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Do Fintech, Tokenization, and Blockchain Capabilities Matter for Sustainable Investment? Evidence from a Cross-Country Analysis

Rashid Khalil

rashid.khalil@polytechnic.bh

Bahrain Polytechnic

Research Article

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Abstract

This study investigates how blockchain-related capabilities; digital infrastructure, regulatory readiness, fintech adoption, and tokenization; affect sustainable investment across countries. Though blockchain and fintech are increasingly positioned as enablers of sustainability, empirical cross-country insights remain limited. Using a balanced panel of 27 developed and emerging economies from 2017 to 2024, this study applies fixed-effects panel regression and cluster analysis to examine the association between digital financial innovation and sustainable investment size. The results reveal that digital infrastructure and fintech adoption are consistently and positively associated with sustainable investment, underscoring the role of technological readiness and innovation ecosystems in scaling ESG finance. Conversely, regulatory readiness and tokenization adoption show statistically significant but negative associations, reflecting transitional frictions and institutional adjustment costs during early adoption phases. Cluster analysis identifies three distinct country groups; leaders, followers, and laggards; based on blockchain and tokenization readiness, revealing heterogeneous development patterns. These findings suggest that blockchain's role in sustainable finance is contingent on broader institutional and digital contexts. The study contributes to the sustainable finance literature by integrating tokenization into ESG investment analysis and highlighting the structural conditions necessary for blockchain-enabled finance to succeed. Policy implications emphasize the need for supportive digital infrastructure, adaptive regulation, and integrated fintech strategies to realize the sustainability potential of emerging financial technologies.

1. Introduction

Sustainable investment has become a cornerstone of modern financial ecosystems, driven by heightened awareness of climate risks, social inequality, and the pursuit of long-term economic resilience. Institutional investors, governments, and capital markets are increasingly embedding environmental, social, and governance (ESG) criteria into financial decision-making frameworks [1, 2]. Despite this growing emphasis, achieving scale in sustainable finance remains challenging due to persisting issues of transparency, trust, and cross-border capital mobilization [3].

Concurrently, blockchain technology is gaining traction as a developing infrastructure capable of reshaping financial intermediation. With its decentralized architecture, immutable ledgers, and programmable contracts, blockchain holds significant promise for enhancing ESG verification, fund traceability, and impact reporting [4, 5]. These attributes are especially valuable in sustainable finance, where credibility of ESG claims and environmental impact measurement are central to investor confidence [6].

Recent academic interest has increasingly focused on the convergence of blockchain and sustainable investment. Studies have highlighted blockchain's potential to facilitate green bond issuance [7], optimize carbon markets [8], and improve ESG disclosure through enhanced data verifiability [9]. However, the extant literature remains fragmented and is often dominated by case studies or conceptual explorations with limited empirical generalizability. Cross-country empirical evidence on how blockchain and related digital capabilities influence sustainable investment outcomes remains notably scarce.

It is critical to recognize that blockchain adoption is not a standalone phenomenon. Its success in driving sustainable finance hinges on several complementary capabilities. Robust digital infrastructure enables scalable blockchain solutions and real-time data processing. Regulatory readiness fosters innovation while ensuring stability and investor protection. Fintech adoption plays an intermediary role, translating technological potential into accessible financial products. Tokenization, as a novel financial mechanism, enables fractionalization and liquidity of sustainable assets, enhancing market participation and monitoring [10, 11]. These interdependencies suggest that the impact of blockchain capabilities on sustainable investment is likely to be heterogeneous and context dependent.

In this light, the present study empirically investigates the role of blockchain-related capabilities in shaping sustainable investment outcomes across 27 countries from 2017 to 2024. The study focuses on four key enablers: digital infrastructure, regulatory readiness, fintech adoption, and tokenization, while controlling macro-institutional and market characteristics such as financial market development, institutional quality, economic development, and carbon pricing mechanisms. A fixed-effects panel regression model is employed to address unobserved heterogeneity and temporal trends, complemented by cluster analysis to reveal country-specific development paths.

2. Literature and Hypotheses Development

2.1. Blockchain Technology and Sustainable Finance

Blockchain technology has increasingly been recognized as a foundational infrastructure capable of reshaping financial markets through the core features of decentralization, immutability, and transparency. By facilitating secure peer-to-peer transactions, tamper-proof record-keeping, and real-time settlement, blockchain offers mechanisms to mitigate information asymmetries and enhance trust among market participants [12,13. These characteristics are particularly relevant in the context of sustainable finance, where integrity, traceability, and accountability of environmental, social, and governance (ESG) claims are critical for mitigating greenwashing risks and fostering investor confidence.

In the sustainable finance domain, blockchain enables real-time verification of ESG data, improves supply-chain transparency, and supports the tokenization of sustainable assets such as green bonds and carbon credits [14, 15]. Through smart contracts, it can automate impact-linked disbursements and compliance enforcement, thereby increasing the efficiency and effectiveness of green financial instruments [16]. These capabilities contribute to a more trustworthy financial ecosystem and promote the alignment of capital flows with long-term sustainability objectives.

However, the deployment of blockchain in sustainable finance is not an inherent development unless supported by complementary institutional and technological conditions. Digital infrastructure is needed to host blockchain platforms and facilitate real-time data flows. Regulatory frameworks must balance innovation and oversight to reduce legal uncertainties and prevent market fragmentation [17]. Additionally, the maturity of fintech ecosystems determines whether blockchain functionalities are accessible to end-

users through digital platforms, while tokenization enables the fractionalization and tradability of sustainable assets, thereby enhancing liquidity and participation [18].

Current empirical and theoretical research underscores the potential of blockchain to address structural inefficiencies in ESG investing but also cautions against over-reliance on technology without systemic readiness. For instance, studies have shown that blockchain's effectiveness varies depending on governance quality, digital adoption levels, and sector-specific applications [19, 20]. As such, blockchain should be viewed not as a panacea but as an enabler whose contribution to sustainable investment is mediated by broader institutional and digital ecosystems. Consistent with prior reviews highlighting blockchain's innovative role in sustainable finance ecosystems [21, 22], the current study positions blockchain as a foundational enabler of ESG innovation.

2.2. Digital Infrastructure and Sustainable Investment

Digital infrastructure serves as a fundamental enabler for deploying blockchain-based financial ecosystems and fostering innovation in sustainable finance. It encompasses broadband internet penetration, mobile and digital payment systems, cloud computing capacity, and access to information and communication technologies (ICTs). These elements collectively reduce transaction costs, improve data availability, and enable real-time financial transactions, thus creating a conducive environment for sustainable digital finance [3, 23].

In countries with well-developed digital infrastructure, financial institutions and investors can leverage integrated platforms for ESG data analytics, digital green bond issuance, and decentralized finance (DeFi) solutions for environmental projects. For example, mobile banking and e-wallets enhance accessibility for retail investors seeking ESG-aligned products, while APIs and open data protocols facilitate integration between financial service providers and ESG verification platforms [24] (Bazarbash & Beaton, 2020). Such connectivity accelerates capital flows toward sustainable assets, particularly in emerging markets where traditional financial intermediation is constrained [25] (Demirgüç-Kunt et al., 2020).

From a theoretical standpoint, improved digital infrastructure reduces frictions in capital allocation and enhances market completeness, allowing investors to better integrate sustainability preferences into portfolio decisions [26]. (Beck, Lin, & Qian, 2022). Furthermore, digital channels improve investor reach and reduce informational asymmetries, enhancing market discipline and demand for authentic ESG performance. As reported by Chiu and Wong [27] (2021), digitally enabled financial systems also exhibit higher responsiveness to climate risk disclosures, suggesting a reinforcing loop between infrastructure quality and sustainable investment adoption.

Several empirical studies have substantiated the positive relationship between digitalization and sustainability outcomes. For instance, countries with higher ICT readiness exhibit greater sustainable development financing, whereas digital infrastructure significantly moderates the effect of financial development on green innovation [27, 28]. These findings support the notion that digital ecosystems act as multipliers for sustainability-driven capital flows and investment innovation. Similar findings have been

observed in the e-governance domain, where digital infrastructure enhances institutional performance and trust in digital systems, reinforcing its foundational role in technology-enabled transformation [29].

Accordingly, this study posits the following hypothesis:

H1: Digital infrastructure is significantly associated with sustainable investment size.

2.3. Blockchain Regulatory Readiness and Sustainable Investment

The maturity of regulatory frameworks is a pivotal determinant of how blockchain innovations integrate with sustainable finance ecosystems. Regulatory readiness refers to the presence of coherent, adaptive, and enforceable legal structures that govern the deployment of blockchain technologies in financial markets. When effectively designed, such frameworks reduce legal uncertainty, enhance investor protection, and mitigate systemic risks factors essential for facilitating trust in emerging technologies and fostering innovation in green finance [30, 31].

In the context of sustainable investment, regulatory readiness can support the issuance of blockchain-based green bonds, ensure compliance in carbon trading platforms, and establish standards for ESG tokenization and disclosure. For instance, sandbox regimes and pilot frameworks introduced in countries like Singapore, Switzerland, and the UK have enabled blockchain applications to develop under supervised conditions, stimulating the creation of sustainable financial products [32, 33].

However, the benefits of regulatory clarity may come with short-term trade-offs. Overly prescriptive or prematurely rigid regulations can limit experimentation, raise compliance burdens, and deter early-stage blockchain startups from entering sustainable finance markets [34]. In many jurisdictions, the evolving nature of digital asset laws; combined with gaps in ESG taxonomy, creates regulatory ambiguity, which slows down market adoption and cross-border collaboration [27].

Moreover, transitional frictions may arise when regulators attempt to balance innovation with financial stability. As new tokenization models emerge for ESG assets, questions around custody, taxation, investor rights, and jurisdictional accountability complicate the regulatory landscape [35]. These institutional adjustment costs can suppress the short-run scalability of blockchain-based sustainable finance solutions, even when long-run benefits are expected.

Empirical studies reveal mixed results. For example, Anagnostopoulos [36] finds that excessive regulatory intervention can delay blockchain adoption in ESG markets, whereas moderate and flexible frameworks catalyze innovation without compromising oversight. Similarly, de la Rosa & Stankovic [37] argue that sustainable finance regulation often lags behind technological capabilities, creating a disconnect between ESG goals and digital finance implementation.

Considering this duality, the relationship between blockchain regulatory readiness and sustainable investment is hypothesized to be significant but potentially negative in the short term due to transitional costs and regulatory inertia.

H2: Regulatory readiness is significantly associated with sustainable investment size.

2.4. Fintech Adoption and Sustainable Investment

Fintech adoption represents the maturity and dynamism of a country's digital financial ecosystem, encompassing innovations in digital payments, peer-to-peer (P2P) lending, robo-advisory services, crowdfunding platforms, and decentralized financial applications (DeFi). These tools have revolutionized the delivery of financial services by reducing reliance on traditional intermediaries, expanding financial access, and lowering participation thresholds; conditions vital for the democratization of sustainable investment [38, 39].

In the context of sustainable finance, fintech acts as a gateway between blockchain infrastructure and end users, enabling seamless interaction with green investment products. Crowdfunding platforms, for example, have been instrumental in financing clean energy and community-led environmental projects [40]. Similarly, algorithmic investment platforms that integrate ESG screening criteria allow retail and institutional investors to allocate capital in alignment with sustainability goals [41]. Fintech solutions can also enable more dynamic pricing and risk management in carbon trading, impact investing, and ESG-linked lending markets [36].

Theoretically, fintech supports the transmission of blockchain capabilities into practical financial services, reinforcing the infrastructure-application-user adoption chain. By reducing information asymmetry, improving transaction efficiency, and lowering search and verification costs, fintech tools contribute to allocative efficiency in sustainable capital markets [42]. Moreover, by expanding access to financial services among underbanked populations and SMEs, fintech fosters inclusive green finance, thereby aligning with global sustainability and SDG financing agendas [43].

Recent empirical studies confirm the catalytic role of fintech in sustainable investment. For instance, Li and Yu [44] find that countries with higher fintech penetration exhibit significantly greater issuance of green bonds and ESG funds. Similarly, Zhang et al. [45] argued that fintech development positively moderates the relationship between institutional quality and sustainable investment flows in emerging markets. These findings suggest that fintech is not merely a channel but a critical enabler of sustainable finance innovation.

Accordingly, the following hypothesis is proposed:

H3: Fintech adoption is significantly associated with sustainable investment size.

2.5. Tokenization Adoption and Sustainable Investment

Tokenization involves converting rights to a real-world asset into a digital token that is issued, transferred, and stored on a blockchain platform. In the context of sustainable finance, tokenization presents a novel mechanism for enabling fractional ownership of green infrastructure projects, carbon credits, and ESG-compliant securities, thereby enhancing liquidity, investor accessibility, and transparency [46–47]. By lowering the minimum capital required to participate, tokenization can significantly democratize access to

sustainable investment opportunities and widen the investor base, particularly among retail participants and small institutional investors.

Moreover, tokenization enhances traceability and real-time monitoring of environmental outcomes through smart contracts and immutable ledgers, facilitating a more accountable system of sustainability-linked finance [48]. It also allows for more efficient impact reporting, ESG claim verification, and secondary market trading of illiquid green assets, such as solar farms or reforestation credits [49]. These features align well with broader goals of green financial innovation and contribute to enhanced market efficiency and credibility.

However, despite its theoretical promise, tokenization remains in an early phase of adoption across most jurisdictions. Real-world implementation faces a range of frictions: limited legal and regulatory clarity around tokenized asset ownership, lack of interoperability across platforms, and challenges related to custody, taxation, and investor protection [50]. Many tokenized ESG assets are currently limited to pilot projects or sandbox regimes, particularly in the EU, Asia-Pacific, and the Middle East, where institutional learning curves and fragmented digital infrastructure pose hurdles to scalability [51–52].

Furthermore, while tokenization can improve liquidity under ideal conditions, its effectiveness depends on active participation, secondary market depth, and confidence in valuation mechanisms, elements not yet fully developed in most green asset classes. Recent empirical studies indicate that tokenization has a nonlinear and stage-dependent relationship with sustainable investment outcomes: early-stage adoption may initially disrupt traditional capital flows due to market uncertainty, before generating positive outcomes at later stages when infrastructure, regulation, and market trust align [53–54].

Given this duality of potential and constraint, the following hypothesis is proposed:

H4: Tokenization adoption is significantly associated with sustainable investment size.

2.6. Conceptual Framework

Building upon the preceding theoretical foundations, this study proposes a conceptual framework that links blockchain-related capabilities with sustainable investment outcomes. The model integrates four key independent variables; digital infrastructure, regulatory readiness, fintech adoption, and tokenization adoption; as determinants of sustainable investment size. These factors reflect both technological readiness and institutional maturity, capturing the multifaceted environment necessary for blockchain-enabled financial innovation to thrive.

From this perspective, blockchain technology serves as an enabling infrastructure, whose efficacy in advancing sustainable finance depends on the interplay among digital connectivity, regulatory governance, financial service innovation, and asset digitization. While each of these dimensions has independent significance, their joint contribution shapes a country's capacity to support scalable and credible sustainable investment solutions.

Note

Figure 1 visually summarizes the hypothesized relationships. Arrows represent the direct associations between each capability and the dependent variable, sustainable investment size, as posited in hypotheses H1-H4.

As shown in Fig. 1, the proposed framework assumes that countries with advanced digital infrastructure and robust fintech ecosystems are better positioned to translate blockchain capabilities into practical, user-facing sustainable finance products. Besides, the effect of regulatory readiness is likely conditional, potentially enabling long-term institutional support while introducing transitional frictions in early phases of adoption. Moreover, Tokenization may expand access and liquidity, yet its short-term effects could be constrained by legal, technical, and market immaturity. This framework guides the empirical strategy employed in the study. By testing the hypotheses derived (H1-H4), the analysis explores how differences in blockchain-related capabilities influence sustainable investment outcomes across varying developmental and regulatory contexts.

3. Data and Methodology

3.1. Sample and Data Sources

This study constructs a balanced panel dataset of 27 countries across five economic regions; Developed Economies, European Union, Asia-Pacific, Gulf Cooperation Council (GCC), and Emerging Economies; covering the period 2017 to 2024. The sample includes countries with demonstrable activity in blockchain development, fintech diffusion, and sustainable finance initiatives, and was selected based on the availability of consistent cross-country data across key indicators. The inclusion of GCC countries reflects both their growing interest in blockchain initiatives and the broader macroeconomic policy environment influencing investment capacity [55]. The temporal range captures the rapid evolution of blockchain-related capabilities following 2016 and aligns with the scaling up of sustainable investment practices and tokenization pilots in the post-COP21 regulatory environment. Table 1 presents the regional and economic composition of the sample, while Table 2 summarizes variable definitions and data sources.

Table 1
Sample Composition by Country, Region, and Economy Category

Region	Country	Economy Category	Income Group	Carbon Market Presence
Developed Economies	Switzerland	Developed	High Income	Yes
	United States	Developed	High Income	Yes
	United Kingdom	Developed	High Income	Yes
	Germany	Developed	High Income	Yes
	Canada	Developed	High Income	Yes
	Australia	Developed	High Income	Yes
European Union	Netherlands	Developed	High Income	Yes
	France	Developed	High Income	Yes
	Spain	Developed	High Income	Yes
	Italy	Developed	High Income	Yes
	Sweden	Developed	High Income	Yes
	Denmark	Developed	High Income	Yes
Asia-Pacific	Singapore	Developed	High Income	Yes
	Japan	Developed	High Income	No
	South Korea	Developed	High Income	Yes
	China	Emerging	Upper-Middle Income	Yes
	Hong Kong	Developed	High Income	Yes
	Malaysia	Emerging	Upper-Middle Income	No
GCC	United Arab Emirates	Emerging	High Income	Yes
	Saudi Arabia	Emerging	High Income	No
	Qatar	Emerging	High Income	No
	Bahrain	Emerging	High Income	Yes
Emerging Economies	India	Emerging	Lower-Middle Income	No

Source: Author’s work

Region	Country	Economy Category	Income Group	Carbon Market Presence
	Brazil	Emerging	Upper-Middle Income	Yes
	South Africa	Emerging	Upper-Middle Income	Yes
	Indonesia	Emerging	Upper-Middle Income	No
	Mexico	Emerging	Upper-Middle Income	Yes
Source: Author’s work				

All country-level indicators are derived from publicly accessible and internationally recognized data repositories. Principal sources include the World Bank’s Digital Adoption Index and World Development Indicators, the IMF Financial Access Survey, the World Governance Indicators (WGI), the Global Sustainable Investment Review (GSIR), and the OECD and BIS policy databases on fintech and tokenization. Additional data on regulatory readiness and tokenization activity were sourced from national financial authorities and regulatory disclosures. Data across countries were harmonized using standardized measurement techniques and normalized where necessary to ensure comparability across jurisdictions and time periods.

Table 2
Variable Classification, Definitions, Measurement, and Data Sources

Variable Role	Variable	Symbol	Measurement	Expected Sign	Data Source
Dependent Variable	Sustainable Investment Size	SIS	Sustainable investment assets as a percentage of GDP, incorporating ESG bond issuance and carbon market participation	-	Global Sustainable Investment Review; World Bank
Independent Variable	Digital Infrastructure	DIG	Composite index capturing internet penetration, digital payments usage, and ICT access (0–100 scale)	+	World Bank Digital Adoption Index; ITU
	Regulatory Readiness	REG	Index reflecting the presence and maturity of blockchain and fintech regulatory frameworks (0–100 scale)	+	World Bank; OECD fintech and blockchain policy reports
	Fintech Adoption	FIN	Measure of fintech ecosystem depth and user adoption, including digital financial services usage (0–100 scale)	+	World Bank; IMF Financial Access Survey
	Tokenization Adoption Index	TOK	Ordinal index capturing the extent of real-world asset tokenization (0 = none; 1 = pilot; 2 = active; 3 = institutionalized)	+	BIS; national regulatory authorities and public disclosures
Control Variable	Financial Market Development	FMD	Domestic credit to private sector as a percentage of GDP	+	World Bank World Development Indicators
	Institutional Quality	INST	Regulatory quality index ranging from − 2.5 (weak) to + 2.5 (strong)	+	World Governance Indicators (WGI)
	Economic Development	GDPpc	Natural logarithm of GDP per capita (constant USD)	+	World Bank World Development Indicators
Dummy Variable	Carbon Market Presence	CARB	Binary indicator (1 = emissions trading system or carbon	+	World Bank Carbon Pricing Dashboard

Source: Author’s work

Variable Role	Variable	Symbol	Measurement	Expected Sign	Data Source
			pricing mechanism in place; 0 = otherwise)		
Source: Author’s work					

3.2. Variable Measurement

3.2.1. Dependent Variable

The dependent variable, Sustainable Investment Size (SIS), serves as the central measure of a country’s sustainable finance depth. It is computed as the ratio of sustainable investment assets to gross domestic product (GDP), integrating ESG-aligned fund flows, green and social bond issuance, and verified carbon market participation. This indicator captures the breadth and systemic importance of sustainable finance, rather than focusing solely on niche segments or isolated market instruments. The use of this macro-financial perspective aligns with prior studies examining ESG investment scale in cross-country contexts [38].

3.2.2. Independent Variables

To examine the influence of blockchain-related capabilities on sustainable finance development, the empirical model incorporates four key independent variables. Digital Infrastructure (DIG) represents a country’s technological capacity to support blockchain-based financial platforms. It is operationalized as a composite index covering internet penetration, digital payments usage, and access to information and communication technology, with values scaled from 0 to 100. Regulatory Readiness (REG) captures the maturity and scope of blockchain and fintech regulation, based on the presence of licensing frameworks, supervisory oversight, and innovation sandboxes. This index also follows a normalized 0-100 scale to reflect variation in legal and institutional development across countries.

The Fintech Adoption (FIN) variable reflects the breadth and depth of digital financial services within each country. It encompasses indicators of mobile money usage, alternative lending volumes, and the adoption of automated investment tools. Higher values reflect stronger integration of financial innovation into mainstream capital allocation mechanisms. Tokenization Adoption (TOK), a central innovation proxy in this study, is measured as an ordinal variable ranging from 0 (no observable tokenization) to 3 (institutionalized adoption), capturing the progressive evolution of tokenized real asset markets across countries and years.

3.2.3. Control Variables

To isolate the effects of these technological and regulatory dimensions, the model includes several structural control variables. Financial Market Development (FMD), expressed as domestic credit to the private sector relative to GDP, accounts for differences in financial system depth. Institutional Quality (INST) is proxied by the regulatory quality sub-index from the World Governance Indicators, representing the robustness of governance systems. Economic Development is captured by the natural logarithm of GDP per capita in constant USD, providing a scale-sensitive measure of national income. Additionally,

Carbon Market Presence (CARB) is included as a binary control (1 = yes, 0 = no), accounting for the influence of national carbon pricing frameworks on sustainable investment flows.

These variables jointly form the basis of the panel regression analysis, allowing for an empirical test of the hypotheses developed in Section 2 and facilitating a multi-dimensional examination of blockchain readiness and its impact on sustainable investment. The operationalization strategy ensures compatibility with previous empirical models in sustainable finance and digital policy research [42, 56, 30].

3.3. Empirical Model

To empirically investigate the influence of blockchain-related capabilities on sustainable investment outcomes, this study employs a fixed-effects panel regression model that accounts for both cross-country heterogeneity and time-specific global factors. The model specification is designed to capture the structural and institutional factors that may condition the relationship between blockchain ecosystem maturity and sustainable finance development.

The core econometric model is expressed as follows:

$$SIS_{it} = \alpha + \beta_1 DIG_{it} + \beta_2 REG_{it} + \beta_3 FIN_{it} + \beta_4 TOK_{it} + \beta_5 FMD_{it} + \beta_6 INST_{it} + \beta_7 \ln(GDPpc_{it}) + \beta_8 CARB_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

where i, indexes countries and t indexes years. The dependent variable SIS_{it} represents the sustainable investment size in country i at time t, measured as the ratio of ESG-aligned financial assets to GDP. The key explanatory variables include: DIG_{it} for digital infrastructure, REG_{it} for regulatory readiness, FIN_{it} for fintech adoption, and TOK_{it} for tokenization adoption level. Control variables include financial market development (FMD_{it}), institutional quality ($INST_{it}$), economic development captured by the natural logarithm of GDP per capita [$\ln(GDPpc_{it})$], and carbon market presence ($CARB_{it}$).

The model includes country fixed effects (μ_i) to control for time-invariant national characteristics, such as legal traditions, political culture, and structural economic conditions, that may influence both blockchain deployment and sustainable investment independently. It also incorporates year fixed effects (λ_t) to absorb global shocks, common macroeconomic trends, or international regulatory shifts that could affect all countries simultaneously, such as the Paris Agreement compliance push or COVID-19-related policy interventions.

The inclusion of these fixed effects ensures that the estimated coefficients reflect within-country variation over time, thereby mitigating bias from omitted variables that are constant across countries or common across time periods. The error term ϵ_{it} captures idiosyncratic shocks unaccounted for by the included covariates. This fixed-effects framework has been widely adopted in cross-country policy and finance studies where both structural and temporal factors may shape institutional change and market evolution [57, 31]. To ensure robust inference, standard errors are clustered at the country level to account for serial correlation in the error structure.

3.4. Estimation Strategy

To estimate the relationship between blockchain-related capabilities and sustainable investment size, this study applies an ordinary least squares (OLS) estimation with country and year fixed effects. This specification is well-suited for panel data where unobserved time-invariant country characteristics, such as legal infrastructure, governance traditions, or macroeconomic fundamentals, may correlate with both the explanatory variables and the dependent variable. The inclusion of year fixed effects accounts for global shocks and macro-trends, such as international climate policy changes or major fintech adoption waves, that could uniformly influence all countries within the panel.

Standard errors are clustered at the country level to address issues of heteroskedasticity and serial correlation, a common practice in empirical studies using macro panel data. This approach improves inference robustness by accounting for within-country error dependence across time periods. Before estimating the model, descriptive statistics and pairwise correlation analysis are conducted to assess the distributional properties of the variables and to evaluate potential multicollinearity. While moderate to high correlations are observed among some blockchain-related indicators, these associations are theoretically expected due to the intertwined nature of digital infrastructure, regulatory maturity, and fintech development. The fixed-effects structure, along with robustness checks introduced in later sections, helps address concerns regarding omitted variable bias and overlapping variance.

In addition to the regression analysis, the study incorporates a cluster analysis to group countries based on their levels of blockchain and tokenization readiness. This unsupervised learning technique complements the econometric model by enabling a structural typology of countries, highlighting differences in the technological and institutional pathways through which blockchain influences sustainable finance. The classification enables comparative insights into heterogeneity in adoption patterns across developed, emerging, and transitional economies. All statistical estimations and data visualizations are implemented using Python (version 3.x), utilizing established scientific libraries including pandas, NumPy, statsmodels, and scikit-learn. This approach ensures transparency and reproducibility of empirical results, aligning with open science practices increasingly adopted in the field of sustainable finance.

4. Data Analysis and Findings

4.1. Descriptive Analysis

Table 3 presents the descriptive statistics for all variables used in the analysis over the 2017–2024 period. The dependent variable, Sustainable Investment Size (SIS), exhibits a mean value of 2.81% of GDP, with a minimum of 2.00% and a maximum of 3.75%, reflecting substantial variation in the scale of sustainable finance across countries. This degree of dispersion underscores the heterogeneous nature of ESG investment activity globally and supports the panel structure of the dataset for econometric analysis.

Table 3
Descriptive Statistics of Key Variables.

Variable	Mean	Std. Dev.	Min	Max
Sustainable Investment Size (SIS)	2.810	0.556	2.000	3.750
Digital Infrastructure (DIG)	77.231	10.349	57.000	95.500
Regulatory Readiness (REG)	72.565	10.433	53.000	93.500
Fintech Adoption (FIN)	72.306	10.079	52.000	91.500
Tokenization Adoption Index (TOK)	2.231	0.842	0.000	3.000
Financial Market Development (FMD)	132.407	40.217	55.000	190.000
Institutional Quality (INST)	1.076	0.703	−0.300	2.050
Economic Development (ln GDP per capita)	10.531	0.898	7.940	11.440
Carbon Market Presence (CARB)	0.778	0.417	0.000	1.000
Source: Author’s calculations				

The blockchain-related variables also demonstrate meaningful variation. Digital Infrastructure (DIG) has a mean of 77.23, ranging from 57.00 to 95.50, indicating that most sample countries possess moderate to high levels of technological readiness. Regulatory Readiness (REG) and Fintech Adoption (FIN) show similar patterns, with means of 72.57 and 72.31, respectively, and standard deviations exceeding 10 points, reflecting differentiated institutional maturity and digital finance adoption. Tokenization Adoption (TOK), measured on a 0–3 ordinal scale, has a mean of 2.23 and a wider relative spread (standard deviation of 0.84), consistent with its emerging nature and varying stages of experimentation across jurisdictions.

Among the control variables, Financial Market Development (FMD) shows significant variation, with values ranging from 55.00 to 190.00 (as a percentage of GDP), indicating wide disparities in financial sector depth. Institutional Quality (INST) spans from − 0.30 to 2.05, with a mean of 1.08, capturing differences in governance and regulatory effectiveness. The natural log of GDP per capita exhibits a mean of 10.53, consistent with a sample that includes both advanced and emerging economies. Lastly, Carbon Market Presence (CARB), a binary variable, shows that approximately 78% of the country-year observations involve a functioning carbon pricing mechanism or emissions trading system.

Together, the descriptive statistics confirm the presence of both cross-sectional and temporal heterogeneity in the dataset, which is essential for identifying meaningful relationships between blockchain readiness and sustainable investment. The variation observed across technological, institutional, and economic indicators provides a strong empirical foundation for testing the proposed hypotheses (H1-H4) in subsequent regression analysis.

4.2. Correlation Analysis

Table 4 reports on the pairwise correlation coefficients among the key variables. The dependent variable, Sustainable Investment Size (SIS), is positively correlated with all four blockchain-related indicators, offering preliminary evidence of their association with sustainable finance outcomes. Notably, Tokenization Adoption (TOK) shows the strongest positive correlation with SIS (r = 0.679), suggesting that countries actively piloting or institutionalizing tokenization frameworks tend to host larger ESG-aligned investment volumes. This finding is consistent with theoretical expectations that tokenization enhances capital accessibility, liquidity, and investor participation in green finance.

Moderate positive correlations are also observed between SIS and the broader digital finance variables: Digital Infrastructure (DIG) (r = 0.284), Regulatory Readiness (REG) (r = 0.281), and Fintech Adoption (FIN) (r = 0.285). These results lend preliminary directional support to hypotheses H1 through H3, suggesting that digital and regulatory readiness may complement the scaling of sustainable financial instruments, although further testing is required within the multivariate framework.

Table 4
Pairwise Correlation Matrix

Variable	SIS	DIG	REG	FIN	TOK	FMD	INST	ln(GDPpc)	CARB
SIS	1.000								
DIG	0.284	1.000							
REG	0.281	0.990	1.000						
FIN	0.285	0.978	0.992	1.000					
TOK	0.679	0.663	0.663	0.672	1.000				
FMD	0.196	0.777	0.750	0.718	0.398	1.000			
INST	0.206	0.922	0.908	0.898	0.554	0.854	1.000		
ln (GDPpc)	0.217	0.855	0.837	0.825	0.493	0.805	0.939	1.000	
CARB	0.050	0.413	0.418	0.366	0.227	0.421	0.369	0.370	1.000
Source: Author’s calculations									

As anticipated, the explanatory variables DIG, REG, and FIN are strongly intercorrelated (r > 0.97), reflecting their interconnected role in shaping the enabling environment for blockchain-based finance. Similarly, Institutional Quality (INST) and GDP per capita (ln(GDPpc)) are strongly correlated with each other (r = 0.939) and with the digital readiness variables, as higher-income economies often exhibit stronger institutions and deeper digital ecosystems. These relationships reflect conceptual proximity and co-evolution within digital finance ecosystems, as also observed in prior studies on technological complementarities in financial infrastructure development [58, 42]. Carbon Market Presence (CARB) shows weaker correlations with the other variables, as expected for a binary policy indicator.

Despite these high intercorrelations, multicollinearity is not expected to bias estimation results due to two key design features: the use of country fixed effects, which control for time-invariant country characteristics, and subsequent robustness diagnostics, which assess variance inflation and specification stability. These safeguards ensure the reliability of coefficient estimates in the regression analysis. In sum, the correlation results align with the theoretical framework established in Section 2 and provide preliminary empirical justification for the inclusion of the blockchain-related variables in the panel regression model. They suggest that technological readiness, regulatory maturity, and financial innovation are not only conceptually but also statistically associated with sustainable investment dynamics across countries.

4.3. Panel Regression Results

Table 5 presents the results of the panel regression model estimated with country and year fixed effects, with standard errors clustered at the country level. The overall model fit is high, with an R^2 of 0.978 and adjusted R^2 of 0.973, indicating that the explanatory variables collectively explain a substantial portion of the variation in sustainable investment size across countries and over time.

The coefficient for Digital Infrastructure (DIG) is positive and statistically significant at the 1% level (β = 0.031; t = 10.426), suggesting that improvements in digital infrastructure are strongly associated with an expansion in sustainable investment as a share of GDP. This result confirms H1, highlighting the role of digital readiness in enabling blockchain-based platforms and ESG-related financial services. The presence of robust ICT infrastructure, widespread internet penetration, and digital payment systems appears to reduce frictions in sustainable capital allocation.

Table 5
Blockchain, Tokenization, and Sustainable Investment: Panel Regression Results (Country FE + Year FE)

Variable	Coefficient	(Clustered Std. Error)	t-stat	Sig.
Digital Infrastructure (DIG)	0.031	(0.003)	10.426	***
Regulatory Readiness (REG)	−0.025	(0.003)	−9.771	***
Fintech Adoption (FIN)	0.029	(0.002)	13.490	***
Tokenization Adoption (TOK)	−0.114	(0.047)	−2.420	**
Financial Market Development (FMD)	0.001	(0.000)	3.808	***
Institutional Quality (INST)	−0.202	(0.015)	−13.173	***
Economic Development (ln GDP per capita)	−0.024	(0.009)	−2.662	***
Carbon Market Presence (CARB)	−0.073	(0.003)	−23.252	***
Source: Author’s calculations				

Similarly, Fintech Adoption (FIN) is also positively associated with sustainable investment (β = 0.029; t = 13.490), providing empirical support to H3. This indicates that digitally mature financial ecosystems are

more capable of converting blockchain and technological advancements into scalable ESG investment products. These findings are consistent with recent studies showing that fintech innovations enhance investor inclusion and facilitate ESG-aligned capital flows through more efficient financial intermediation [57, 42, 59].

In contrast, Regulatory Readiness (REG) shows a negative and statistically significant relationship with sustainable investment (β = -0.025; t = -9.771), consistent with H2. While regulatory frameworks are necessary for ensuring investor protection and legal certainty, overly rigid or transitional regimes may raise compliance costs and create short-term barriers to innovation. Similarly, Tokenization Adoption (TOK) is also negatively associated with sustainable investment (β = -0.114; t = – 2.420; p < 0.05), supporting H4. These results suggest that although tokenization holds long-term promise for democratizing green assets, its early-stage implementation may be constrained by legal uncertainties, institutional learning curves, and limited market depth. Similar transitional frictions have been observed in cross-country studies examining green fintech regulation and tokenization ecosystems [60–61].

Among the control variables, Financial Market Development (FMD) is positively and significantly associated with sustainable investment (β = 0.001; t = 3.808), reaffirming the role of financial depth in facilitating ESG-related capital flows. Conversely, Institutional Quality (INST) (β = -0.202; t = -13.173) and Economic Development (ln GDP per capita) (β = -0.024; t = -2.662) exhibit negative coefficients. These results may reflect within-country temporal dynamics, such as policy realignment or ESG rebalancing, rather than a lack of institutional or economic maturity per se. Interestingly, Carbon Market Presence (CARB) is negatively associated with sustainable investment (β = -0.073; t = -23.252), indicating that the existence of carbon pricing mechanisms does not automatically translate into larger ESG investment volumes and may even reflect policy inefficiencies or lagged implementation impacts.

Overall, the panel regression results confirm that blockchain-related capabilities, particularly digital infrastructure and fintech adoption, serve as significant enablers of sustainable investment. However, their positive effects may be moderated by transitional constraints in regulatory and tokenization domains, particularly in jurisdictions undergoing early-stage ecosystem development.

4.4. Robustness Checks

To analyse the robustness of the main regression findings, additional model specifications are estimated and presented in Table 6. Model A excludes Carbon Market Presence (CARB), while Model B excludes Institutional Quality (INST) to evaluate whether the core results are sensitive to these control variables. Both models maintain the use of country and year fixed effects and cluster standard errors at the country level.

In Model A, the coefficient for Digital Infrastructure (DIG) remains positive and significant (β = 0.030; p < 0.01), consistent with the baseline result and supporting H1. Fintech Adoption (FIN) also maintains a strong positive relationship (β = 0.038; p < 0.01), further supporting H3. Regulatory Readiness (REG) and Tokenization Adoption (TOK) continue to show negative and statistically significant coefficients (β =

−0.034; p < 0.01 and β = −0.114; p < 0.05, respectively), which affirms the findings for H2 and H4 even after excluding policy-specific variables.

Table 6
Robustness Checks Using Alternative Model Specifications.

Model	Variable	Coefficient	(Clustered Std. Error)	Sig.
Model A: Excluding CARB	Digital Infrastructure (DIG)	0.030	(0.003)	***
	Regulatory Readiness (REG)	−0.034	(0.002)	***
	Fintech Adoption (FIN)	0.038	(0.002)	***
	Tokenization Adoption (TOK)	−0.114	(0.047)	**
	Financial Market Development (FMD)	0.001	(0.000)	***
	Institutional Quality (INST)	−0.202	(0.015)	***
	Economic Development (ln GDP per capita)	−0.023	(0.009)	**
Model B: Excluding INST	Digital Infrastructure (DIG)	0.019	(0.004)	***
	Regulatory Readiness (REG)	−0.019	(0.003)	***
	Fintech Adoption (FIN)	0.028	(0.002)	***
	Tokenization Adoption (TOK)	−0.114	(0.047)	**
	Financial Market Development (FMD)	−0.002	(0.000)	***
	Economic Development (ln GDP per capita)	0.028	(0.013)	**
	Carbon Market Presence (CARB)	−0.073	(0.003)	***
Source: Author's calculations				

In Model B, when Institutional Quality is excluded, the signs and statistical significance of all blockchain-related predictors remain intact. DIG shows a slightly lower coefficient (β = 0.019; p < 0.01), yet still significant, while FIN remains strong and positive (β = 0.028; p < 0.01). REG continues to demonstrate a negative and significant association (β = −0.019; p < 0.01), and TOK again retains its negative sign (β = -0.114; p < 0.05), reinforcing the conclusion that early-stage tokenization may entail institutional frictions or transitional inefficiencies.

The variation in control variables slightly affects the magnitude of coefficients, but not their signs or significance levels. For instance, the FMD variable switches from positive (β = 0.001) in Model A to

negative (β = -0.002) in Model B, yet the blockchain-related variables remain stable. The Economic Development (ln GDP per capita) variable changes sign between models, reflecting possible collinearity with the dropped controls, but this does not influence the core findings.

Overall, these results confirm that the associations identified in the main regression, especially the positive roles of digital infrastructure and fintech, and the transitional constraints linked to regulation and tokenization, are robust to alternate specifications (Table 7).

Table 7
Summary of Hypotheses and Empirical Results.

Hypothesis	Variable	Theoretical Link	Literature Insight	Observed Sign	Statistical Significance	Empirical Support
H1	Digital Infrastructure (DIG)	Technology readiness → Sustainable Investment Size (SIS)	Enhances ESG access and digital finance integration	Positive (+)	*** p < 0.01	Supported
H2	Regulatory Readiness (REG)	Institutional conditions ↔ SIS	May introduce short-run compliance frictions during transition	Negative (−)	*** p < 0.01	Supported
H3	Fintech Adoption (FIN)	Fintech maturity → SIS	Facilitates democratized and data-driven sustainable investing	Positive (+)	*** p < 0.01	Supported
H4	Tokenization Adoption (TOK)	Innovation stage ↔ SIS	Tokenization in early phases may entail institutional and market adjustment costs	Negative (−)	** p < 0.05	Supported
Source: Author's calculations						
Notes:						

SIS = Sustainable Investment Size (dependent variable).

Directions: "→" indicates theoretical direction; "↔" denotes potentially bidirectional or context-dependent influence.

Significance levels: *** p < 0.01, ** p < 0.05, * p < 0.10.

4.5. Cluster Analysis

To complement the regression analysis and explore structural patterns across countries, cluster analysis is conducted using k-means classification (k = 3), based on country-level averages of four blockchain-related indicators: Digital Infrastructure (DIG), Regulatory Readiness (REG), Fintech Adoption (FIN), and Tokenization Adoption (TOK) for the period 2017–2024. The clustering algorithm groups countries into three distinct categories; Leaders, Followers, and Laggards; according to their relative blockchain readiness and tokenization development.

Table 8 presents the resulting classification. The Leaders cluster includes high-income countries from the Asia-Pacific (e.g., Singapore, Hong Kong), European Union (e.g., France, Netherlands, Sweden), GCC (UAE), and major developed economies such as the United States, United Kingdom, and Germany. These countries are characterized by high scores in digital infrastructure (mean DIG = 86.44), regulatory maturity (REG = 81.67), fintech adoption (FIN = 80.83), and institutionalized tokenization (TOK = 2.71), with a mean sustainable investment size (SIS) of 2.88% of GDP.

Table 8
Cluster Classification of Countries Based on Blockchain and Tokenization Readiness

Cluster	Countries	Cluster Profile (Mean Values)
Leaders	Australia, Canada, Denmark, France, Germany, Hong Kong, Netherlands, Singapore, Sweden, Switzerland, UAE, United Kingdom, United States	DIG = 86.44; REG = 81.67; FIN = 80.83 TOK = 2.71; SIS = 2.88
Followers	Bahrain, China, Italy, Japan, Malaysia, Qatar, Saudi Arabia, South Korea, Spain	DIG = 72.64; REG = 68.08; FIN = 68.42 TOK = 1.96; SIS = 2.88
Laggards	Brazil, India, Indonesia, Mexico, South Africa	DIG = 61.55; REG = 56.95; FIN = 57.15 TOK = 1.48; SIS = 2.52
Source: Author’s calculations		

The Followers cluster consists of countries such as South Korea, Japan, China, Malaysia, and select GCC states like Qatar and Saudi Arabia. These countries demonstrate moderate blockchain capabilities (DIG = 72.64; REG = 68.08; FIN = 68.42), emerging tokenization initiatives (TOK = 1.96), and a comparable sustainable investment size to Leaders (SIS = 2.88). This suggests that tokenization and regulatory conditions may act as transitional factors in scaling sustainable finance.

The Laggards cluster includes large emerging economies, Brazil, India, Mexico, Indonesia, and South Africa, that exhibit relatively lower technological and institutional readiness (DIG = 61.55; REG = 56.95; FIN = 57.15) and less developed tokenization practices (TOK = 1.48). These countries record a smaller sustainable investment size (SIS = 2.52), highlighting potential barriers to scaling blockchain-enabled sustainable finance.

The heatmap in Fig. 2 displays country-level averages of the four blockchain-related indicators (DIG, REG, FIN, TOK) over 2017–2024. Figure 2 visually summarizes the blockchain-related indicators across countries, showing notable heterogeneity in digital infrastructure, regulatory maturity, fintech adoption, and tokenization. The heatmap highlights the concentration of high scores among the leaders, particularly in Western Europe, North America, and parts of Asia.

Figure 3 plots the standardized digital infrastructure and regulatory readiness scores, revealing a clear grouping of countries. Cluster visualization is based on standardized averages of Digital Infrastructure and Regulatory Readiness. Color coding reflects the three clusters: leaders (green), followers (yellow), and laggards (purple). The top-right quadrant reflects blockchain leaders with high technological and regulatory capacity, while countries in the bottom-left demonstrate lower levels of both dimensions, aligning with the laggard profile. The follower countries fall near the center, confirming a transitional position.

The cluster results reinforce the regression findings by providing structural evidence that blockchain and tokenization capabilities are systematically associated with differences in sustainable investment performance across countries. Leaders with higher readiness consistently exhibit larger SIS values, validating H1-H4 in a non-parametric framework. The follower group reflects countries progressing toward institutional maturity but facing regulatory or technological bottlenecks. Laggards demonstrate the importance of foundational infrastructure for unlocking sustainable finance potential.

5. Discussion and Policy Implications

5.1. Discussion of Findings

This study examined how blockchain-related capabilities influence sustainable investment across countries, offering new empirical insights into the technological, institutional, and financial foundations of blockchain-enabled sustainable finance. The panel regression and cluster analyses reveal that the effect of blockchain is not uniform, but context-dependent; shaped by the interplay of digital infrastructure, fintech adoption, regulatory maturity, and tokenization development.

First, the robust positive association between digital infrastructure and sustainable investment underscores the importance of digital readiness as a prerequisite for blockchain-based financial innovation. This finding aligns with prior studies suggesting that high internet penetration, ICT access, and digital payment infrastructure reduce transaction frictions and improve market accessibility [62–63]. Blockchain-based solutions, such as ESG data verification and decentralized finance (DeFi), require the foundation of a well-developed digital ecosystem to scale effectively. Hence, blockchain amplifies the benefits of existing digital networks rather than substituting them.

Second, fintech adoption emerges as a key intermediary that translates blockchain capabilities into tangible sustainable investment outcomes. As shown in prior literature, fintech platforms improve financial inclusion, streamline capital allocation, and foster innovation in ESG financial products [64–65]. Our findings suggest that fintech acts as a gateway through which blockchain solutions, such as tokenized

green bonds or smart contract-based investments, reach broader investor segments. This result reinforces the idea that blockchain and fintech operate synergistically rather than in isolation [66]. Fintech ecosystems that integrate advanced analytics and AI tools further enable responsive and inclusive sustainable finance platforms by leveraging real-time information and behavioral signals [67]. This finding aligns with ESG-augmented investment literature emphasizing innovation and financial value generation across Asian economies [68], further confirming the relevance of fintech ecosystems in supporting sustainable capital formation.

In contrast, regulatory readiness is negatively associated with sustainable investment during the study period. While this may appear counterintuitive, it is consistent with the notion of transitional frictions [30, 69]. Regulatory tightening, compliance complexity, and legal uncertainty can inhibit experimentation and raise costs for emerging blockchain-based financial instruments. As such, overly rigid or rapidly evolving regulatory frameworks may constrain early-stage sustainable finance applications of blockchain, even if they promote long-term market integrity.

Similarly, the negative association of tokenization adoption with sustainable investment highlights the early-stage and experimental nature of tokenization in many countries. Tokenization initiatives may face legal ambiguity, infrastructure fragmentation, or insufficient market demand, leading to a temporary disconnect between technological potential and measurable investment outcomes [70–71]. Over time, as tokenization ecosystems mature and regulatory clarity improves, their contribution to sustainable finance may increase.

The cluster analysis supports and contextualizes these findings by identifying structural groupings. Countries in the “leader” cluster exhibit advanced digital and regulatory capacity, high fintech adoption, and more institutionalized tokenization efforts, translating into larger sustainable investment markets. “Follower” and “laggard” countries, on the other hand, face structural gaps that hinder the effective scaling of blockchain-based ESG finance.

5.2. Policy Implications

The empirical results generate important policy insights for governments, regulators, and financial actors seeking to harness blockchain technologies for advancing sustainable finance.

First, investment in digital infrastructure should be a strategic priority. Expanding broadband access, secure data platforms, and digital ID systems will enable countries to adopt blockchain applications more effectively. These efforts form the technical backbone for ESG transparency, traceable green finance, and tokenized asset platforms [27].

Second, fostering fintech ecosystems is critical. Governments can promote fintech growth through regulatory innovation hubs, digital sandbox environments, and open banking policies. Fintech firms help translate blockchain potential into market-ready ESG solutions and increase investor participation in sustainable finance [32].

Third, regulatory policy must be adaptive and phased. Policymakers should avoid excessive rigidity in early stages of blockchain or tokenization regulations. Instead, proportionate and iterative regulatory strategies, such as pilot licenses and graduated compliance schemes, can reduce transitional frictions and build long-term resilience [30].

Fourth, tokenization development should be supported through legal modernization and cross-sector collaboration. Clarifying rules around digital asset ownership, custody, settlement, and interoperability can reduce uncertainty and foster the integration of tokenized ESG assets into mainstream markets [71–72].

Finally, global coordination will be essential. Blockchain-enabled finance is inherently cross-border. International organizations, such as the Financial Stability Board (FSB), BIS, and IMF, should work with national authorities to harmonize standards, share best practices, and ensure regulatory coherence across jurisdictions.

5.3. Implications for Sustainable Finance Strategy

From a strategic perspective, blockchain should be viewed not as a standalone fix but as an enabling infrastructure that depends on supportive conditions, digital, institutional, and financial. Sustainable finance strategies must integrate blockchain deployment with broader digital and ESG financial system development.

For governments, this means designing holistic strategies that align sustainability goals with digital innovation, including digital finance roadmaps and ESG-focused fintech support. For private sector actors, especially financial institutions and asset managers, the implication is to embed blockchain solutions within ESG frameworks, ensuring interoperability, scalability, and investor trust.

Ultimately, the transition to blockchain-enabled sustainable finance will require cross-disciplinary collaboration, phased institutional change, and deliberate investment in infrastructure and governance capacity. Only then can blockchain’s promise for credible, transparent, and inclusive ESG finance be fully realized.

6. Conclusion

This study examined the relationship between blockchain-related capabilities and sustainable investment using a balanced panel of 27 countries over the period 2017–2024. By integrating digital infrastructure, regulatory readiness, fintech adoption, and tokenization adoption into a unified empirical framework, the analysis provides new cross-country evidence on how blockchain-enabled ecosystems shape sustainable finance outcomes. The results demonstrate that blockchain’s influence on sustainable investment is contingent, context-dependent, and significantly shaped by a country's broader technological and institutional ecosystem.

Digital infrastructure and fintech adoption emerge as robust and consistent enablers of sustainable investment, affirming that technological readiness and digitally mature financial systems play a critical role in amplifying blockchain's potential. These findings are consistent with earlier literature emphasizing the

enabling role of innovation ecosystems in financial inclusion and ESG investing [68]. Countries with advanced digital connectivity and strong fintech ecosystems are better positioned to translate blockchain potential into scalable, accessible, and credible sustainable finance solutions.

In contrast, the negative association observed between regulatory readiness and sustainable investment suggests the presence of short-term transitional frictions. While regulation is essential for market stability, overly stringent or rapidly evolving frameworks can constrain innovation and experimentation in the early phases of blockchain deployment. This finding aligns with prior discussions on the trade-offs between regulatory oversight and innovation flexibility [57]. Similarly, adoption of tokenization is negatively associated with sustainable investment in the short run, possibly due to early-stage implementation hurdles, legal uncertainties, and underdeveloped market infrastructure [22].

This study contributes to sustainable finance and digital innovation literature in several ways. First, it advances empirical research on blockchain and ESG finance by moving beyond conceptual or country-specific evidence to a robust, large-scale, cross-country analysis. Second, it explicitly integrates tokenization into the sustainable finance discourse, offering empirical insights into its early-stage impact, an area largely unexplored in current literature. Third, by combining panel regression with cluster analysis, the study reveals heterogeneous country groupings and validates that the evolution of blockchain-enabled sustainable finance is uneven and path-dependent.

From a practical perspective, the findings emphasize that blockchain should be viewed as an enabling infrastructure within a broader digital finance strategy, not a standalone fix. Policymakers and market actors should adopt integrated strategies that align digital infrastructure development, fintech ecosystem strengthening, and regulatory adaptability. Investments in foundational digital public goods, such as broadband networks and digital payment systems, are essential to unlock the potential of blockchain in ESG-oriented finance [29].

Despite its contributions, the study is subject to several limitations. The use of aggregate sustainable investment measures may obscure variation in ESG asset types or sectors. The tokenization indicator, while novel, captures only the stage of adoption rather than transactional volume or liquidity. Future research should explore more granular, asset-level data and investigate dynamic or nonlinear interactions between blockchain adoption and sustainable investment, especially as tokenized markets and legal clarity evolve. Emerging areas such as AI-enabled blockchain analytics and real-time ESG impact measurement, using sentiment and unstructured data [67], may also offer promising directions.

Overall, this study offers timely, data-driven insights into the evolving nexus between blockchain, fintech, and sustainable finance. It provides a foundation for future research and policy efforts at the intersection of digital innovation, capital markets, and sustainability transition.

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Consent to participate

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Artificial intelligence declarations

The author/contributor declares commitment to the ethical use of artificial intelligence. The author pledges to uphold the principles of fairness, transparency, accountability, and inclusivity in the development and deployment of AI technologies.

Data availability statement

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Rashid Khalil: Methodology, Data curation, Conceptualization, Writing, Review & editing, Validation, Supervision, Software, Investigation, Formal analysis.

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Data availability

Data will be made available on request.

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Figures

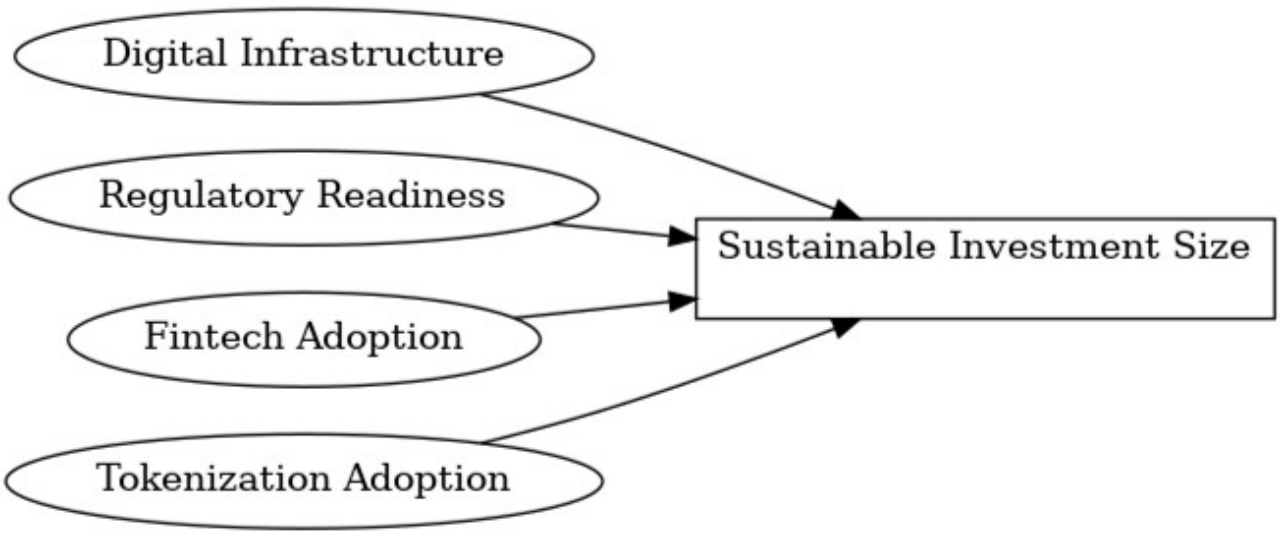


Figure 1

Conceptual Framework

Note: Figure 1 visually summarizes the hypothesized relationships. Arrows represent the direct associations between each capability and the dependent variable, sustainable investment size, as posited in hypotheses H1-H4.

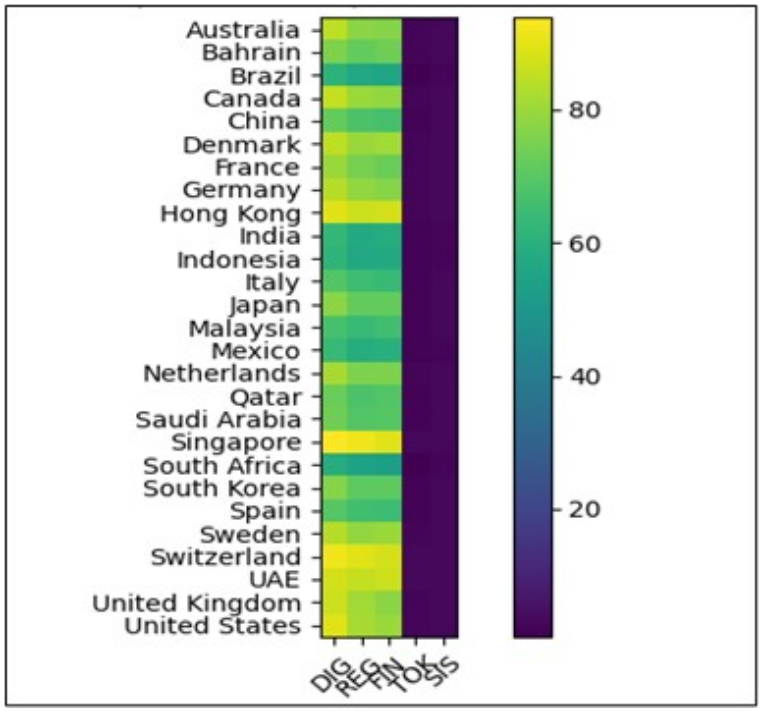


Figure 2

Blockchain Readiness, Tokenization, and Sustainable Investment (Country Averages)

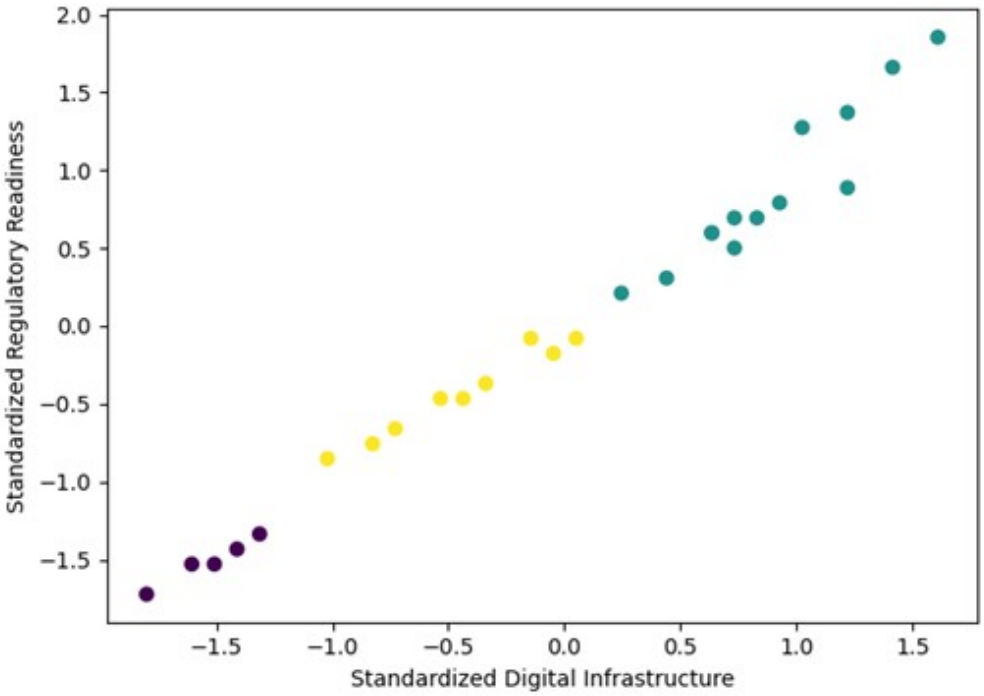


Figure 3

Country Clusters Based on Blockchain and Tokenization Readiness