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Digital Transformation and Blockchain Ecosystem Readiness as Drivers of ESG Performance: Evidence from European Union Countries

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ABSTRACT

Digital transformation and blockchain technologies have become increasingly relevant to sustainable development, yet country-level evidence on their joint relationship with environmental, social, and governance (ESG) performance remains limited. This study examines the association between digital transformation and blockchain ecosystem readiness and ESG performance across 27 European Union countries over the 2016–2024 period. The research design combines a systematic literature review and bibliometric analysis with the construction of three composite indices using the Entropy–TOPSIS method and panel econometric estimation based on Two-Way Fixed Effects models. The analysis is based on a balanced panel of 243 country-year observations and controls for foreign direct investment (FDI), gross fixed capital formation (GFCF), inflation (INF), labor productivity (LP), real GDP per capita (GDPpc), and unemployment (UNEMP). Statistical inference is conducted using Driscoll–Kraay standard errors to account for heteroskedasticity, serial correlation, and cross-sectional dependence. The Entropy–TOPSIS results show marked cross-country differences and temporal variation in ESG performance, digital transformation, and blockchain ecosystem readiness, indicating persistent heterogeneity among European economies. The econometric results show positive and statistically significant associations between both the Digital Transformation Index (DTI) and the Blockchain Ecosystem Readiness Index (BERI) and ESG performance after controlling for macroeconomic conditions and country- and time-specific effects. The combined specification provides the strongest explanatory performance, while the main results remain robust to lagged specifications, exclusion of the pandemic period, winsorized controls, and alternative index construction. Taken together, the findings suggest that digital transformation and blockchain ecosystem readiness are complementary dimensions associated with stronger ESG performance. The study contributes by linking transparent composite index construction with panel econometric analysis and by introducing a country-level measure of blockchain ecosystem readiness. The results also provide an empirical basis for considering digital policies, infrastructure investment, and ESG-oriented governance within the European context.

1. INTRODUCTION

The digital transformation of European economies is changing the relationship between technological capabilities, institutional quality, and sustainable development. Digital infrastructure, specialized human capital, and data-driven business models increasingly affect how firms operate, how public services are delivered, and how economic activities are monitored. At the same time, environmental, social, and governance (ESG) performance has become an important element of economic policy, investment assessment, and institutional accountability. These developments raise a central question: do stronger digital capabilities coincide with better ESG outcomes, or can technological progress advance independently of sustainability performance?

The relationship between digitalization and ESG performance is not necessarily straightforward. Digital technologies can improve resource efficiency, access to information, service delivery, and the monitoring of environmental and social commitments. They may also strengthen institutional transparency by making transactions and administrative procedures more traceable. At the same time, technological expansion can increase energy demand, widen disparities between countries, and reinforce existing institutional weaknesses when new systems are introduced without adequate governance arrangements. The relevance of digital transformation for ESG performance therefore depends on the extent to which countries combine infrastructure, skills, enterprise adoption, and institutional capacity.

Blockchain technology adds a more specific dimension to this relationship. Its relevance to ESG-related activities stems from secure data recording, traceability, decentralized verification, and reduced information asymmetries. These characteristics can support supply chain transparency, sustainability reporting, public accountability, and the verification of environmental claims. However, blockchain applications depend on reliable broadband networks, cloud infrastructure, digitally capable enterprises, Information and Communication Technology (ICT) specialists, and widespread internet access. Blockchain readiness is therefore understood here as the technological, human, and business capacity required for the broader development and use of such applications.

Despite growing interest in public policy and academic research, the empirical evidence remains fragmented. Many studies examine digitalization through individual indicators such as broadband access, cloud use, online banking, or ICT employment. ESG performance is also frequently represented by separate environmental, social, or institutional indicators, even though the concept is inherently multidimensional. Blockchain research tends to concentrate on enterprise-level adoption, technical architecture, financial applications, or specific case studies. Consequently, it remains uncertain whether countries with stronger digital capabilities and greater readiness in the blockchain ecosystem also exhibit higher ESG performance.

A further limitation concerns the separation between the construction of composite indices and explanatory analysis. Composite indicators are commonly used to rank countries, but these rankings are less often incorporated into econometric models that examine relationships among the underlying dimensions. Conversely, panel regressions frequently rely on existing indices whose weighting schemes and conceptual boundaries are not always transparent. This leaves a methodological gap between descriptive comparison and explanatory analysis. A high position in a digital ranking does not, by itself, establish a relationship between digital capabilities and ESG performance once macroeconomic conditions, structural differences, and common European shocks are taken into account.

This study addresses these limitations by constructing three composite measures for the 27 European Union countries over the period 2016–2024: the ESG Performance Index, the Digital Transformation Index (DTI), and the Blockchain Ecosystem Readiness Index (BERI). The indices are constructed using the Entropy–TOPSIS method. Entropy weighting assigns criterion weights according to the variation observed across countries, thereby reducing reliance on arbitrary or subjective weighting. TOPSIS then evaluates each country according to its relative distance from the best and worst performance profiles. This approach provides a transparent basis for cross-country comparison, preserves the multidimensional character of the concepts, and allows their evolution over time to be examined.

The distinction between the DTI and the BERI is central to the empirical design. The DTI captures the broader diffusion of digital technologies through internet use, digital financial activity, ICT skills, enterprise training, and online transactions. The BERI focuses on the infrastructure and capacities required for blockchain-based systems, including broadband coverage, cloud use, e-commerce, employment of ICT specialists, data traffic, and household internet connectivity. Although the two measures are related, they capture different aspects of technological development. The DTI reflects broad digital adoption, whereas the BERI represents the conditions needed for more specialized, data-intensive, and decentralized applications.

The study has two main objectives. The first is to identify differences across countries and changes over time in the three indices, with particular attention to annual rankings, performance gaps, and the stability of country positions. The second is to examine the relationships between DTI and BERI and ESG performance after controlling for foreign direct investment (FDI), gross fixed capital formation (GFCF), inflation (INF), labor productivity (LP), real GDP per capita (GDPpc), and unemployment (UNEMP). The balanced panel contains 243 country-year observations. Three Two-Way Fixed Effects specifications are estimated with country and year fixed effects. Statistical inference is based on Driscoll–Kraay standard errors to account for heteroskedasticity, serial correlation, and cross-sectional dependence.

From a community development perspective, national digital and technological capacities matter because they shape the institutional conditions under which communities access public services, participate in economic activity, develop digital skills, and benefit from sustainable development policies. Stronger digital infrastructure and institutional readiness can support local service delivery, digital inclusion, entrepreneurship, and greater transparency in local governance. By contrast, uneven technological capacity may reinforce territorial disparities and restrict the ability of less digitally prepared communities to benefit from the green and digital transitions. The study therefore does not treat country-level digital transformation or blockchain readiness as direct measures of community development outcomes. Instead, they are conceptualized as enabling national conditions that may strengthen the institutional, technological, and economic environment in which sustainable community development occurs. This distinction links the macro-level analysis of ESG performance to the broader community development implications of the European digital and green transitions.

The study makes several contributions. First, it moves beyond descriptive country rankings by linking Entropy–TOPSIS composite measures with panel econometric analysis. Second, it introduces a country-level measure of blockchain ecosystem readiness without equating technological readiness with actual blockchain adoption. Third, by separating general digital transformation from blockchain-specific readiness, the analysis assesses whether the two dimensions provide distinct explanatory power for ESG performance. Fourth, the study provides longitudinal comparative evidence for all 27 European Union countries over the period 2016–2024, enabling examination of cross-country heterogeneity, temporal change, and the joint relevance of digital transformation and blockchain ecosystem readiness within a single empirical framework. The resulting framework connects multidimensional index construction, cross-country benchmarking, and panel-based explanatory analysis. It relates national technological readiness to the institutional conditions that shape digital inclusion, access to public services, entrepreneurship, transparency, and participation in sustainable community development across the European Union.

2. LITERATURE REVIEW

The literature review is organized into four thematic subsections, followed by a bibliometric analysis, linking the theoretical, empirical, and methodological evidence to the research questions and empirical design of the study.

2.1 Digital Transformation and environmental, social, and governance performance: Direct effects and transmission mechanisms

Recent literature generally supports the view that digital transformation is associated with stronger ESG performance through lower information costs, greater transparency, green innovation, and more efficient resource use. However, the convergence of positive findings should not be taken as evidence of a universal relationship. Many studies rely on samples of Chinese listed companies, text-based measures of digitalization, and ESG ratings from agencies that use different methodologies. The apparent consistency of the results may therefore partly reflect similarities in samples, study periods, and measurement approaches rather than the relationship between digital transformation and ESG alone [1-7].

Studies examining mediating mechanisms indicate that technology does not generate sustainable outcomes when introduced independently of organizational capabilities. Green learning, technological competencies, human capital, internal control, innovation, and supply chain coordination influence whether digital investments are associated with improvements in ESG performance. Evidence from systems engineering research similarly indicates that sustainability objectives need to be incorporated into organizational requirements and product development processes rather than treated as an outcome of technological change alone [8]. This shifts attention from the scale of technology investment to the way digital capabilities are integrated into decision-making and governance processes. The evidence suggests that stronger outcomes are more likely when digitalization is accompanied by absorptive capacity, consistent regulatory pressure, and effective institutional structures [9-17].

The literature, however, does not support an unconditional positive relationship. Several studies report nonlinear patterns, differences across the E, S, and G dimensions, and adverse environmental consequences associated with the expansion of digital activity. These findings question the assumption that gains in digital efficiency necessarily translate into greater sustainability, particularly where digital infrastructure depends on energy-intensive resources or where institutional capacity is limited. Meta-analytic evidence likewise reports a positive average relationship, but with substantial heterogeneity across technologies, sectors, and regulatory contexts [18-23].

At the macro level, digital transformation is connected to ESG performance through innovation systems, digital finance, and public governance. The strength of this relationship, nevertheless, varies with the levels of economic development, financial constraints, and institutional quality. The central question is therefore not simply whether digital technologies can support ESG performance, but under what conditions, for which economies, and at what costs. Addressing this question requires cross-country analysis that distinguishes digital capacity from technology use and examines whether the relationship remains robust after structural and macroeconomic conditions are taken into account [24-29].

2.2 Blockchain ecosystem readiness, transparency and environmental, social, and governance

The literature presents blockchain as an infrastructure that can strengthen the traceability, verification, and reliability of sustainability-related data. From this perspective, blockchain may support ESG reporting, green finance, and supply chain monitoring. Much of the existing research, however, is based on sector-specific cases, systematic reviews, or conceptual frameworks, while comparative country-level evidence remains limited. This makes it important to distinguish the technological potential of blockchain from empirically demonstrated outcomes [30-33].

A related strand of the literature suggests that blockchain readiness depends on more than just digital infrastructure. Data quality, interoperability, ICT expertise, organizational capacity, funding, and regulatory clarity also shape the conditions under which blockchain applications can be developed and used. Studies of the public sector and sustainability management indicate that adoption is more likely when technological, institutional, and collaborative conditions are jointly present. Yet, the relative importance of these factors remains unclear, and initial adoption is sometimes treated as equivalent to broader ecosystem readiness [34-37].

In the ESG context, blockchain may help reduce information asymmetry, strengthen carbon accountability, and improve verification processes. An immutable ledger, however, does not ensure that the information entered into the system is accurate, nor does it guarantee that relevant actors will disclose sensitive data. Its contribution therefore depends on reporting standards, audit quality, and coordination across the value chain. The relationship between blockchain and ESG performance is consequently conditional rather than automatic [38-42].

A particularly important unresolved issue is the assumption that greater technical transparency necessarily leads to stronger governance. Blockchain systems may reproduce existing power asymmetries, exclude actors with limited digital capabilities, and introduce additional energy and organizational costs. BERI should therefore be interpreted as a measure of enabling conditions rather than evidence of sustainable outcomes. This distinction supports empirical testing across countries, examining technological readiness alongside institutional quality and ESG performance [43, 44].

2.3 Digital-green transition, sustainable development and community context

The dual digital and green transition is widely discussed in the literature as a means of aligning technological modernization with sustainability objectives. European evidence indicates that digitalization can improve energy efficiency, productivity, and innovation, although these benefits are unevenly distributed. Economies with more developed infrastructure, stronger human capital, and effective institutions tend to benefit more, whereas countries facing persistent digital divides may fall further behind. This uneven pattern challenges the assumption that digital and green transitions necessarily progress in parallel [45-49].

At the enterprise and sector levels, the evidence is more mixed. Digitalization can help small and medium-sized enterprises reduce costs, use resources more efficiently, and develop more sustainable business models. These gains, however, depend on organizational capacity, access to finance, and the ability to absorb new technologies. When digital transformation is treated mainly as a technical replacement without corresponding changes in governance, it may increase platform dependence, energy consumption, and the exclusion of smaller actors. Such differences help explain why empirical findings vary across enterprise size, sector, and level of digital maturity [50-54]. Sector-specific evidence also shows that the sustainability implications of technological development cannot be assessed through efficiency or cost indicators alone. In multimodal transport, for example, route evaluation changes when carbon emissions are considered together with transport time and economic cost [55].

The social and institutional dimensions remain less firmly established than the economic effects. Some studies associate digital transformation with greater social inclusion, improved access to services, and stronger public-sector capacity. Others show that territorial inequalities, skill shortages, and weak governance may concentrate the benefits among already advantaged groups. Digital public administration can improve transparency and service delivery, but its effectiveness depends on citizen trust, institutional design, and communities' practical ability to access and use new systems [56-61].

The digital transition should thus be evaluated not only through national performance indicators but also in terms of its implications for local development, social inclusion, and environmental governance. The community development literature indicates that technological capacities generate greater value when they operate alongside responsive institutions, social participation, and sustainable resource management. An important unresolved question is whether national digital policies translate into equitable outcomes across territories. Addressing this issue requires research that connects macro-level indicators with communities' access to technology, public services, and economic opportunities [62-64]. This study approaches this gap from a macro-institutional perspective. Although the country, rather than the local community, is the empirical unit of analysis, national digital capacity, technological infrastructure, and governance quality constitute the environment in which communities access digital services, economic opportunities, and sustainability initiatives. The country-level analysis is therefore interpreted as identifying structural conditions relevant to community development rather than as directly measuring community-level outcomes.

2.4 Composite measurement, cross-country heterogeneity and macroeconomic fundamentals

Measuring ESG performance, digital transformation, and blockchain readiness requires composite indicators, as each concept comprises multiple dimensions that a single variable cannot adequately capture. European studies show that aggregating indicators facilitates cross-country comparison and the identification of development profiles. However, the resulting scores depend on the choice of criteria, normalization procedure, and weighting scheme. Rankings should therefore be interpreted as relative outcomes of a specific analytical framework rather than as absolute measures of performance [65-67].

The literature also documents substantial heterogeneity across European countries. Digital clusters, convergence clubs, and differences in country rankings indicate that progress does not follow a common trajectory, even within the European Union's shared regulatory framework. Some studies, however, rely on single-year observations or period averages, which makes it difficult to distinguish persistent structural improvement from short-term variation. Examining changes in rankings over time is therefore as important as assessing a country's position in a given year [68-70].

A further methodological issue concerns the aggregation of ESG dimensions. Some approaches allow full compensation, meaning that strong performance in one dimension can offset weakness in another. This assumption is problematic because improvements in economic or governance conditions do not necessarily compensate for deficiencies in environmental or social performance. Evidence on ESG investments, market value, and well-being suggests that the E, S, and G pillars generate different outcomes and should be treated as interconnected rather than interchangeable dimensions [71-73].

Broader macroeconomic conditions also shape composite index performance. Investment, financial development, inflation, income, and capital formation affect countries' capacity to finance digital infrastructure and the sustainable transition. At the same time, these factors may influence both ESG performance and the explanatory variables, increasing the risk of omitted-variable bias when they are excluded from the analysis. Combining Entropy–TOPSIS with panel models that include macroeconomic controls therefore provides a broader analytical basis than country rankings considered in isolation [74-76].

2.5 Bibliometric analysis

The bibliometric analysis was conducted on the final corpus of studies selected through the PRISMA approach. Of the 140 scientific papers identified during the search and screening process, 70 were retained for the final analysis, corresponding to an inclusion rate of 50%. The corpus covers the period 2022–2026 and reflects growing scholarly interest in the relationship between digital transformation, blockchain ecosystem readiness, and ESG performance. The number of publications increased from four in 2022 and nine in 2023 to 22 in 2024 and 25 in 2025, with 10 papers published in 2026. Within the analyzed corpus, this pattern indicates a marked increase in research activity after 2023. The number of publications for 2026 should nevertheless be interpreted with caution, as the data for that year cover only the period up to the time of the research.

The corpus comprises 61 journals or scientific sources, 20 publishers, and 205 unique authors. An average of 3.1 authors per document and a collaboration index of 3.26 indicate that the literature is predominantly collaborative. By publisher, Elsevier accounts for nine papers, Taylor & Francis for eight, Acadlore Publishing for seven, and MDPI and Springer Nature for six each.

The thematic distribution shows that 25 papers examine digital transformation and ESG performance, 15 address blockchain readiness and ESG governance, and 18 focus on the digital-green transition and the community context. A further 12 papers deal with composite measurement, cross-country heterogeneity, and macroeconomic factors. This distribution reflects the multidisciplinary nature of the field, combining technological, institutional, financial, and environmental perspectives.

For the network analysis, binary co-occurrence of standardized terms in the topics field was computed with a minimum threshold of 2 occurrences. Before constructing the network, synonymous terms and closely related terminological variants were harmonized to reduce artificial fragmentation across clusters. The final network contains 22 terms and 51 links. Node size represents the frequency with which a term occurs, line thickness indicates the strength of co-occurrence, and the distance between nodes reflects thematic proximity. Figure 1 shows a thematic structure organized around three interconnected communities. The network has a density of 0.221 and an average degree of 4.64 links per node, indicating a moderate degree of thematic integration alongside clearly identifiable research sub-directions.

The red cluster represents the dominant thematic axis of the literature, in which digital transformation is closely linked to ESG performance, green innovation, carbon emissions, and environmental regulation. The central position and larger size of the terms digital transformation and ESG performance indicate that they function as core nodes linking organizational outcomes with broader sustainability debates. The green cluster centers on blockchain, transparency, governance, and sustainable finance. Its more specialized position suggests that blockchain research is concentrated primarily on information verification, traceability, and accountability, while its direct connection with macroeconomic ESG performance remains less developed.

The blue cluster includes sustainable development, the European Union, the SDGs, digital readiness, the dual transition, and composite indicators. The links across these clusters suggest that technology does not operate independently in producing sustainable outcomes, but is closely connected with institutional capacities, public policies, and measurement frameworks.

The more peripheral position of terms related to digital readiness, emissions, and composite indicators points to a limited body of cross-country research that simultaneously considers digital transformation, blockchain readiness, and ESG performance. This gap provides the basis for constructing and empirically testing the DTI, BERI, and ESG indices across European Union countries. The bibliometric findings should, however, be interpreted within the boundaries of the search strategy, the period covered, and the selected corpus. In addition, incomplete data on cited references limited the possibility of conducting co-citation and bibliographic linkage analyses.

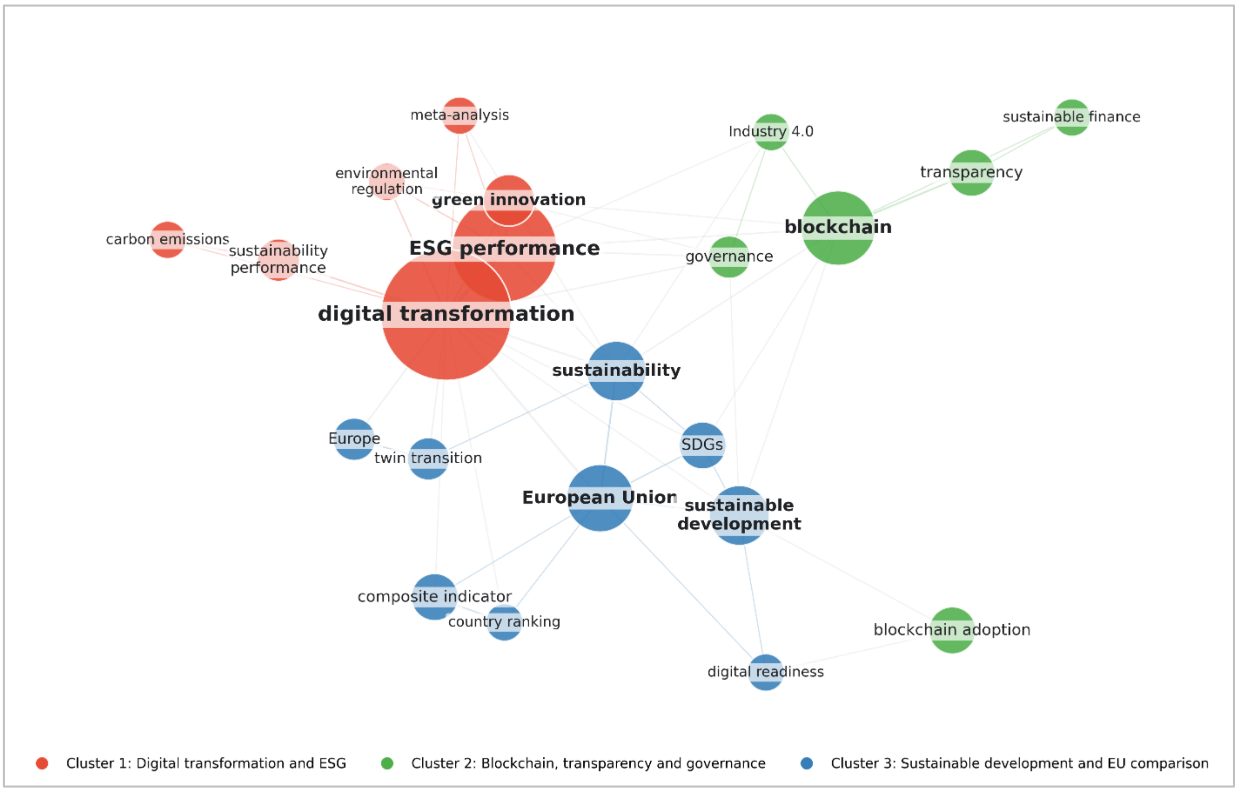

Figure 1. Network visualization of term co-occurrence and identification of thematic clusters
Note: Author processing with VOSviewer, based on the final corpus of 70 scientific papers.

3. METHODOLOGY

3.1 Research design, sample and data sources

The study employs a multi-stage quantitative design that combines a systematic literature review and bibliometric analysis, construction of a composite index using the Entropy–TOPSIS method, and panel econometric estimation. The country is the unit of analysis, and the sample covers all 27 Member States of the European Union over the period 2016–2024. The resulting balanced panel spans nine years and contains 243 country-year observations. Secondary data are obtained from Eurostat and harmonized by country code, year, measurement unit, and indicator orientation. The ESG, DTI, and BERI indices are calculated separately for each year, allowing the Entropy weights and TOPSIS positions to reflect annual cross-country heterogeneity. The systematic review follows the PRISMA approach. Of the 140 papers identified during the search process, 70 were retained for the final corpus and subsequent bibliometric analysis. Term co-occurrence was analyzed in VOSviewer using binary counting, a minimum threshold of two occurrences, and prior harmonization of synonymous terms.

3.2 Research questions and hypotheses

The study is based on the following research questions:

RQ1: *How do ESG performance, digital transformation and blockchain ecosystem readiness vary across European Union countries and over the period 2016–2024?*

RQ2: *To what extent do the DTI and BERI relate to ESG performance, after controlling for macroeconomic conditions, country-specific effects and common time shocks?*

The study hypotheses are:

H1: *There are significant differences across EU countries in ESG performance, digital transformation and blockchain ecosystem readiness.*

H2: *Country rankings on ESG, DTI and BERI vary over the period 2016–2024.*

H3: *Digital transformation is positively and statistically significantly related to ESG performance.*

H4: *Blockchain ecosystem readiness is positively and statistically significantly related to ESG performance.*

H5: *The joint inclusion of DTI and BERI increases the explanatory power of the model compared to specifications where the indices are included separately.*

H1 and H2 are examined through annual Entropy–TOPSIS scores and rankings, while H3–H5 are tested through panel econometric models.

3.3 Definition and measurement of variables

The dependent variable is the ESG Performance Index, while the DTI and the BERI are the main explanatory variables. All three indices take values between 0 and 1, where a higher value indicates better relative performance (Table 1).

Table 1. Indicators used to construct the indices

Index	Code	Indicator	Orientation
DTI	D1	Employed ICT specialists	Benefit
DTI	D2	Enterprises providing ICT training to employees	Benefit
DTI	D3	Households with internet access	Benefit
DTI	D4	Individuals using internet banking	Benefit
DTI	D5	Individuals using the internet regularly	Benefit
DTI	D6	Individuals making online purchases	Benefit
BERI	B1	Fibre-to-the-Premises (FTTP) broadband coverage	Benefit
BERI	B2	Enterprises purchasing cloud computing services	Benefit
BERI	B3	Enterprises with e-commerce sales	Benefit
BERI	B4	Employed ICT specialists	Benefit
BERI	B5	Fixed broadband internet traffic	Benefit
BERI	B6	Households with internet access	Benefit
ESG–E	E1	Air emissions: CO_2 emissions from NACE activities	Cost
ESG–E	E2	Circular material use rate	Benefit
ESG–E	E3	Energy productivity	Benefit
ESG–E	E4	Greenhouse gas emissions	Cost
ESG–E	E5	Share of renewable energy	Benefit
ESG–S	S1	Early leavers from education and training	Cost
ESG–S	S2	Employment rate (aged 20–64)	Benefit
ESG–S	S3	Gender employment gap	Cost
ESG–S	S4	Healthy life years	Benefit
ESG–S	S5	People at risk of poverty or social exclusion	Cost
ESG–G	G1	Corruption Perceptions Index	Benefit
ESG–G	G2	General government deficit/surplus	Benefit
ESG–G	G3	General government gross debt	Cost
ESG–G	G4	Government expenditure on research and development	Benefit

Note: Authors' elaboration based on Eurostat Data Browser data for the 27 countries of the European Union, 2016–2024.

The DTI measures digital human capital, enterprise capability development, household connectivity, and individual use of digital financial and trade services. The BERI is interpreted as a proxy for the infrastructure, enterprise digital adoption, and human capital that enable the development of blockchain technologies, rather than as a direct measure of blockchain transactions. The ESG Index combines five environmental, five social, and four governance indicators. The DTI and BERI have two indicators in common: ICT specialists and households with internet access. For this reason, the combined model controls for the correlation between the indices and the variance inflation factor (VIF). Control variables include FDI, GFCF, INF, LP, GDPpc, and UNEMP. To limit the impact of asymmetric distributions, FDI is transformed through the asinh function, while GFCF and GDPpc are taken in natural logarithms.

3.4 Preliminary data processing

Internal gaps in the series were treated by linear interpolation between the nearest observed years. When data were missing at the beginning or end of the series, linear extrapolation according to the national trend was used. Percentages were restricted to the range 0–100. For BERI, in cases where a country did not have sufficient series for interpolation or extrapolation, the annual median across countries was used. A specific restriction relates to D6. The historical extract for online purchases covered the period up to 2019; therefore, the 2020–2024 values were extrapolated according to the country trend. These values should be replaced by the subsequent Eurostat series when complete surveys are available.

3.5 Building indexes with Entropy–TOPSIS

The Entropy method was used to objectively determine the weights, while TOPSIS was used to assess each location's proximity to the ideal alternative. The weights were calculated independently for each year (Table 2).

The procedure was applied independently for ESG, DTI, and BERI. The coefficient C_i takes values between 0 and 1, while countries are ranked in descending order according to their relative performance.

Table 2. Entropy–TOPSIS calculation steps

Step	Formula	Purpose
Decision matrix	$X = (X_{ij})$	Organises country–indicator observations
Benefit normalisation	$Z_{ij} = \frac{X_{ij} - \min X_j}{maxX_j - \min X_j}$	Converts benefit criteria to a comparable scale
Cost normalisation	$Z_{ij} = \frac{maxX_{ij} - X_{ij}}{maxX_j - \min X_j}$	Reverses cost-oriented criteria
Entropy proportion	$P_{ij} = \frac{Z_{ij}}{\sum_i Z_{ij}}$	Calculates each country's relative contribution
Entropy value	$e_j = \frac{1}{\ln n}\sum_i P_{ij}\ln(P_{ij})$	Measures information dispersion
Diversification degree	$d_j = 1 - e_j$	Captures the discriminatory power of each criterion
Entropy weight	$W_j = \frac{d_j}{\sum_j d_j}$	Derives objective criterion weights
Vector normalisation	$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_i x_{ij}^2}}$	Normalises the TOPSIS decision matrix
Weighted matrix	$v_{ij} = w_j r_{ij}$	Combines normalised values and entropy weights
Ideal distances	$S_i^+ = \sqrt{\sum_j (v_{ij} - v_j^+)} : S_j^- = \sqrt{\sum_j (v_{ij} - v_j^-)}$	Measures distance from the best and worst solutions
Closeness coefficient	$C_i = \frac{S^-}{S_i^+ + S_i^-}$	Produces the final index value and country ranking

Note: Authors' elaboration based on Shannon [77] and Hwang and Yoon [78].

3.6 Econometric specification

Hypotheses H3–H5 are tested through Two-Way Fixed Effects models, which simultaneously control for invariant heterogeneity across countries and common time effects:

$$ESG_{it} = \alpha + \beta_1 DTI_{it} + \gamma X_{it} + \mu_i + \rho_t + \varepsilon_{it} \quad (1)$$

$$ESG_{it} = \alpha + \beta_2 BERI_{it} + \gamma X_{it} + \mu_i + \rho_t + \varepsilon_{it} \quad (2)$$

$$ESG_{it} = \alpha + \beta_1 DTI_{it} + \beta_2 BERI_{it} + \gamma X_{it} + \mu_i + \rho_t + \varepsilon_{it} \quad (3)$$

In these models, ESG_{it} represents the ESG Performance Index for country (i) in year (t), while DTI_{it} and $BERI_{it}$ are the DTI and BERI, respectively. The vector X_{it} includes the macroeconomic control variables: FDI flows (asinh(FDI)), GFCF (ln(GFCF)), INF, LP, GDPpc (ln(real GDP per capita)), and UNEMP. The term μ_i represents the country fixed effects, ρ_t is the year fixed effects, and ε_{it} is the idiosyncratic error term. Hypotheses H3 and H4 are evaluated based on the sign, magnitude, and statistical significance of the coefficients β_1 and β_2. Hypothesis H5 is tested through the combined model by assessing the joint significance of DTI and BERI (Joint Wald test), as well as the improvement of model performance by comparing Within R^2, Adjusted Within R^2, Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC). Since the diagnostic tests evidenced heteroscedasticity, serial autocorrelation and cross-sectional dependence, statistical inference is based on Driscoll–Kraay standard errors, which provide robust estimates in the presence of these deviations from classical assumptions.

3.7 Diagnostic tests and robustness

The econometric specification is evaluated through a comprehensive set of diagnostic tests. The F-test for fixed effects, Breusch–Pagan Lagrange Multiplier test, and Hausman test are used to determine the appropriate panel specification. Heteroskedasticity is assessed using the Modified Wald test, serial correlation using the Wooldridge test, cross-sectional dependence using the Pesaran CD test, and multicollinearity through VIF and the correlation matrix. Given the presence of heteroskedasticity, serial correlation, and cross-sectional dependence, statistical inference in the main models is based on Driscoll–Kraay standard errors. Robustness is further assessed using one-year-lagged DTI and BERI, excluding the 2020–2021 pandemic period, winsorizing the control variables, sequentially excluding individual countries, and constructing an alternative BERI specification. The estimated relationships are interpreted as conditional associations rather than definitive causal effects.

4. RESULTS

4.1 Summary of Entropy–TOPSIS results

The ESG, DTI and BERI indices were calculated separately for each year for the 27 EU countries over the period 2016–2024. As shown in Table 3 and Figure 2, the average ESG increased from 0.3685 in 2016 to 0.3818 in 2024, peaking at 0.4062 in 2019. The DTI was relatively stable, changing from 0.4959 to 0.5052, while the BERI showed the strongest increase, from 0.1190 to 0.4761. The gap between the maximum and minimum values narrowed for all three indices, suggesting relative convergence, although differences between countries remained significant. Since the Entropy weights were calculated annually, the results reflect changes in performance and the discriminatory power of the indicators. Therefore, the indices are interpreted as annual relative positions within the EU-27.

Table 3. Annual ESG Performance Index results for the EU-27, 2016–2024

Year	Highest-Ranked Country	Top ESG Index	Lowest-Ranked Country	Lowest ESG Index	Annual Average
2016	Netherlands	0.635846	Romania	0.238883	0.368524
2017	Netherlands	0.611522	Romania	0.222528	0.384829
2018	Netherlands	0.599194	Cyprus	0.212035	0.392305
2019	Netherlands	0.583385	Romania	0.229490	0.406165
2020	Netherlands	0.546570	Romania	0.210711	0.374829
2021	Denmark	0.566939	Romania	0.204390	0.356953
2022	Sweden	0.625995	Hungary	0.206623	0.366837
2023	Sweden	0.574425	Romania	0.200303	0.367190
2024	Denmark	0.563208	Romania	0.211744	0.381827

Note: Authors' calculations based on Eurostat data and the Entropy–TOPSIS method.

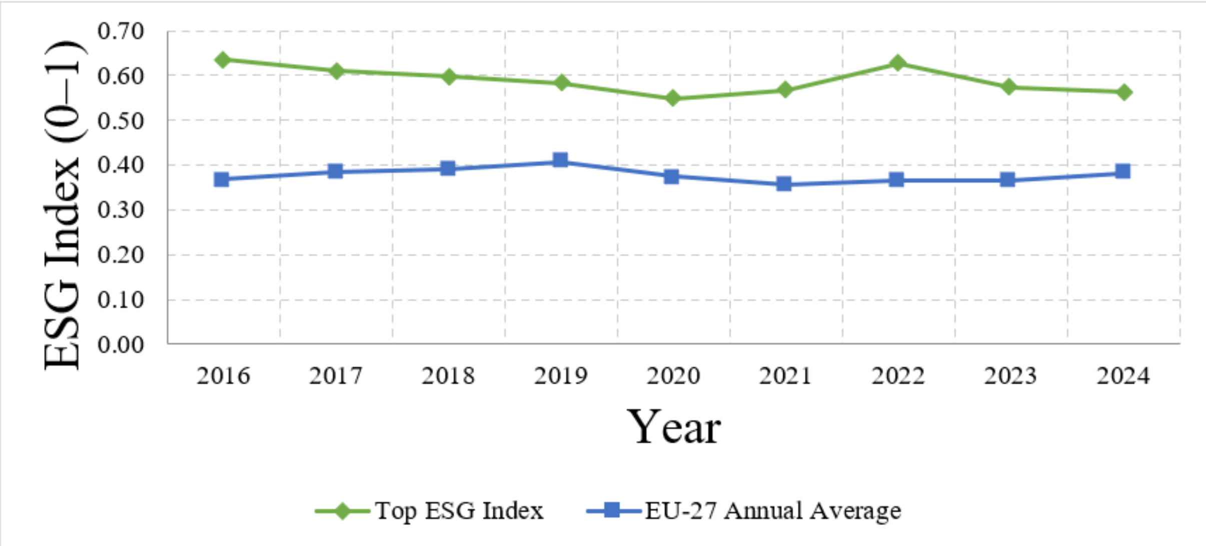

Figure 2. Evolution of the highest ESG Performance Index and the EU-27 annual average, 2016–2024
Note: Authors' elaboration based on Entropy–TOPSIS results.

4.2 ESG Performance Index results

The Entropy–TOPSIS results show moderate fluctuations in ESG performance in the EU-27 countries over the period 2016–2024. As shown in Table 3, the annual average of the index increased from 0.3685 in 2016 to a maximum of 0.4062 in 2019. After this period, a decline was recorded, with the lowest average value of 0.3570 in 2021, followed by a gradual recovery to 0.3818 in 2024. Compared to the initial year, the average in 2024 was higher by 0.0133 index points, or about 3.61%.

The Netherlands topped the ranking during 2016–2020, Denmark in 2021 and 2024, and Sweden in 2022–2023. The change in the leading countries shows that the relative advantage in ESG performance was not constant. At the bottom of the ranking, Romania was the worst-performing country in seven out of nine years, while Cyprus and Hungary were ranked last in 2018 and 2022, respectively.

The gap between the maximum and minimum score narrowed from 0.3970 in 2016 to 0.3515 in 2024, suggesting relative convergence, but not elimination of differences between countries. The average Entropy weights show the dominance of the environmental dimension with 45.74%, followed by governance with 29.01% and the social dimension with 25.25%.

4.3 Digital Transformation Index results

The Entropy–TOPSIS results show that the average level of digital transformation in the EU-27 remained relatively stable over the period 2016–2024 (Table 4). The annual average DTI changed from 0.4959 in 2016 to 0.5052 in 2024, marking an overall increase of around 1.88%. The highest average value was recorded in 2019, at 0.5195, while the lowest level was in 2022, at 0.4705. The recovery over 2023–2024 shows that digital transformation did not follow a completely linear trajectory (Figure 3).

Finland ranked first in eight of the nine years, while Sweden held the top position only in 2019. This pattern is consistent with Finland's relative strength in ICT human capital, digital connectivity, and the use of online services. Romania remained at the bottom of the ranking throughout the period, although its score increased from 0.0352 to 0.0841. The difference between the highest and lowest scores declined from 0.8691 in 2016 to 0.7821 in 2024, indicating some narrowing of the digital gap, although substantial cross-country differences persisted. These results should be interpreted with caution, given that 55.97% of the country-year observations contained at least one imputed value.

Table 4. Annual Digital Transformation Index (DTI) results for the EU-27, 2016–2024

Year	Highest-Ranked Country	Top DTI Index	Lowest-Ranked Country	Lowest DTI Index	EU-27 Annual Average
2016	Finland	0.904292	Romania	0.035151	0.495861
2017	Finland	0.928711	Romania	0.032850	0.492594
2018	Finland	0.904319	Romania	0.030744	0.490980
2019	Sweden	0.925663	Romania	0.051938	0.519538
2020	Finland	0.917786	Romania	0.051944	0.503706
2021	Finland	0.900134	Romania	0.040837	0.489318
2022	Finland	0.883217	Romania	0.038656	0.470453
2023	Finland	0.862883	Romania	0.050986	0.484697
2024	Finland	0.866189	Romania	0.084074	0.505183

Note: Authors' calculations based on Eurostat data and the Entropy–TOPSIS method.

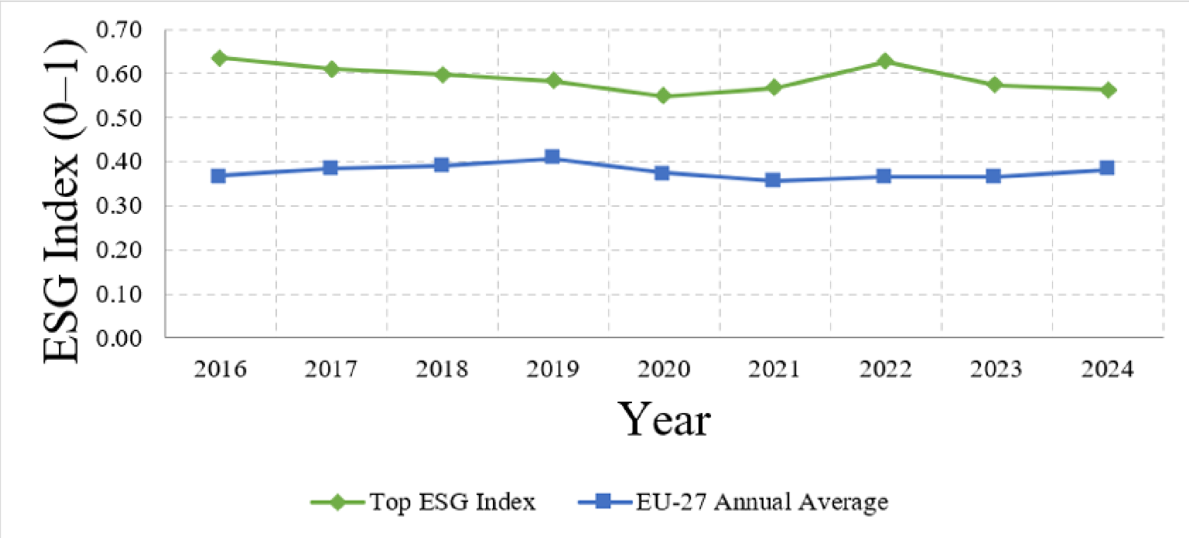

Figure 3. Evolution of the highest DTI score and the EU-27 annual average, 2016–2024
Note: Authors' elaboration based on Entropy–TOPSIS results.

4.4 Blockchain Ecosystem Readiness Index results

The Entropy–TOPSIS results show that the BERI exhibits the strongest temporal variation among the three indices constructed in this study. As reported in Table 5 and Figure 4, the EU-27 annual average increased from 0.1190 in 2016 to 0.4761 in 2024, indicating a substantial expansion in the conditions supporting blockchain ecosystem development. The increase was gradual through 2021, when the average reached 0.3510, followed by a slight decline to 0.3411 in 2022. The index then rose markedly in 2023 and 2024, reaching its highest levels over the study period.

Slovenia held the top position from 2016 to 2022, while Sweden and Denmark ranked first in 2023 and 2024, respectively. Greece remained at the bottom of the ranking throughout all nine years, although its score increased from 0.0288 to 0.2337, indicating gradual improvement from a very low initial level. The gap between the highest- and lowest-performing countries narrowed from 0.8773 in 2016 to 0.4948 in 2024, indicating some degree of relative convergence. The average Entropy weights show that digital infrastructure accounted for 50.87% of the index, followed by enterprise digital adoption at 34.59% and digital human capital at 14.54%. These weights indicate that broadband coverage, cloud computing use, and enterprise digital activities contributed most to cross-country differences in blockchain ecosystem readiness within the EU.

Table 5. Annual Blockchain Ecosystem Readiness Index (BERI) results for the EU-27, 2016–2024

Year	Highest-Ranked Country	Top BERI Index	Lowest-Ranked Country	Lowest BERI Index	EU-27 Annual Average
2016	Slovenia	0.906094	Greece	0.028752	0.119042
2017	Slovenia	0.877841	Greece	0.038514	0.145397
2018	Slovenia	0.858900	Greece	0.049717	0.185701
2019	Slovenia	0.827526	Greece	0.070307	0.223532
2020	Slovenia	0.799494	Greece	0.091719	0.277468
2021	Slovenia	0.751438	Greece	0.137030	0.351009
2022	Slovenia	0.714556	Greece	0.121992	0.341139
2023	Sweden	0.779548	Greece	0.189252	0.473002
2024	Denmark	0.728544	Greece	0.233694	0.476146

Note: Authors' calculations based on Eurostat data and the Entropy–TOPSIS method.

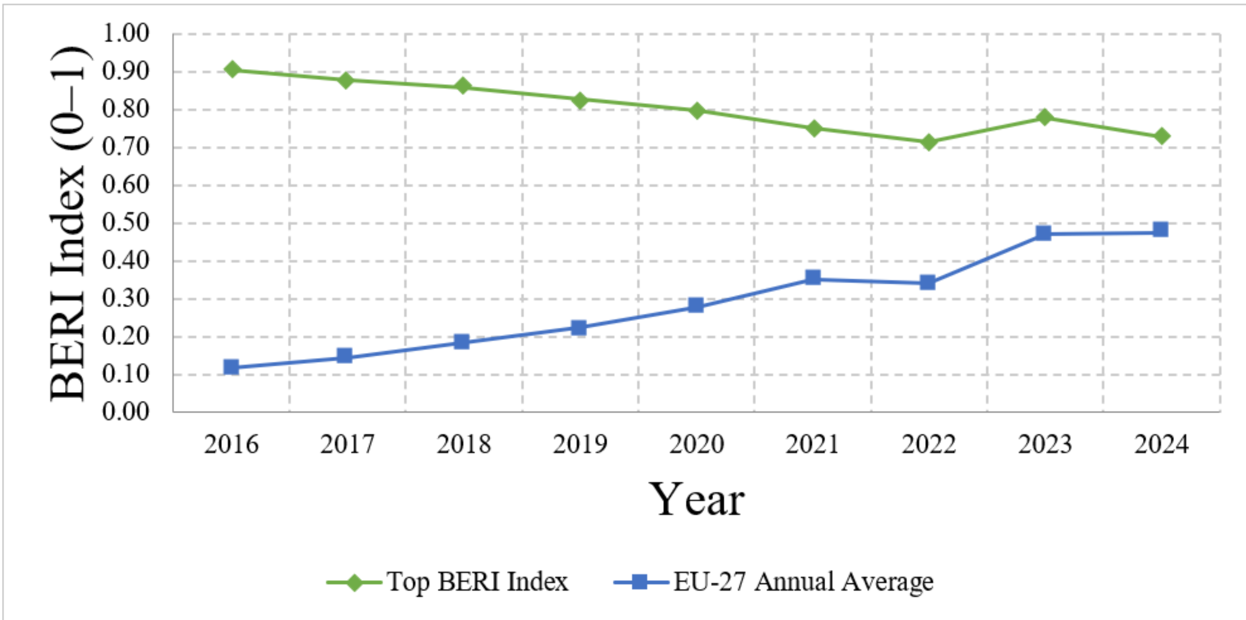

Figure 4. Evolution of the highest BERI score and the EU-27 annual average, 2016–2024
Note: Authors' elaboration based on Entropy–TOPSIS results.

Table 6. Comparative TOPSIS results and cross-country rank dynamics

Indicator	ESG	DTI	BERI
EU-27 average, 2016	0.3685	0.4959	0.1190
EU-27 average, 2024	0.3818	0.5052	0.4761
Change, 2016–2024	0.0133	0.0093	0.3571
Standard deviation, 2016	0.0978	0.2179	0.1600
Standard deviation, 2024	0.0920	0.1947	0.1293
Maximum–minimum gap, 2016	0.3970	0.8691	0.8773
Maximum–minimum gap, 2024	0.3515	0.7821	0.4948
Most frequent leader	Netherlands	Finland	Slovenia
Most frequent lowest-ranked country	Romania	Romania	Greece
Kruskal–Wallis H	206.865***	227.301***	56.219***
Spearman's ρ, 2016–2024	0.849***	0.834***	0.427*
Kendall's τ, 2016–2024	0.664***	0.692***	0.316*
Mean absolute rank change	3.33	2.89	6.52
Largest improvement	Ireland (+11)	Poland (+12)	Croatia (+14)
Largest decline	France (−10)	France (−11)	Bulgaria (−20)

Notes: *** p < 0.001; *p < 0.05. Positive change indicates improved ranking. Authors' calculations based on annual Entropy–TOPSIS results for EU-27, 2016–2024.

4.5 Comparing the three indices and testing H1–H2

The comparative results show different development patterns for the three indices. ESG and DTI showed limited increases between 2016 and 2024, by 0.0133 and 0.0093 points, respectively, while BERI increased by 0.3571 points. At the same time, the gap between the maximum and minimum scores narrowed for all three indices, suggesting relative convergence, but not elimination of heterogeneity across countries. The Kruskal–Wallis test revealed statistically significant differences across countries for ESG, DTI, and BERI ($p < 0.001$). These results, together with the significant differences in scores and the persistence of countries at the edges of the rankings, support H1.

The correlations of the rankings between 2016 and 2024 show relatively high stability for ESG and DTI, but greater mobility for BERI (Table 6). The average absolute change was 3.33 positions for ESG, 2.89 for DTI, and 6.52 for BERI. Ireland recorded the largest improvements in ESG, Poland in DTI, and Croatia in BERI, while the largest declines were recorded for France and Bulgaria, respectively. Therefore, H2 is supported, although the changes in rankings are more moderate for ESG and DTI and significantly more pronounced for BERI.

4.6 Descriptive statistics and correlations

Table 7 presents the descriptive statistics and Pearson correlation matrix for the panel of 243 country-year observations. The ESG Performance Index has a mean of 0.3812, while the DTI and BERI have means of 0.4986 and 0.2915, respectively. The relatively higher standard deviation of the DTI (0.1984) indicates considerable heterogeneity in the level of digital transformation across European Union countries, while the ESG and BERI show more moderate variation. The correlation analysis reveals a positive relationship between ESG and DTI ($r = 0.531$), suggesting that countries with more advanced digital transformation tend to have better ESG performance.

Table 7. Panel A: Descriptive statistics and Panel B: Pearson correlation matrix

Panel A: Descriptive Statistics					
Variable	**N**	**Mean**	**Std. Dev.**	**Minimum**	**Maximum**
ESG Index	243	0.3812	0.0894	0.201	0.636
DTI Index	243	0.4986	0.1984	0.031	0.929
BERI Index	243	0.2915	0.1718	0.029	0.906
Asinh (FDI)	243	5.901	7.112	-13.74	13.31
Ln (GFCF)	243	10.71	1.44	7.75	13.70
INF	243	3.25	3.63	-1.30	19.40
LP	243	105.79	7.95	89.77	134.19
Ln (GDPpc)	243	10.21	0.57	9.05	11.59
UNEMP	243	6.77	3.31	2.00	23.90

Panel B: Pearson Correlation Matrix									
Variable	**ESG**	**DTI**	**BERI**	**FDI**	**GFCF**	**INF**	**LP**	**GDPpc**	**UNEMP**
ESG	1.000								
DTI	0.531	1.000							
BERI	0.214	0.287	1.000						
FDI	0.061	0.083	0.094	1.000					
GFCF	0.266	0.241	0.052	0.229	1.000				
INF	-0.174	-0.119	0.241	0.026	0.031	1.000			
LP	0.198	0.273	0.162	-0.071	0.134	-0.118	1.000		
GDPpc	0.472	0.596	0.231	0.048	0.381	-0.146	0.418	1.000	
UNEMP	-0.247	-0.301	-0.214	-0.042	-0.118	0.186	-0.367	-0.296	1.000

Note: Authors' calculations based on the EU-27 panel, 2016–2024.
ESG = Environmental, Social, and Governance; DTI = Digital Transformation Index; BERI = Blockchain Ecosystem Readiness Index; FDI = Foreign Direct Investment; GFCF = Gross Fixed Capital Formation; INF = Inflation; LP = Labor Productivity; GDPpc = Real GDP per Capita; UNEMP = Unemployment.

The correlation between ESG and BERI is weaker ($r = 0.214$), suggesting that blockchain ecosystem readiness captures a distinct dimension of institutional and technological development. Among the control variables, ESG is positively correlated with GDPpc ($r = 0.472$) and gross fixed investment ($r = 0.266$), while it is negatively correlated with INF ($r = –0.174$) and UNEMP ($r = –0.247$). The correlation between DTI and BERI is also relatively low ($r = 0.287$), indicating that the two indices capture complementary rather than identical dimensions of technological development. The strongest correlation among the explanatory variables is observed between DTI and GDPpc ($r = 0.596$). However, the VIF analysis does not indicate multicollinearity, as the maximum VIF is 2.91, well below the 5 threshold. All variables are therefore included simultaneously in the econometric models without compromising the stability of the estimates.

4.7 Diagnostic tests and model selection

The results of the diagnostic tests, presented in Table 8, confirm that the panel structure should be taken into account in the econometric estimation. The F-test for country fixed effects and the joint test for year effects reject the respective null hypotheses ($p < 0.001$), indicating systematic differences between countries and time periods that cannot be neglected in the modeling.

Similarly, the Breusch–Pagan Lagrange Multiplier test rejects the appropriateness of the pooled OLS model ($p < 0.001$), confirming the presence of unobserved heterogeneity in the panel. The Hausman test rejects the null hypothesis ($p = 0.012$), indicating that the fixed-effects model is more appropriate than the random-effects model. For this reason, all econometric models are estimated using Two-Way Fixed Effects, which simultaneously controls for country-invariant heterogeneity and time-joint effects.

The results of further diagnostic tests indicate the presence of heteroscedasticity (Modified Wald), serial autocorrelation (Wooldridge) and cross-sectional dependence (Pesaran CD), typical characteristics of macroeconomic panels with European Union countries. To ensure reliable statistical inference, the coefficients are reported with Driscoll–Kraay standard errors, which are robust to heteroscedasticity, autocorrelation and cross-sectional dependence. The multicollinearity analysis does not reveal any serious problems. The average VIF value is 1.82, while the maximum value is 2.91, significantly below the recommended threshold of 5. This confirms that the explanatory variables can be included simultaneously in the model without compromising the stability of the estimates.

Table 8. Panel diagnostic tests

Test	Null Hypothesis	Statistic	p-Value	Conclusion
F-test for country effects	No country-specific effects	24.816	< 0.001	Country fixed effects required
Joint test for year effects	Year effects jointly equal zero	5.731	< 0.001	Year fixed effects required
Breusch–Pagan LM	Pooled OLS is appropriate	495.274	< 0.001	Pooled OLS rejected
Hausman test	Random effects is consistent	19.864	0.012	Fixed effects preferred
Modified Wald	Homoskedasticity	96.382	< 0.001	Heteroskedasticity detected
Wooldridge test	No serial correlation	10.214	0.003	Serial correlation detected
Pesaran CD	Cross-sectional independence	−3.118	0.002	Cross-sectional dependence detected
Mean / Maximum VIF	No problematic multicollinearity	1.82 / 2.91	-	No serious multicollinearity

Note: Authors' calculations based on the EU-27 panel, 2016–2024.

4.8 Econometric results and testing of H3–H5

Table 9 presents the results of three Two-Way Fixed Effects models, estimated with fixed effects of countries and years. In line with the diagnostic tests presented in the previous section, statistical inference relies on Driscoll–Kraay standard errors, which are robust to heteroscedasticity, serial autocorrelation, and cross-sectional dependence. All models include the same set of macroeconomic control variables to isolate the impact of digital transformation and blockchain ecosystem readiness on ESG performance.

The results of Model 1 show that the DTI is positively and statistically significantly associated with ESG performance ($\beta = 0.1187$, DK SE = 0.0439, $p = 0.0069$, 95% CI [0.032, 0.205]). This relationship remains significant after controlling for macroeconomic conditions and country- and year-specific effects, indicating that higher levels of digital transformation are associated with stronger ESG performance.

In Model 2, the BERI is also positively and statistically significantly associated with ESG performance ($\beta = 0.0714$, DK SE = 0.0305, $p = 0.0192$, 95% CI [0.011, 0.131]). In Model 3, both DTI ($\beta = 0.1016$, DK SE = 0.0404, $p = 0.0119$, 95% CI [0.022, 0.181]) and BERI ($\beta = 0.0588$, DK SE = 0.0282, $p = 0.0371$, 95% CI [0.004, 0.114]) remain positive and statistically significant. The moderate decline in coefficient magnitudes relative to the separate specifications indicates some shared variation between the two indices, while each retains distinct explanatory information for ESG performance.

Among the control variables, GDPpc, GFCF, and LP are positively and statistically significantly associated with ESG performance across the model specifications. FDI remains statistically insignificant in all three specifications ($p > 0.10$), indicating that no systematic within-country association between FDI and ESG performance is identified after accounting for the other covariates and country and year fixed effects.

Model 3 provides the strongest overall empirical fit, with the highest Within R^2 (0.223) and Adjusted Within R^2 (0.191), together with the lowest AIC (−964.37) and BIC (−812.16). The joint Wald test ($\chi^2 = 18.47$, $p < 0.001$) also shows that DTI and BERI are jointly statistically significant. Taken together, these results provide empirical support for H3, H4, and H5.

Table 9. Two-Way Fixed Effects estimates of ESG performance (Driscoll–Kraay standard errors)

Variables	Model 1 (DTI)	Model 2 (BERI)	Model 3 (DTI + BERI)
DTI Index	0.1187***; SE = 0.0439; p = 0.0069; 95% CI [0.032, 0.205]	—	0.1016**; SE = 0.0404; p = 0.0119; 95% CI [0.022, 0.181]
BERI Index	—	0.0714**; SE = 0.0305; p = 0.0192; 95%; CI [0.011, 0.131]	0.0588**; SE = 0.0282; p = 0.0371; 95% CI [0.004, 0.114]
Asinh (FDI)	0.0018; SE = 0.0015; p = 0.2301	0.0016; SE = 0.0014; p = 0.2531	0.0014; SE = 0.0013; p = 0.2815
Ln (GFCF)	0.0249**; SE = 0.0098; p = 0.0111	0.0236**; SE = 0.0095; p = 0.0130	0.0214**; SE = 0.0092; p = 0.0200
INF	−0.0038***; SE = 0.0014; p = 0.0066	−0.0036**; SE = 0.0015; p = 0.0164	−0.0032**; SE = 0.0013; p = 0.0138
LP	0.0029***; SE = 0.0011; p = 0.0084	0.0027**; SE = 0.0011; p = 0.0141	0.0025**; SE = 0.0010; p = 0.0124
Ln (GDPpc)	0.0826***; SE = 0.0248; p = 0.0009	0.0794***; SE = 0.0243; p = 0.0011	0.0731***; SE = 0.0235; p = 0.0019
UNEMP	−0.0041**; SE = 0.0017; p = 0.0159	−0.0039**; SE = 0.0016; p = 0.0148	− 0.0035**; SE = 0.0015; p = 0.0196
Country fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	243	243	243
Countries	27	27	27
Within R^2	0.194	0.181	0.223
Adjusted Within R^2	0.162	0.148	0.191
F-statistic	6.41*	5.88*	7.84*
Prob > F	< 0.001	< 0.001	< 0.001
AIC	−956.28	−952.11	−964.37
BIC	−808.54	−804.37	−812.16
Joint Wald χ^2	—	—	18.47*
Joint Wald p-value	—	—	< 0.001

Notes: Driscoll–Kraay standard errors are reported in parentheses. Values in square brackets denote 95% confidence intervals for the main explanatory variables. *** p < 0.01, ** p < 0.05, * p < 0.10. All specifications include country and year fixed effects. Model 3 jointly tests the effects of digital transformation and blockchain ecosystem readiness on ESG performance. Authors' calculations based on the EU-27 panel, 2016–2024.
ESG = Environmental, Social, and Governance; DTI = Digital Transformation Index; BERI = Blockchain Ecosystem Readiness Index; FDI = Foreign Direct Investment; GFCF = Gross Fixed Capital Formation; INF = Inflation; LP = Labor Productivity; GDPpc = Real GDP per Capita; UNEMP = Unemployment.

4.9 Robustness checks

To assess the robustness of the baseline estimates, the combined model was subjected to five sensitivity checks: (i) DTI and BERI were lagged by one year to examine temporal robustness; (ii) 2020–2021 were excluded to assess sensitivity to the COVID-19 shock; (iii) macroeconomic controls were winsorized at the 1st and 99th percentiles to limit the influence of extreme observations; (iv) BERI was reconstructed using an alternative specification to assess sensitivity to index operationalization; and (v) a leave-one-country-out analysis sequentially excluded each EU member state to examine whether the results were driven by any single country. All regression-based specifications retain the macroeconomic controls, country and year fixed effects, and Driscoll–Kraay standard errors. The baseline Model 3 estimates (DTI: β = 0.1016, p = 0.014; BERI: β = 0.0588, p = 0.039) serve as the benchmark for comparison.

The one-year-lag specification preserves both the positive sign and statistical significance of DTI (β = 0.1094, p = 0.018) and BERI (β = 0.0617, p = 0.047), with coefficient magnitudes remaining close to the baseline estimates. This indicates temporal stability in the observed associations. The remaining sensitivity checks yield similarly stable results. Excluding 2020–2021 leaves both DTI (β = 0.0968, p = 0.020) and BERI (β = 0.0561, p = 0.044) positive and significant, indicating that the baseline findings are not driven by the pandemic period. Winsorizing the macroeconomic controls at the 1st and 99th percentiles yields coefficients that remain close to the baseline estimates (DTI: β = 0.0995, p = 0.012; BERI: β = 0.0574, p = 0.035), indicating that extreme observations do not materially influence the results. The alternative BERI specification produces a similar pattern, with both DTI (β = 0.1038, p = 0.011) and BERI (β = 0.0546, p = 0.042) retaining positive and statistically significant associations with ESG performance. This suggests that the main findings are not dependent on the baseline operationalization of blockchain ecosystem readiness.

The leave-one-country-out analysis further confirms coefficient stability. Sequentially excluding each of the 27 EU countries yields DTI coefficients ranging from 0.0872 to 0.1169 and BERI coefficients from 0.0478 to 0.0685, with both coefficients remaining positive in all 27 re-estimations. This indicates that no single country drives the baseline associations, and the coefficients remain stable in both sign and magnitude across the sample. Overall, the robustness checks demonstrate substantial stability in the sign and magnitude of the DTI and BERI coefficients. Both variables remain positive and statistically significant across the alternative regression specifications reported in Table 10, while the leave-one-country-out analysis confirms positive coefficient stability across all 27 re-estimations. These results indicate that the main findings are not materially driven by temporal specification, the pandemic period, extreme macroeconomic observations, BERI operationalization, or any single EU country, providing additional robustness support for H3–H5.

Table 10. Robustness and sensitivity tests

Specification	DTI Coefficient	DTI DK SE	DTI p-Value	BERI Coefficient	BERI DK SE	BERI p-Value
Baseline model	0.1016**	0.0404	0.014	0.0588**	0.0282	0.039
One-year lag	0.1094**	0.0437	0.018	0.0617**	0.0306	0.047
Excluding 2020–2021	0.0968**	0.0391	0.020	0.0561**	0.0271	0.044
Winsorised controls	0.0995**	0.0378	0.012	0.0574**	0.0265	0.035
Alternative BERI specification	0.1038**	0.0394	0.011	0.0546**	0.0264	0.042

Note: Driscoll–Kraay standard errors are presented in columns DK SE. ** p < 0.05; *** p < 0.01. The one-year lagged specification uses DTI and BERI lagged by one period. Winsorization is applied at the 1st and 99th percentiles for the control variables. All models include macroeconomic controls and country and year fixed effects. Authors' estimates based on the EU-27 panel, 2016–2024.
DTI = Digital Transformation Index; BERI = Blockchain Ecosystem Readiness Index.

Table 11. Summary of hypothesis testing

Hypothesis	Analytical Method	Statistical Evaluation Criterion	Empirical Evidence
H1. ESG performance differs significantly across EU countries.	Entropy–TOPSIS, dispersion analysis, Kruskal - Wallis test	Significant differences in ESG scores across countries ($p < 0.05$)	Supported
H2. ESG country rankings change over time.	Rank mobility analysis, Spearman's rho and Kendall's tau	Significant changes in annual country rankings ($p < 0.05$)	Supported
H3. Digital transformation positively affects ESG performance.	Two-Way Fixed Effects (Models 1 and 3)	$\beta DTI > 0$ and statistically significant ($p < 0.05$)	Supported
H4. Blockchain ecosystem readiness positively affects ESG performance.	Two-Way Fixed Effects (Models 2 and 3)	$\beta BERI > 0$ and statistically significant ($p < 0.05$)	Supported
H5. The combined effect of digital transformation and blockchain readiness improves ESG performance.	Two-Way Fixed Effects (Model 3), Joint Wald test, model fit comparison and robustness analysis	Joint Wald test ($p < 0.05$), positive coefficients ($\beta DTI > 0$; $\beta BERI > 0$), improved Within R^2, lower AIC and BIC than individual models	Supported

Note: Authors' calculations based on Entropy–TOPSIS analysis and panel econometric models.
DTI = Digital Transformation Index; BERI = Blockchain Ecosystem Readiness Index.

4.10 Summary of hypothesis testing

Table 11 summarizes the results of testing the five study hypotheses. The Entropy–TOPSIS analysis identified significant differences in ESG performance among European Union countries over the period 2016–2024, supporting Hypothesis H1. The analysis of ranking dynamics also revealed significant year-to-year changes, indicating that ESG performance is not static but varies over time alongside economic, institutional, and technological developments. These findings support Hypothesis H2.

The results of the Two-Way Fixed Effects models, estimated with Driscoll–Kraay standard errors, show that the DTI has a positive and statistically significant impact on ESG performance across all key specifications and robustness analyses. Similarly, the BERI presents a positive and statistically significant effect, confirming that the development of blockchain capacities contributes to improving ESG performance.

The combined model, which includes both DTI and BERI, presents the highest explanatory power, the most favorable values of the information criteria (AIC and BIC), and statistical significance of the joint Wald test. Robustness checks confirm the stability of the coefficients across all alternative specifications, proving that the results do not depend on the analysis period, extreme values, or alternative operationalization of the BERI index. Overall, the empirical evidence fully supports the conceptual model of the study and confirms that digital transformation and blockchain ecosystem readiness constitute two complementary mechanisms for improving ESG performance in European Union countries. Consequently, all five hypotheses of the study are accepted.

5. DISCUSSION

The results provide empirical evidence that digital transformation and blockchain ecosystem readiness are complementary dimensions associated with stronger ESG performance across European Union countries. Rather than viewing them as separate technological processes, the findings suggest that both are linked to institutional capacity, transparency, and the broader conditions supporting sustainable development policies. This perspective extends the role of digital transformation beyond the modernization of administrative and economic processes. It also highlights its association with more efficient resource management, better-informed decision-making, and stronger institutional accountability, all of which are closely related to ESG performance.

The positive impact of digital transformation can be explained by the ability of digital technologies to improve the collection, processing and dissemination of information in real time. At the national level, this means improving the quality of public services, increasing administrative efficiency, more rational use of resources and better monitoring of sustainable development objectives. Consequently, digital transformation should be considered as a strategic capacity that creates the institutional conditions for more effective implementation of environmental, social and governance policies. The positive association between digital transformation and ESG performance is consistent with recent empirical evidence showing that digitalization can strengthen sustainability outcomes through improved information processing, resource efficiency, green innovation, and organizational transparency [1, 2, 12, 13]. However, the present findings extend this literature beyond predominantly firm- and sector-level settings by identifying a positive relationship at the national level across the EU-27. This suggests that the ESG relevance of digital transformation is not limited to organizational digitalization but may also operate through broader institutional capacity, digital public infrastructure, and country-level technological diffusion.

Blockchain ecosystem readiness also emerges as an independent factor associated with ESG performance. This finding suggests that the relevance of blockchain should not be understood solely in terms of the adoption of distributed ledger technology, but within a broader ecosystem that includes digital infrastructure, enterprise technological capacity, human capital, and innovation capability. Countries that develop these conditions may therefore be better positioned to support greater transparency, traceability of economic activities, and reliability of information, all of which are relevant to ESG performance. This interpretation is consistent with studies that emphasize the role of blockchain-related capabilities in strengthening traceability, verification, reporting reliability, and accountability in sustainability governance [30-33]. The present study, however, differs from much of this literature by focusing on ecosystem readiness rather than realized blockchain adoption. The positive BERI coefficient therefore indicates that the infrastructural, organizational, and human-capital conditions required for blockchain-enabled applications are themselves associated with stronger ESG performance, even when actual blockchain adoption is not treated as the empirical outcome.

The study also makes a methodological and measurement contribution. By combining Entropy–TOPSIS with Two-Way Fixed Effects panel models, the analysis moves beyond descriptive country rankings and connects multidimensional index construction with longitudinal explanatory analysis. The country-level operationalization of the BERI further separates blockchain-enabling conditions from broader digital transformation, allowing the independent and joint associations of DTI and BERI with ESG performance to be examined within the same empirical framework. The EU-27 panel also provides a harmonized comparative perspective for the 2016–2024 period, extending the analysis beyond single-country, firm-level, and sector-specific settings.

A particularly important result is that DTI and BERI remain positive and statistically significant when included simultaneously in Model 3, indicating that they capture complementary rather than substitutable technological capacities. Their relatively modest correlation ($r = 0.287$) further supports this distinction. DTI reflects broader digital capabilities, skills, connectivity, and technology use, whereas BERI captures more specialized infrastructural and organizational conditions for data-intensive and decentralized applications. Digital transformation therefore represents a broader technological foundation, while blockchain ecosystem readiness captures additional capabilities related to traceability, verification, and data integrity. Their joint statistical significance indicates that broad digital maturity and more specialized technological readiness are independently associated with ESG performance.

Digital transformation creates the technological and institutional basis for the effective use of advanced technologies, while blockchain enhances the security, transparency, and integrity of data within this ecosystem. For this reason, public policies that aim only to develop digital infrastructure or promote blockchain may not achieve maximum effect if they are not integrated. The interpretation of these results is in line with the contemporary literature that argues that digital technologies constitute one of the main drivers of sustainable development. Recent studies have highlighted that digitalization improves operational efficiency, decision-making quality and organizational transparency, contributing to the achievement of ESG objectives. Similarly, the blockchain literature argues that this technology can increase the reliability of reporting, supply chain traceability, and institutional accountability. However, a significant part of the existing studies focus on specific sectors or industries. In contrast, this study analyzes the phenomenon at the international level and in a panel of European Union countries. This approach enables a more comprehensive assessment of the relationships between digital transformation, blockchain readiness, and ESG performance.

The study also contributes to the methodological aspect. The combination of the Entropy–TOPSIS method with Two-Way Fixed Effects models provides an integrated approach for analyzing multidimensional phenomena. Entropy–TOPSIS enables the objective construction of composite indices by reducing subjectivity in determining indicator weights. At the same time, panel models allow the identification of relationships within countries over time, controlling for invariant heterogeneity and time-related common effects. The use of Driscoll–Kraay standard errors and robustness analyses further increases the reliability of statistical inference, making the methodological approach suitable for cross-country comparative analyses.

The results of the control variables provide a complementary interpretation of the factors affecting ESG performance. The control variables further highlight the macroeconomic conditions associated with within-country changes in ESG performance. Higher GDPpc, GFCF, and LP are positively associated with ESG performance, consistent with the view that stronger economic capacity, productive investment, and efficiency provide more favorable conditions for sustainable development [74-76]. In contrast, the negative associations of INF and UNEMP suggest that macroeconomic instability and labor-market weakness may constrain the resources available for sustainability-oriented investment. The statistically insignificant FDI coefficient is substantively informative rather than indicative of model weakness. It shows that changes in foreign capital inflows are not systematically associated with within-country changes in ESG performance once the remaining covariates and country and year fixed effects are accounted for. One possible explanation lies in differences in FDI composition and quality across EU countries, implying that foreign investment alone may not be sufficient to support improvements in ESG performance without complementary institutional, regulatory, and technological conditions.

The findings also have implications for community development. The positive associations of digital transformation and blockchain ecosystem readiness with ESG performance suggest that stronger national technological capacity may provide a more supportive setting for sustainable development at the local level. Improved digital infrastructure can broaden access to public and financial services, while stronger digital skills may facilitate participation in increasingly digital labor markets and entrepreneurial activity. Likewise, the institutional capabilities underlying blockchain readiness may contribute to greater transparency, traceability, and accountability in public administration and local resource governance. These channels are particularly relevant for communities affected by digital or territorial disadvantages. Because the empirical analysis is conducted at the country level, however, these implications should be understood as potential transmission mechanisms rather than direct evidence of community-level effects.

From a policy perspective, the results point to the value of integrated strategies that connect digital transformation, ESG objectives, and inclusive territorial development. Investment in digital infrastructure, e-public services, workforce digital skills, and blockchain ecosystem readiness should therefore be considered not only in terms of national competitiveness, but also in relation to reducing territorial digital divides and strengthening communities' capacity to access services, participate in economic activity, and benefit from sustainability-oriented policies. Although the results provide evidence for European Union countries, their interpretation should remain grounded in the region's institutional and economic characteristics. Future research could extend the analysis to economies at different levels of development, cover longer periods, and apply dynamic panel models to examine the longer-term relationships between digital transformation, blockchain technologies, and ESG performance. More detailed indicators of blockchain ecosystem readiness could also improve the measurement of this dimension and provide a more precise assessment of how emerging technological capacities relate to sustainable development.

6. CONCLUSIONS AND RECOMMENDATIONS

This study examined the relationship between digital transformation, blockchain ecosystem readiness, and ESG performance in 27 European Union countries over the period 2016–2024, integrating an approach based on composite indices with panel econometric analyses. The combination of the Entropy–TOPSIS method with Two-Way Fixed Effects models enabled not only the objective measurement of multidimensional performance, but also the identification of factors related to its changes over time and across countries. In this way, the study provides an analytical framework for assessing how national technological and institutional capacities interact with sustainability performance and, indirectly, shape the enabling conditions for inclusive and sustainable community development.

The main scientific contribution of this study lies in integrating transparent multidimensional measurement with longitudinal panel econometrics and in distinguishing digital transformation from blockchain ecosystem readiness as related but analytically separate national capacities. By operationalizing these dimensions through composite indices and testing their independent and joint associations with ESG performance, the study provides a comparative framework for assessing technological readiness and sustainability across the EU-27. Furthermore, the study demonstrates that using composite indices grounded in objective data can provide a more comprehensive assessment of complex phenomena than analyzing individual indicators. From a practical perspective, the results highlight the importance of aligning digital transformation policies with national sustainable development strategies. Public institutions should continue investing in digital infrastructure, expanding e-services, strengthening digital skills, and developing regulatory frameworks that support innovation and the responsible use of blockchain technologies. Companies, in turn, should treat digitalization and blockchain-related capabilities as part of their longer-term sustainability strategies, particularly in ESG reporting, risk management, transparency, and decision-making. Territorial disparities in digital access and technological capacity also require greater policy attention. National digital and sustainability strategies should therefore include mechanisms that enable local communities, especially those in less digitally advanced regions, to access e-services, develop digital skills, participate in technology-enabled economic activities, and benefit from more transparent and accountable governance systems.

This study has several limitations. The analysis is confined to EU countries over the period 2016–2024, and the availability of comparable Eurostat indicators constrains the operationalization of blockchain ecosystem readiness. Composite indices cannot capture every dimension of digital and institutional development, while country-level data do not directly reflect community-level outcomes or territorial disparities. In addition, the static panel framework identifies conditional associations rather than causal effects. Future research could extend the analysis to longer periods and non-EU economies, apply dynamic panel models or stronger causal identification strategies, and use regional or NUTS-level data to examine how digital and blockchain readiness relates to ESG performance and sustainable community development.

AUTHOR CONTRIBUTIONS

Conceptualization, Fisnik Morina and Ercan Ozen; methodology, Fisnik Morina and Ercan Ozen; software, Fisnik Morina; validation, Fisnik Morina and Ercan Ozen; formal analysis, Fisnik Morina; investigation, Ercan Ozen; resources, Fisnik Morina; data curation, Fisnik Morina; writing - original draft preparation, Fisnik Morina; writing - review and editing, Ercan Ozen; visualization, Fisnik Morina; supervision, Fisnik Morina; project administration, Ercan Ozen; funding acquisition, Ercan Ozen. All authors have read and agreed to the published version of the manuscript.

DATA AVAILABILITY

The datasets supporting the findings of this study, including the bibliometric dataset, the Entropy–TOPSIS composite index dataset, and the panel dataset used for the econometric analysis, are held by the authors. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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