence of startup-specific indicators limits the study's ability to explore whether young, innovation-driven firms contribute differently to green economic outcomes. Acknowledging these limitations provides a clearer basis for interpreting the results and defining priorities for further research. It uses proxy indicators (e.g., e-commerce turnover and adjusted net savings) that may not fully capture the complexity of digitalisation and GEG. The analysis does not account for sectoral differences, relies on a relatively short time period, and is limited to EU countries, which may reduce its global applicability. Future research should use firm-level data, include a longer timeframe, and explore sector-specific and regional differences. The broader ESG impacts of SME digitalisation should also be considered.

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Use of Artificial Intelligence

The text of this study is free of AI/GAI usage.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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