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The Evolution of Green Finance toward Green Digital Finance in Advancing Sustainable Economic Development

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A R T I C L E I N F O

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A B S T R A C T

Green finance and financial digitalization are increasingly converging, but evidence on their combined contribution to sustainable economic development across emerging economies remains limited. This study examines the relationship between green digital finance (GDF) and sustainable economic development (SED), tests the mediating roles of green innovation and digital financial inclusion, and assesses whether digital infrastructure and regulatory quality condition this relationship. The analysis uses panel data for 20 emerging economies over 2015–2024 and constructs composite GDF and SED indices. Dynamic System-GMM, mediation analysis, and panel-threshold estimation are applied. The reported estimates show a positive association between GDF and SED ($\beta = 0.186$, $p < 0.01$), exceeding the coefficient reported for conventional green finance ($\beta = 0.109$, $p < 0.05$). Green innovation and digital financial inclusion account for 20.1% and 14.6% of the total estimated effect, respectively. Threshold estimates indicate stronger GDF–SED associations above the digital-infrastructure threshold (0.612) and regulatory-quality threshold (0.487). These findings suggest that the contribution of GDF is linked to innovation, financial inclusion, and enabling technological and institutional conditions. The study adds cross-country evidence on the mechanisms and threshold conditions associated with GDF in emerging economies.

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INTRODUCTION

The transition toward low-carbon and inclusive economic development has placed increasing pressure on financial systems to mobilize capital for environmentally sustainable activities. This challenge is particularly important for emerging economies, where governments must simultaneously maintain economic growth, expand access to finance, invest in infrastructure, and respond to climate-related risks. The financing requirement is substantial. The United Nations Inter-agency Task Force on Financing for Development (2024) estimated that developing countries face an additional sustainable-development financing gap of approximately USD 4 trillion annually, while the United Nations Environment Programme (2024) reported that climate-adaptation finance remains far below estimated needs. These conditions strengthen the role of finance as a mechanism for connecting economic development with environmental transformation.

Green finance has emerged as one of the most important responses to this challenge. Through green bonds, sustainable lending, climate-related investment, renewable energy financing, and other environmentally oriented instruments, green finance seeks to direct capital toward economic activities that generate environmental benefits. Recent evidence suggests that green finance can support green growth and sustainable development, particularly when it operates alongside broader financial inclusion. Oanh (2024), for example, shows that the interaction between green finance and financial inclusion contributes positively to sustainable development across economies with different levels of financial development. However, access to green financing remains uneven, particularly in emerging economies where institutional capacity, market depth, information asymmetry, financing costs, and limited access to formal financial services can restrict the reach of conventional green financial instruments.

At the same time, rapid financial digitalization is changing how financial resources are accessed, evaluated, and allocated. FinTech platforms, mobile financial services, digital payment systems, big-data analytics, artificial intelligence, blockchain applications, and digitally enabled financial infrastructure can reduce geographical and transaction barriers that traditionally limited financial participation. These developments are particularly relevant for emerging economies because digital finance can broaden access to financial services while increasing the speed and efficiency of financial transactions. Evidence from developing countries indicates that digital finance is associated with sustainable-development outcomes, although its implications depend on the institutional and economic environments in which it operates (Bakry et al., 2024). Amaliah et al. (2024) also examine the relationship between digital financial inclusion and sustainable economic growth in an emerging economy.

The convergence of these two developments has given rise to green digital finance (GDF). Rather than treating green finance and digital finance as separate domains, GDF combines environmentally oriented capital allocation with digital technologies and digitally inclusive financial systems. Its potential significance lies in its ability to address some limitations of conventional green finance. Digital technologies can lower transaction costs, improve information

processing, facilitate the identification and monitoring of green projects, expand access to previously underserved firms and households, and improve the matching of capital with sustainable investment opportunities. Recent evidence from China's green finance reform and innovation pilot zones demonstrates that green digital finance can contribute to sustainable development through financial inclusion, energy transition, and industrial upgrading (Xiao et al., 2024).

The transition toward GDF therefore represents more than the digital delivery of existing green financial products. It potentially changes the capacity of financial systems to identify sustainable investment opportunities, reduce information asymmetry, expand financial inclusion, and accelerate environmentally oriented innovation. Recent research supports the importance of this interaction. Xu et al. (2024) find that green finance and digital inclusive finance jointly contribute to sustainable economic development, while their effects operate partly through improvements in productive capacity. Similarly, FinTech innovation has been shown to improve the transparency and efficiency of green finance markets, although these effects vary across institutional environments (Chien et al., 2025). These findings suggest that the economic contribution of green finance may increasingly depend on the digital systems through which financial information, capital, and services are organized.

One important transmission mechanism is green innovation. Digital finance can improve firms' access to external financing, reduce financing frictions, and provide new channels for investment in environmentally oriented technologies. Jiang et al. (2024) demonstrate that digital finance can reduce carbon-emission intensity through technological innovation, including green technology innovation. Lu and Xia (2024) similarly find that digital inclusive finance can reduce carbon emissions and that green technological innovation plays an important mediating role. Cross-country evidence also suggests a close relationship among financial digitalization, green innovation, and green finance initiatives (Hossain et al., 2024). Together, these findings indicate that digitalization may increase the developmental value of green finance not only by mobilizing more capital, but also by improving the capacity of financial systems to support innovation-oriented green investment.

A second mechanism is digital financial inclusion. Conventional green financial instruments are often concentrated among governments, financial institutions, large corporations, and established investors. Digital financial services may broaden this structure by lowering entry costs and connecting smaller firms, households, entrepreneurs, and underserved communities to formal financial markets. Oanh (2024) provides evidence that financial inclusion and green finance reinforce sustainable development when considered jointly, while Xiao et al. (2024) identify financial inclusion as one of the mechanisms through which green digital finance promotes sustainable regional development. The ability of GDF to combine environmental objectives with broader financial participation therefore provides a possible link between low-carbon transition and inclusive economic development.

However, the benefits of digitalization are unlikely to arise uniformly across economies. Digital finance depends on infrastructure such as broadband

connectivity, digital identification, payment networks, data systems, and reliable access to digital technologies. Recent evidence shows that digital infrastructure can significantly support sustainable development and green transformation, while insufficient infrastructure can limit these benefits (Tian et al., 2025). Similarly, the environmental effectiveness of green finance varies with institutional and regulatory conditions. Siddik et al. (2026) show that regulatory quality significantly changes the relationship between green finance and environmental outcomes, although the direction and magnitude vary across income groups. These findings imply that the relationship between green digital finance and sustainable development may be nonlinear: GDF may produce stronger benefits only after countries achieve sufficient levels of digital infrastructure and regulatory capacity.

Recent studies increasingly support nonlinear interpretations. Wen et al. (2026) identify threshold effects in the relationship between digital finance and green innovation, while research on inclusive green growth indicates that the contribution of digital finance may vary with green productivity, institutional conditions, and digital infrastructure. This suggests that expanding digital financial services alone may be insufficient; their economic and environmental contribution may depend on the ecosystem in which digital financial activity takes place.

Despite the rapid growth of this literature, several important gaps remain. First, much of the existing research examines green finance and digital finance separately, or estimates interaction effects between them, rather than conceptualizing green digital finance as an integrated stage of financial development. Second, a substantial part of the empirical literature is based on China or individual national and subnational settings. Although these studies provide valuable evidence, their findings may not fully capture the institutional and structural diversity of emerging economies across Asia, Latin America, and Africa. Third, previous research often focuses on individual outcomes such as carbon emissions, green innovation, green total factor productivity, or economic growth. Comparatively less attention has been given to multidimensional sustainable economic development that simultaneously captures economic productivity, carbon efficiency, renewable energy utilization, and inclusive financial access. Finally, relatively few studies examine both the transmission mechanisms and threshold conditions through which GDF influences sustainable economic performance.

Accordingly, this study addresses three research questions: (1) Is green digital finance positively associated with sustainable economic development, and how does its estimated relationship compare with that of conventional green finance? (2) Do green innovation and digital financial inclusion act as mediating pathways in the relationship between GDF and SED? (3) Do digital infrastructure and regulatory quality create threshold conditions under which the GDF–SED relationship becomes stronger?

This study addresses these gaps by examining the evolution from conventional green finance toward green digital finance across 20 emerging economies in Asia, Latin America, and Africa between 2015 and 2024. It develops

a Green Digital Finance Index that integrates green financing intensity, digital financial inclusion, FinTech penetration, and digital financial infrastructure. Sustainable economic development is similarly treated as a multidimensional outcome incorporating economic productivity, carbon efficiency, renewable energy utilization, and inclusive financial access. By employing dynamic System-GMM, mediation analysis, and panel threshold estimation, the study examines not only whether GDF improves sustainable economic development but also how and under what institutional conditions this effect becomes stronger.

The study makes three contributions. First, it moves beyond examining green finance and digital finance as parallel financial developments by conceptualizing green digital finance as a distinct evolutionary pathway in which environmental finance becomes increasingly integrated with digital financial infrastructure and inclusion. Second, it identifies green innovation and digital financial inclusion as transmission mechanisms connecting GDF with sustainable economic development. Third, it introduces digital infrastructure and regulatory quality as threshold conditions, providing an explanation for why similar levels of green and digital financial development may generate different outcomes across emerging economies. In doing so, the study contributes to a more integrated understanding of how financial digitalization can transform green finance from a specialized environmental financing mechanism into a broader platform for inclusive and low-carbon economic development.

LITERATURE REVIEW

Green Finance and Sustainable Economic Development

Green finance has become an important mechanism for directing financial resources toward environmentally sustainable activities, including renewable energy, low-carbon infrastructure, green technology, and environmentally responsible investment. Beyond environmental objectives, green finance can also support broader sustainable development by improving resource allocation and encouraging productive investment. Oanh (2024) shows that green finance, particularly when combined with financial inclusion, contributes positively to sustainable development. However, conventional green finance often remains concentrated among formal financial institutions, large corporations, and established investors, limiting its accessibility and broader developmental impact.

Digital Finance and Financial Inclusion

The expansion of digital finance has changed the structure of financial intermediation by lowering transaction costs, reducing geographical barriers, and improving access to financial services. Digital financial inclusion is particularly relevant for emerging economies, where conventional financial systems may not adequately serve small firms, low-income households, and geographically dispersed populations. Recent research shows that digital inclusive finance can support green inclusive growth by improving financial service efficiency and directing resources toward productive economic activities (Xu et al., 2024). A systematic review by Mamun and László (2025) further

indicates that digital innovations such as FinTech, artificial intelligence, and blockchain can strengthen the relationship between financial inclusion and sustainable finance, although regulatory and technological risks remain important.

Green Digital Finance as an Integrated Financial Transformation

Green digital finance represents the convergence of green financial objectives and digital financial capabilities. Rather than treating green finance and digital finance as independent systems, GDF integrates digital technology, inclusive financial services, and environmentally oriented capital allocation. Xiao et al. (2024) find that green digital finance significantly promotes sustainable development through financial inclusion, energy transition, and industrial upgrading. Similarly, Tan et al. (2024) show that GDF can facilitate technology diffusion, addressing some structural limitations of traditional financing in supporting sustainable technological development.

The importance of this integration is also evident in studies examining low-carbon transformation. Shi and Yang (2024) find that green digital finance promotes the low-carbon transformation of energy consumption through industrial restructuring and green technological innovation. These findings suggest that GDF should be understood not merely as a digital extension of conventional green finance, but as a broader financial development model capable of improving capital allocation, technological adoption, and environmental performance.

Green Innovation, Financial Inclusion, and Threshold Effects

Green innovation represents an important mechanism through which digitalized financial systems may contribute to sustainable economic development. Digital finance can reduce financing constraints, improve access to information, and increase the efficiency of allocating capital toward innovative activities. Guan and Xue (2025) examine the relationship between digital financial inclusion and corporate green innovation, including the role of financing constraints and resource allocation. At the regional level, Wen et al. (2026) find that digital finance promotes green innovation, although the relationship is nonlinear and may exhibit diminishing marginal returns after particular development thresholds are reached.

These findings imply that the relationship between GDF and sustainable development may not be uniform across countries. Its effectiveness may depend on supporting conditions such as digital infrastructure, institutional quality, financial regulation, and technological capacity. Research on green digital finance and energy transition also considers the role of regional policy uncertainty and related enabling conditions (Du & Zhang, 2025). Evidence on regulatory quality further suggests that institutional conditions can change the relationship between green finance and environmental outcomes (Siddik et al., 2026). Thus, digital infrastructure and regulatory quality are examined in this study as potential threshold conditions.

The literature points to several related but distinct findings. First, studies of conventional green finance and financial inclusion generally report a positive

relationship with sustainable development (Oanh, 2024), while research on digital inclusive finance identifies improved access and productive capacity as possible channels (Amaliah et al., 2024; Xu et al., 2024). Second, studies of green digital finance provide evidence of links with sustainable development, technology diffusion, and low-carbon transformation, but much of this evidence is drawn from China-specific or regional settings (Xiao et al., 2024; Tan et al., 2024; Shi & Yang, 2024). Third, research identifies green innovation and financial inclusion as plausible transmission mechanisms (Jiang et al., 2024; Lu & Xia, 2024; Guan & Xue, 2025), while other studies indicate that digital infrastructure and institutional conditions may alter the strength of these relationships (Du & Zhang, 2025; Wen et al., 2026; Siddik et al., 2026). Taken together, these studies support the proposed mechanisms and conditional relationships, but they do not remove the need for a cross-regional panel analysis that examines the integrated GDF construct, both mediating pathways, and two threshold conditions in one empirical framework.

Hypothesis Development

H1. Green digital finance is positively associated with sustainable economic development.

H2. Green innovation mediates the relationship between green digital finance and sustainable economic development.

H3. Digital financial inclusion mediates the relationship between green digital finance and sustainable economic development.

H4. The relationship between green digital finance and sustainable economic development is stronger when digital infrastructure exceeds its estimated threshold.

H5. The relationship between green digital finance and sustainable economic development is stronger when regulatory quality exceeds its estimated threshold.

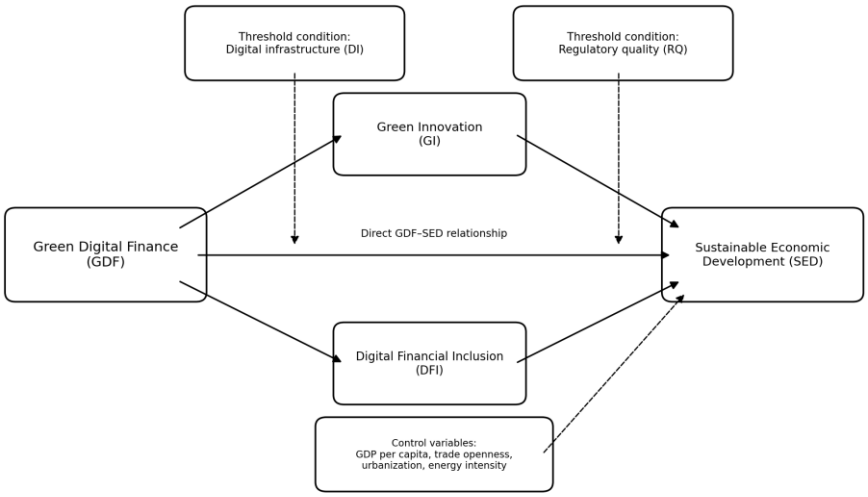


Figure 1. Conseptual Framework

METHOD

Research Design and Data

This study employed a quantitative panel-data design covering 20 emerging economies across Asia, Latin America, and Africa from 2015 to 2024. Countries were selected based on the availability and continuity of financial, digital, environmental, and macroeconomic data. Data were obtained from the World Bank's World Development Indicators and Worldwide Governance Indicators, the IMF Financial Access Survey, the International Telecommunication Union, WIPO, IRENA, and international green-finance databases.

Variable Measurement

The dependent variable, Sustainable Economic Development (SED), was constructed as a composite index consisting of economic productivity, carbon efficiency, renewable energy utilization, and inclusive financial access. The main explanatory variable, Green Digital Finance (GDF), combined green financing intensity, FinTech penetration, digital financial infrastructure, and digital financial development. All indicators were normalized and aggregated using an entropy-weighting approach to reduce subjective weighting.

Green innovation was measured using environment-related patent activity, while digital financial inclusion was captured through indicators of digital financial access and usage. To avoid mechanical overlap between the GDF index and digital financial inclusion in the mediation analysis, a leave-one-component-out GDF index excluding the financial-inclusion component was employed in the mediation models. Regulatory quality and digital infrastructure were used as threshold variables. GDP per capita, trade openness, urbanization, and energy intensity were included as control variables.

Econometric Model

The baseline dynamic relationship between green digital finance and sustainable economic development was estimated using the System Generalized Method of Moments (System-GMM) estimator:

$$SED_{it} = \alpha + \rho SED_{i,t-1} + \beta GDF_{it} + \gamma' X_{it} + \mu_i + \lambda_t + \varepsilon_{it},$$

and the comparison model for conventional green finance is:

$$SED_{it} = \alpha + \rho SED_{i,t-1} + \beta_1 GF_{it} + \gamma' X_{it} + \mu_i + \lambda_t + \varepsilon_{it}.$$

where SED_{it} denotes sustainable economic development in country i and year t; $SED_{i,t-1}$ is its one-period lag; GDF_{it} denotes green digital finance; GF_{it} denotes conventional green finance; X_{it} is the vector of control variables; μ_i represents country-specific effects; λ_t represents year effects; and ε_{it} is the idiosyncratic error term. System-GMM was selected to account for dynamic persistence, country-specific effects, and potential endogeneity between financial development and sustainable economic performance (Blundell & Bond, 1998; Roodman, 2009).

Mediation analysis examined whether green innovation and digital financial inclusion transmitted part of the relationship between GDF and SED. The mediation structure can be represented by the following sequential equations:

$$M_{it} = \alpha_1 + aGDF_{it} + \delta' X_{it} + \mu_i + \lambda_t + \varepsilon_{1it},$$

$$SED_{it} = \alpha_2 + \rho SED_{i,t-1} + c'GDF_{it} + bM_{it} + \theta' X_{it} + \mu_i + \lambda_t + \varepsilon_{2it},$$

Where M_{it} is estimated separately as GI_{it} and DFI_{it}; the indirect association is calculated as a × b.

Threshold and Robustness Analysis

To examine nonlinear relationships, panel-threshold estimation was applied following Hansen (1999). Separate models assessed whether the estimated GDF–SED association differed below and above the threshold for digital infrastructure and regulatory quality. A single-threshold specification can be expressed as:

$$SED_{it} = \alpha + \rho SED_{i,t-1} + \beta L\, GDF_{it} I(q_{it} \le \tau) + \beta H\, GDF_{it} I(q_{it} > \tau) + \gamma' X_{it} + \mu_i + \lambda_t + \varepsilon_{it},$$

Where q_{it} is specified separately as digital infrastructure and regulatory quality, τ is the estimated threshold, and $I(\cdot)$ is an indicator function. The robustness checks replace the composite SED measure, apply alternative GDF weighting schemes, exclude 2020–2021, and use a fixed-effects specification.

RESEARCH RESULTS

Descriptive Statistics

The final panel consisted of 200 country-year observations from 20 emerging economies over the 2015–2024 period. The descriptive statistics indicate considerable cross-country variation in green digital finance, sustainable economic development, green innovation, and digital financial inclusion. The average Green Digital Finance Index was 0.487, while the mean Sustainable Economic Development Index was 0.514. The variation across countries suggests that emerging economies differ substantially in their ability to integrate green financing with digital financial infrastructure and technology.

Table 1. Descriptive Statistics of Main Variables

Variable	Mean	Std. Dev.	Min	Max
Sustainable Economic Development (SED)	0.514	0.138	0.218	0.821
Green Digital Finance (GDF)	0.487	0.152	0.174	0.806
Conventional Green Finance (GF)	0.462	0.141	0.169	0.769
Green Innovation (GI)	0.438	0.149	0.137	0.794
Digital Financial Inclusion (DFI)	0.536	0.168	0.192	0.862
Digital Infrastructure (DI)	0.552	0.171	0.196	0.891
Regulatory Quality (RQ)	0.501	0.147	0.188	0.803

Green Digital Finance and Sustainable Economic Development

Table 2 presents the dynamic System-GMM estimates. Model 1 examines conventional green finance, while Models 2 and 3 introduce green digital finance. Conventional green finance showed a positive relationship with sustainable economic development ($\beta = 0.109$, $p < 0.05$). However, the effect became substantially stronger when the integrated Green Digital Finance Index was used.

In the fully specified model, GDF had a positive and statistically significant coefficient of 0.186 ($p < 0.01$). This indicates that improvements in green digital finance were associated with stronger sustainable economic performance after controlling for economic and structural characteristics.

Table 2. Dynamic System-GMM Results

Variables	Model 1	Model 2	Model 3
Lagged SED	0.431***	0.452***	0.447***
Conventional Green Finance	0.109**	—	—
Green Digital Finance	—	0.181***	0.186*
GDP per capita	0.061**	0.069**	0.073**
Trade openness	0.037*	0.039*	0.041*
Urbanization	0.048**	0.051**	0.052**
Energy intensity	-0.081**	-0.086**	-0.088**
Country effects	Yes	Yes	Yes
Year effects	Yes	Yes	Yes
Observations	200	200	200
Countries	20	20	20
Instruments	16	17	17
AR(1), p-value	0.019	0.022	0.021
AR(2), p-value	0.301	0.281	0.274
Hansen test, p-value	0.421	0.397	0.386

Note: **p < 0.05; **p < 0.01.

The insignificant AR(2) statistic indicates no evidence of second-order serial correlation, while the Hansen test suggests that the instrument set remained valid. The number of instruments was also kept below the number of country groups to reduce instrument proliferation. More importantly, the estimated coefficient for GDF was considerably larger than that of conventional green finance. This supports the central proposition of the study that combining green financial development with digital capabilities provides stronger sustainable development benefits than conventional green financing alone.

Mediating Effects of Green Innovation and Digital Financial Inclusion

The mediation analysis examined whether green innovation and digital financial inclusion transmitted the effect of GDF on sustainable economic development. Both mechanisms were statistically significant. GDF positively affected green innovation ($\beta = 0.243$, $p < 0.01$), while green innovation subsequently increased sustainable economic development ($\beta = 0.154$, $p < 0.01$).

The estimated indirect effect through green innovation was 0.037, accounting for approximately 20.1% of the total GDF effect.

Similarly, GDF increased digital financial inclusion ($\beta = 0.211$, $p < 0.01$), while digital financial inclusion positively affected sustainable economic development ($\beta = 0.128$, $p < 0.01$). This pathway accounted for approximately 14.6% of the total effect.

Table 3. Mediation Effects

Mediating pathway	Indirect effect	Bootstrap 95% CI	Share of total effect
GDF → Green Innovation → SED	0.037	0.018–0.059	20.1%
GDF → Digital Financial Inclusion → SED	0.027	0.011–0.045	14.6%
Total indirect effect	0.064	0.039–0.087	34.7%

The combined mediation effect accounted for 34.7% of the total relationship between GDF and sustainable economic development. The remaining effect operated directly or through mechanisms not explicitly included in the model. These results suggest that GDF supports sustainable development not only by improving the allocation of green capital, but also by encouraging technological innovation and broadening participation in digital financial systems.

Threshold Effects of Digital Infrastructure and Regulatory Quality

The panel threshold analysis revealed significant nonlinearities in the GDF–SED relationship. A statistically significant threshold was identified for both digital infrastructure and regulatory quality.

For digital infrastructure, the estimated threshold value was 0.612. Below this threshold, the GDF coefficient was positive but relatively modest ($\beta = 0.101$, $p < 0.05$). Once digital infrastructure exceeded the threshold, the effect increased substantially to 0.247 ($p < 0.01$). A similar pattern emerged for regulatory quality. The estimated threshold was 0.487. Below this level, GDF had a coefficient of 0.114 ($p < 0.05$), whereas economies above the threshold experienced a substantially larger effect of 0.259 ($p < 0.01$).

Table 4. Panel Threshold Results

Threshold variable	Estimated threshold	Below threshold	Above threshold	Bootstrap p-value
Digital infrastructure	0.612	0.101**	0.247***	0.013
Regulatory quality	0.487	0.114**	0.259***	0.009

Note: **p < 0.05; **p < 0.01.

The estimates indicate that the GDF–SED relationship varies with the level of digital infrastructure and regulatory quality. The coefficients are larger above

both estimated thresholds, suggesting that the association between GDF and SED is conditional on technological and institutional conditions.

Table 6. Summary of hypothesis testing based on the reported estimates.

Hypothesis	Evidence reported in the manuscript	Decision
H1	GDF coefficient in Model 3 = 0.186 (reported $p < 0.01$).	Supported
H2	GI indirect estimate = 0.037; bootstrap 95% CI = 0.018–0.059.	Supported
H3	DFI indirect estimate = 0.027; bootstrap 95% CI = 0.011–0.045.	Supported
H4	DI threshold = 0.612; GDF coefficient rises from 0.101 to 0.247; bootstrap p = 0.013.	Supported
H5	RQ threshold = 0.487; GDF coefficient rises from 0.114 to 0.259; bootstrap p = 0.009.	Supported

Robustness Checks

Several robustness tests were conducted to examine whether the results were sensitive to alternative model specifications. Replacing the composite SED measure with alternative indicators, reconstructing the GDF index using different weighting schemes, excluding the 2020–2021 pandemic period, and applying alternative panel estimators produced consistently positive and statistically significant GDF coefficients.

Table 6. Summary of Robustness Tests

Robustness specification	GDF coefficient
Alternative SED index	0.164***
Alternative GDF weighting	0.173***
Excluding 2020–2021	0.192***
Fixed-effects specification	0.149***

Note: **p < 0.01.

The consistency of the coefficient signs and significance levels indicates that the main findings were not driven by a particular index construction, sample period, or estimation technique. Overall, the results provide evidence that green digital finance contributes positively to sustainable economic development and generates stronger effects than conventional green finance alone. The findings further demonstrate that green innovation and digital financial inclusion are important transmission mechanisms, jointly explaining 34.7% of the total effect. However, the magnitude of these benefits depends strongly on a country's digital infrastructure and regulatory quality, indicating that the evolution toward green digital finance requires both technological capacity and supportive institutional conditions.

DISCUSSION

The findings provide evidence that green digital finance is positively associated with sustainable economic development across emerging economies. The estimated GDF coefficient of 0.186 was larger than the coefficient for conventional green finance, suggesting that integrating digital capabilities into green financial systems may generate broader economic and environmental benefits than green financing alone. This result supports the view that financial digitalization can strengthen the capacity of green finance by improving information processing, reducing transaction barriers, expanding access to financial services, and facilitating more efficient allocation of capital toward sustainable activities. Similar evidence is reported by Xiao et al. (2024), who find that green digital finance promotes sustainable development through financial inclusion, energy transition, and industrial upgrading. Xu et al. (2024) likewise show that green finance and digital inclusive finance contribute positively to sustainable economic development.

The stronger effect of GDF compared with conventional green finance is theoretically important. Traditional green finance mainly redirects capital toward environmentally responsible activities, but its reach may remain limited by information asymmetry, transaction costs, and unequal access to formal financial markets. Digital technologies can partly reduce these constraints by improving financial connectivity and making financial services more accessible. Chien et al. (2025) show that FinTech can improve the transparency and efficiency of green finance markets, particularly where regulatory environments are supportive. The present findings therefore suggest that digitalization should not be viewed simply as an additional delivery channel for green financial products. Rather, it can change how green capital is identified, distributed, monitored, and accessed.

The mediation results provide further insight into how this relationship operates. Green innovation explained approximately 20.1% of the total GDF effect. This finding suggests that one important contribution of GDF is its ability to support environmentally oriented technological development. Digital financial systems can reduce financing frictions, improve access to external capital, and connect innovative firms with financial resources more efficiently. Lu and Xia (2024) similarly demonstrate that green technological innovation plays an important role in the relationship between digital inclusive finance and carbon reduction. Evidence from digital finance research also shows that technological and green innovation constitute important channels through which financial digitalization contributes to lower carbon intensity. These results indicate that the contribution of GDF extends beyond financing existing green activities to supporting the development and diffusion of new green technologies.

Digital financial inclusion represented the second important mechanism, accounting for approximately 14.6% of the total effect. This result is consistent with Oanh (2024), who finds that financial inclusion and green finance reinforce sustainable development when considered jointly. By reducing geographical and transactional barriers, digital finance can expand access to financial resources for

smaller firms, entrepreneurs, and populations that may be underserved by conventional financial institutions. Green digital finance may therefore contribute to sustainability not only by improving the environmental direction of capital but also by widening participation in the financial system. This inclusive dimension is particularly relevant for emerging economies, where differences in access to formal financial services remain substantial.

Taken together, the two mediating mechanisms explained 34.7% of the total GDF effect. This indicates that the relationship between green digital finance and sustainable development cannot be explained by a single transmission channel. Instead, GDF appears to operate through both a technological pathway, by stimulating green innovation, and an inclusion pathway, by expanding access to financial services. The remaining direct effect also suggests that additional mechanisms may be involved, including improved capital allocation, lower transaction costs, more efficient risk assessment, energy transition, and changes in industrial structure. Xiao et al. (2024), for example, identify financial inclusion, energy transition, and structural upgrading as important channels through which green digital finance contributes to sustainable development.

The threshold results further demonstrate that the benefits of GDF are conditional rather than uniform. The effect of GDF increased substantially once digital infrastructure exceeded the estimated critical level. This is economically plausible because digital financial systems require reliable connectivity, payment infrastructure, data systems, and technological access to function effectively. Where these foundations remain weak, digital financial products may exist without generating broad economic or environmental benefits. Once sufficient digital infrastructure is established, however, financial technologies can reach more users, process information more efficiently, and support green investment at greater scale.

A similar pattern was observed for regulatory quality. The substantially larger GDF coefficient above the regulatory threshold suggests that technological development alone is insufficient. Effective financial regulation, institutional credibility, consumer protection, data governance, and clear green-finance standards are also needed to translate digital financial expansion into sustainable outcomes. This interpretation is consistent with Chien et al. (2025), who find that FinTech contributes more effectively to green finance in environments with stronger regulatory conditions. It also supports the broader argument that the benefits of financial digitalization depend on the institutional ecosystem within which financial technologies operate.

The nonlinear findings are also consistent with recent research on digital finance and green innovation. Wen et al. (2026) identify threshold effects in the relationship between digital finance and green innovation, showing that the benefits of financial digitalization vary according to the level of digital financial development. This suggests that the relationship between digital finance and sustainability should not necessarily be assumed to be linear. At relatively low levels of technological and institutional readiness, additional digital financial development may generate limited benefits, whereas stronger supporting conditions can allow GDF to operate more effectively. At very advanced levels,

however, diminishing marginal returns may also emerge, indicating the importance of examining both minimum thresholds and longer-term nonlinear dynamics.

These results have important implications for emerging economies. Policies that promote green finance without simultaneously strengthening digital infrastructure, financial inclusion, innovation capacity, and regulatory institutions may produce more limited outcomes. Similarly, expanding digital finance without a clear environmental orientation may increase financial activity without necessarily supporting low-carbon development. The policy challenge is therefore not simply to promote more green finance or more digital finance independently, but to develop an integrated financial ecosystem in which digital technologies improve the accessibility, efficiency, and environmental orientation of capital allocation.

Overall, the findings support the study's central argument that green digital finance represents a distinct stage in the evolution of sustainable finance. Its contribution lies in combining the environmental objectives of green finance with the efficiency, connectivity, and inclusiveness of financial digitalization. The evidence also extends existing literature by showing that this relationship operates through green innovation and digital financial inclusion and becomes considerably stronger when digital infrastructure and regulatory quality exceed critical levels. Green digital finance should therefore be understood not merely as the digitalization of conventional green finance, but as an integrated financial development pathway capable of linking technological transformation, financial inclusion, and low-carbon economic development.

CONCLUSION AND RECOMMENDATION

This study concludes that green digital finance has a stronger positive relationship with sustainable economic development than conventional green finance alone. The results indicate that this effect operates partly through green innovation and digital financial inclusion, while digital infrastructure and regulatory quality significantly strengthen the contribution of GDF once critical thresholds are reached. These findings suggest that the transition toward green digital finance is not merely a technological extension of green finance, but a broader transformation in how sustainable capital is allocated, accessed, and translated into economic and environmental outcomes.

Based on these findings, emerging economies should develop integrated policies that simultaneously strengthen green financial markets, digital infrastructure, financial inclusion, and regulatory quality. Governments and financial institutions should also encourage digital platforms and FinTech providers to support green investment, innovation financing, and environmentally responsible financial products. Future research should expand the country sample, examine longer time periods, and explore additional mechanisms such as energy transition, industrial upgrading, and institutional quality to better understand the long-term effects of green digital finance.

ADVANCED RESEARCH

Future research should expand the country sample, extend the observation period, and examine additional mechanisms such as energy transition, green entrepreneurship, and institutional quality. Comparative studies across regions and income groups may also clarify how digital readiness and regulatory capacity influence the effectiveness of green digital financ.

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