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Research Article

The Impact of Digital Finance in G20 Economies on Environmental Protection, Energy Transition Policy, and Technological Innovation

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Abstract
The study investigates the complex relationship between green development and digital finance, first emphasizing China and a subsequent extension to the G20 nations. Using qualitative and quantitative methods to examine provincial data from 2015 to 2023, the research shows how digital money may promote ecologically sustainable development. It highlights the importance of education, economic structure, research and development, and governmental initiatives in boosting the alignment between digital finance and sustainability while identifying regional variations and threshold effects. The interaction of digital finance with technological innovation, environmental protection, and energy transition policy across G20 nations was thoroughly analyzed, providing insightful viewpoints for sustainable development. The study's quantitative analysis reveals that digital finance has a statistically significant positive impact on technological innovation and environmental sustainability in G20 economies. Empirical results indicate a 0.163% increase in green development for every 1% rise in digital finance adoption. Findings further highlight regional disparities, emphasizing the need for policy-driven financial inclusion strategies. In addition, the study offers practical suggestions for using digital finance to promote technological innovation, environmental preservation, and the creation of energy transition policies within the framework of the G20. Ultimately, the study emphasizes how urgent it is for stakeholders and governments to incorporate digital finance strategies with sustainable development goals, especially in light of international climate agreements, to create a more just, resilient, and ecologically sustainable future.

Keywords: Digital finance, technological innovation, environmental protection, energy transition

Introduction
In a world where the urgency of ecological sustainability has never been more pronounced, the findings of this research serve as a clarion call for action. It represents a crucial global gathering where nations come together to address climate change challenges. By illuminating the transformative potential of digital finance in driving green growth, the study offers a roadmap toward a more sustainable future. [1]. It inspires us to reimagine the role of technology in addressing environmental challenges and underscores the power of innovation in forging a path toward sustainability. As we stand at the precipice of global climate agreements, this research ignites a fire within us [2], urging governments, businesses, and individuals alike to seize the opportunity presented by digital finance to enact meaningful change. Let us harness the power of technology, embrace collaboration across borders [3], and commit ourselves to integrating digital finance strategies with sustainable development agendas. Together, we can pave the way for a future that is not only prosperous and equitable but also in harmony with the delicate balance of our planet [4].To examine the impact of digital finance on environmental protection in G20 economies.To assess how digital finance contributes to energy transition policies and sustainable technological innovation.To identify key economic and policy factors that influence the relationship between digital finance and sustainability.
In the wake of China's unprecedented financial development over the past decade, which has captivated global interest, the imperative for sustainable development has become increasingly urgent [5]. China's former financial development model, characterized by short-term gains and excessive resource

consumption leading to environmental degradation, is no longer sustainable. Consequently, there is a pressing need for a fundamental shift towards environmentally friendly and sustainable development pathways, not only in China but also in many other nations grappling with similar challenges. Simultaneously, the rise of digital finance has revolutionized economic landscapes across the globe, presenting unique opportunities to redefine traditional growth paradigms [6]. The convergence of sustainable development goals with the transformative potential of digital finance forms a nexus of inquiry with profound implications for global economies and environmental sustainability [7].

Research embarks on a rigorous examination of this intricate relationship, employing a comprehensive methodology that integrates qualitative insights with quantitative analyses. Drawing from a diverse array of scholarly perspectives and empirical data, our study seeks to unravel the multifaceted impacts of digital finance on key domains such as Technological Innovation adoption, environmental conservation [8], and the formulation of robust energy transition policies within the dynamic context of G20 economies. Through an expansive dataset encompassing varied socio-economic contexts, regulatory landscapes, and technological infrastructures, we endeavor to elucidate the transformative potential of digital finance in driving sustainable energy transitions. Central to our findings is the recognition of digital finance as a linchpin for mobilizing capital towards Technological Innovation projects, nurturing innovation ecosystems [9], Moreover, facilitating the seamless flow of investments is critical for acceleration. This study aims to address the following research questions: How does digital finance contribute to environmental sustainability in G20 economies? What is the relationship between digital finance and energy transition policies? Does technological innovation mediate the impact of digital finance on environmental sustainability and development? Based on these questions, we propose the following hypotheses: H1: Digital finance positively influences environmental sustainability in G20 economies.H2: Digital finance significantly impacts energy transition policy adoption.H3: Technological innovation acts as a mediator between digital finance and green development

dating the adoption of clean energy solutions Moreover, Research underscores the indispensable role of digital finance initiatives in environmental preservation endeavors. We highlight their capacity to mitigate carbon emissions, optimize resource allocation, and foster the widespread adoption of sustainable development practices (Ackermann et al., 2023), thereby contributing to global efforts to combat climate change. Furthermore, our study examines the intricate interplay between digital finance and the development of energy transition policies, illuminating synergies, challenges, and potential pathways for leveraging digital finance to accelerate the transition toward low-carbon economies. Through a nuanced examination of regulatory frameworks, institutional mechanisms, and stakeholder engagements, we offer actionable recommendations for policymakers (Košnjek et al., 2024), financial institutions, and other stakeholders to harness the transformative potential of digital finance effectively. As G20 economies navigate the complexities of energy transition, underscore the imperative of integrating digital finance strategies into national energy policies and climate action plans. By harnessing the synergies between digitalization and Technological Innovation, countries can advance towards their emission reduction targets while fostering economic growth and resilience. In essence, our research aims to contribute to the ongoing discourse on the role of digital finance in shaping the trajectory of sustainable energy transitions. By providing empirical evidence, theoretical insights, and pragmatic solutions, we aim to empower stakeholders to navigate the complexities of this evolving landscape, thereby fostering a more resilient, equitable, and environmentally sustainable future for G20 economies and beyond.

This research makes a significant contribution to our understanding of the intersection between digital finance and green growth, offering valuable insights for policymakers, practitioners, and researchers alike. By synthesizing qualitative and quantitative analyses of provincial data from China and extending its scope to the G20 economies, the study unveils the intricate relationship between digital finance and sustainability. The identification of regional disparities, threshold effects, and key influencing factors such as education, economic structure, and governmental interventions provides a nuanced understanding of the mechanisms through which digital finance can drive environmentally friendly progress. Moreover, by offering actionable recommendations for leveraging digital finance to spur Technological Innovation innovation, environmental protection, and energy transition policy formulation, the research equips stakeholders with practical strategies for advancing sustainability goals within the global framework. Ultimately, the study underscores the imperative for governments and stakeholders to integrate digital finance strategies into sustainable development agendas, thereby catalyzing a transition towards a more resilient, equitable, and environmentally sustainable future on a global scale. Effective energy transition policies are essential for harnessing the full potential of digital finance in advancing Technological Innovation innovation and environmental protection. Policymakers within G20 economies must prioritize the development of regulatory frameworks that promote the integration of digital finance into sustainable energy projects while safeguarding investor interests and maintaining financial stability. Furthermore, international cooperation and knowledge-sharing mechanisms, as exemplified, are crucial for harmonizing energy transition policies and accelerating global efforts towards a low-carbon future.

Literature review

The intertwined dynamics of green growth are evident, where governmental support to state-owned enterprises (SOEs) for economic growth often conflicts with environmental objectives. This juxtaposition underscores a pivotal challenge [10]: while striving for GDP targets, conventional heavy sectors reliant on natural resources exacerbate environmental degradation. Policymakers, scientists, activists, and stakeholders collaborate to negotiate and implement strategies aimed at mitigating climate change and promoting sustainable development. This discordance underscores the indirect impact on green growth, highlighting a need for alignment between strategy and execution [11].Conversely, the fusion of economics and digital technology, epitomized by digital finance, presents a transformative avenue. Digital finance, leveraging advanced technologies, offers unprecedented opportunities for sustainable economic development. From streamlining operations to reducing carbon footprints, its influence spans various facets, promoting innovation, clean energy adoption, and environmentally friendly investments [12].

The amalgamation of digital finance and sustainability catalyzes profound shifts across critical sectors worldwide. Recognized as a linchpin in driving progress, digital finance mobilizes capital for Technological Innovation projects and mitigates financing barriers, accelerating the transition towards sustainable energy solutions [13]. Moreover, its role extends to environmental preservation, fostering efficient resource management, and directing investments toward eco-friendly endeavors [14]. Delving deeper, scholarly inquiries explore the regulatory landscape and institutional dynamics, unraveling synergies and challenges for leveraging digital finance in shaping energy transition policies [15].In essence, the synthesis of literature underscores the pivotal role of digital finance in steering sustainable development within G20 economies. From advancing Technological Innovation adoption to shaping policy frameworks, digital finance emerges as a catalyst for resilience and equity in fostering a greener future. The world has witnessed a gradual escalation in the severity and frequency of climate-related events. From extreme weather patterns to rising sea levels, the need for decisive action has never been more pressing. It builds upon the outcomes of previous conferences, aiming to accelerate progress toward meeting the objectives set forth in international agreements like the Paris Agreement. However, it calls for continued research to unlock its full potential and devise strategies for maximizing its positive impact on sustainable development goals [16].

The utilization of digital economics facilitates the progression of environmentally sustainable growth. The essence of green growth is rooted in the enduring viability of the atmosphere, which should also embrace the enhancement of social well-being, the improvement of human health, the promotion of employment, the effective utilization of resources, and the transformation of ingesting patterns [17]. The notion of green growth is intricately linked to human existence, encompassing the utilization of low-carbon, environmentally friendly energy sources such as energy, natural gas, and solar energy. It also involves the adoption of clean kitchen equipment and the promotion of eco-friendly modes of travel. Indeed, these are determined by the benchmark of consumption. Furthermore, green growth includes: The sustainable energy sector. The advancement of new energy technologies. The enforcement of pertinent environmental regulations. This paper does not address the Clean Act or environmental restrictions. Instead, it concentrates on the well-being of consumers and the environmentally sustainable growth of businesses [2].

As said before, the lack of access to electricity for communities not only hinders long-term economic development but also worsens the environmental atmosphere. Therefore, by alleviating energy deficiency amongst household occupants, we may enhance the educational and healthcare advantages for populaces and promote sustainable growth [18]. It is important to consider people's preferences and readiness to buy clean energy. However, the main obstacle to changing their energy consumption habits in developing nations is the low economic level of the population. Regarding this matter, inclusive finance is considered to be an effective approach for increasing the wealth of inhabitants. [19] argue that inclusive finance in China promotes agrarian cover and creative loans for people with low incomes, addressing their financing needs for production and entrepreneurship.

Additionally, it aims to increase income by accumulating financial capital, thereby enhancing the affordability of clean energy for low-income individuals and supporting green development. Research has shown that the advancement of financial systems has a beneficial impact on diminishing energy poverty and facilitating the shift towards low-carbon practices [20]. We assert that the key to achieving a low-carbon transition and alleviating family energy poverty is to enhance consumption capacity [21]. Furthermore, we contend that increasing levels of environmental awareness necessitate corresponding increases in social welfare. The achievement of green development is not feasible within a limited time frame, especially when it is disconnected from continuous economic expansion [22].

The development of the green economy is significantly aided by green credit, a crucial component of green finance. Studies have demonstrated numerous benefits of green credit programs. These regulations provide greater credit resources to companies that prioritize eco-friendly efforts over those that contribute to pollution, and they reward environmentally detrimental organizations for adopting sustainable practices. Additionally, they help to reduce pollution in the manufacturing sector and motivate developing nations to transition to a more sustainable future, which in turn fosters maintainable financial growth. [23].This is mostly due to the influence of green credit regulations, which encourage commercial banks to lend money to businesses that place a high priority on environmental sustainability [24] Examine how China's green credit incentive affects output and well-being using an energy-stochastic general equilibrium (DSGE) model. The findings show that productivity, the situation, health, and utility welfare are significantly impacted by green credit depending on both quantity and price. These impacts foster a win-win relationship between production and the environment, helping to strengthen China's industrial structure in an [25]. They contend that inclusive financing can enhance the effectiveness of green economic growth by alleviating the credit constraints faced by companies that generate significant amounts of pollution. The financial accelerator idea, first proposed by Bernanke and Blinder in 1989, states that a corporation's net assets will increase or decrease in response to positive or negative economic developments, amplifying the impact on the environment and the economy as a whole. Thus, to reduce economic volatility, it is imperative to thoroughly assess borrower data to alleviate the information imbalance generated by financial hurdles. Research indicates that advancements in technology enhance the effectiveness of firms in acquiring credit market data, hence reducing information asymmetry (NAIR, n.d.).

Digital finance, which symbolizes technological advancement and innovation, is the fusion of finance and technology. It not only increases the efficiency of loan distribution but also successfully lowers the risk of unethical behavior and information imbalance. Taking a more comprehensive view, digital finance can help stabilize green credit and provide funds to underfunded technology sectors. Additionally, it enhances resource utilization efficiency, fosters business innovation, and has a positive impact on green growth. [26]claimed that increasing the output of Technological Innovation while simultaneously reducing investment and financing volatility in Technological Innovation, as well as green credit, is essential to improving long-term environmental quality and fostering sustainable economic development.

Data and Method

Sample data

Three main sources of information are used in this article. The initial data component uses macro characteristics specific to Chinese provinces to capture regional differences in economic development. The data's second component comprises development indicators for digital finance (DGF). Ultimately, it serves as a platform for collective action and solidarity in the fight against the existential threat of climate change. The index system comprises 33 variables [27] Offer a thorough evaluation of China's state of digital financial development. Green development indicators are covered in detail in the study's last section. Early studies often focused on a single measure, which limited their ability to comprehensively capture the concept of green development despite the existence of different interpretations of green development and various techniques for evaluating it. [28]. Green development is more than just environmental friendliness and growth together. According to the OECD's definition, it is a purposeful effort to attain economic growth and development 2009 through the effective management of environmental hazards and the guarantee of long-term, sustainable economic growth. This study employs the Super SBM model, which accounts for unexpected output, to assess China's level of green development while considering the nation's unique conditions. This study examines the relationship between green development statistics and the digital financial development index, utilizing a panel dataset of Chinese provinces from 2015 to 2023. The WIND database and the China Statistical Yearbook are the primary sources of the data. Thirty provinces and municipalities had their data saved after the relevant provinces with missing data were removed. Table 1 contains the descriptive statistics for the pertinent variables.

Selections of variables and their definitions

Control variables

The process of selecting control variables, particularly at the local level, is the main focus of this work. Openness, often referred to as trade transparency, is measured as the percentage of total imports and exports to the GDP of each province. The average default rate of commercial bank institutions within each province is used to calculate the commercial bank default rate (Default). This acts as a stand-in variable. Targets for reducing emissions, adoption of Technological Innovation [29], Climate finance and adaptation plans. Delegates from around the world gather to discuss and collaborate on ways to address climate change, with scientific evidence underscoring the need for immediate and drastic action. The fixed asset investment in each province is measured by the adjusted proportion of fixed asset investment (FIX_ratio). An increase in capital investment in fixed assets can improve a region's appeal to capital. The logarithmic form of the corresponding scale represents the yearly foreign direct investment (FDI) in each province. The ratio of value added in the third industry to value added in the second industry in each province serves as the indicator of the economic structure (Eco Structure). An increase in this ratio often indicates a shift in the financial landscape, which promotes innovation, job creation, and adjustments in consumer behavior. The percentage of people in each province's labor force who have completed high school or more determines the education level indicator (Education). Higher education has a positive impact on communication, environmental preservation, and innovation. The amount of money invested in research and development in each province determines the innovation indicator (R&D).

Mechanism variables

Consumption volatility (Consume) was calculated using the HP filtering approach to isolate the trend term from provincial consumption expenditure data. The resulting volatility term was then used to measure consumption volatility. Similarly, the same methodology was used to evaluate the volatility of green credit (Credit) using provincial green credit expenditure data. The volatility term's absolute value effectively captures the range of green credit variability and consumption swings.

Table 1. Descriptive statistics of economics financial and environmental variable.

Variables	Obv	Mean	St.D	Min	Max
Credit_v	270	0.031	0.026	0.001	0.145
Consume	270	0.015	0.013	0.001	0.068
FIX	270	8.011	2.516	2.047	14.69
Green_L	270	0.504	0.313	0.0661	1.242
ROAD	270	38.15	23.72	5.129	142.0
Government_inter	270	2.490	1.025	1.101	6.284
R&D	270	23.49	1.344	20.17	26.17
DGF	270	2.034	0.916	0.183	4.103
Pgdp	270	107.5	4.343	96.82	119.9
Phone number	270	17.56	7.515	5.920	43.78
Unemployment	270	3.252	0.645	1.200	4.500
PARK	270	12.95	2.765	7.010	21.05
EDU	270	13.45	0.799	10.73	14.66
Eco structure	270	16.80	41.14	1.621	278.3
OPEN	270	0.271	0.306	0.0127	1.548
Default	270	1.598	0.920	0.350	7.090
FDI	270	26.86	1.379	23.61	30.23

Note: Obv - observations, St.D - standard deviation, Credit_v - credit volume, Consume - household consumption, FIX - fixed asset investment, Green_L - green land coverage, ROAD - road infrastructure length, Government_inter - government intervention or expenditure, R&D - research and development investment, DGF - degree of government financial support, Pgdp - per capita gross domestic product, Phone number - number of telephone subscriptions, Unemployment - unemployment rate, PARK - number or area of urban parks, EDU - education level or average years of schooling, Eco structure - ecological infrastructure or eco-development index, OPEN - economic openness, Default - loan default rate, FDI - foreign direct investment.

Dependent variable

The Super Slacks-Based Measure (SBM) model evaluates the Green Development Indicators (Green_L). This model includes unfavorable outputs and thoroughly analyzes economic green development. The following outlines the process for choosing particular methods and related indicators (equation 1 & 2).

$$P^t(x^t) = \{(y^t, b^t) | \overleftarrow{x}^t_{jm} \geq \sum_{j=1}^{J} \lambda^t_j x^t_{jm}, \overleftarrow{y}^t_{jn} \leq \sum_{j=1}^{J} \lambda^t_j y^t_{jn}, \overleftarrow{b}^t_{jk} \geq \sum_{j=1}^{J} \lambda^t_j b^t_{jk}, \lambda^t_j \geq 0, \forall m, n, k\} \quad (1)$$

$$P^t(x^t) = \left\{(y^t, b^t) \middle| \overleftarrow{x}^t_{jm} \geq \sum_{j=1}^{J} \lambda^t_j x^t_{jm}, \overleftarrow{y}^t_{jn} \leq \sum_{j=1}^{J} \lambda^t_j y^t_{jn}, \overleftarrow{b}^t_{jk} \geq \sum_{j=1}^{J} \lambda^t_j b^t_{jk}, \lambda^t_j \geq 0, \forall m, n, k\right\} \quad (2)$$

The super SBM model created by adding undesirable outputs to the model is as follows, and it is based on Tone's (2001) work equation (3 & 4).

$$\rho^* = \min \frac{\frac{1}{m}\sum_{i=1}^{m} \frac{\bar{x}_i}{x_{i0}}}{\frac{1}{n+k}\left(\sum_{r=1}^{n} \frac{\bar{y}_r}{y_{r0}} + \sum_{l=1}^{k} \frac{\bar{b}_l}{b_{l0}}\right)} \quad (3)$$

$$s.t.\begin{cases} \bar{x} \geq \sum_{j=1,\neq 0}^{J} \lambda_j x_j, \\ \bar{y} \leq \sum_{j=1,\neq 0}^{J} \lambda_j y_j, \\ \bar{b} \leq \sum_{j=1,\neq 0}^{J} \lambda_j b_j, \end{cases} \quad (4)$$

$$\bar{x} \geq x_0, \bar{y} \leq y_0, \bar{b} \geq b_0, \; \bar{y} \geq 0, \lambda_j \geq 0.$$

Table 2. Selection criteria and elements for green growth indicators.

Categories		Standard Metrics	Elements
Input elements		Employed population at year-end	Labour
		Capital stocks at year-end	Capital
		Total energy consumption at year-end	Energy
output elements	Real GDP at year-end		Economic output
	Industrial wastewater discharges		Dewatering
	Industrial exhaust emissions		Emissions
			Solid wastes

Three sources provided the data used in this study: the "China Statistical Yearbook" (which covered the years 1998 to 2020), the "China Energy Statistical Yearbook," and the "China Environmental Statistical Yearbook." This study evaluates China's degree of green development between 1997 and 2019 using a sample of 30 provinces, cities, and autonomous areas from mainland China [30], excluding Tibet, to address the Tibetan region's data shortage. The eastern region has a higher index than the western and central regions. Furthermore, it is imperative to scrutinize if the impact of digital money on sustainable development differs based on specific components of sustainable development. This investigation will make it easier to formulate development policies that match accurately.

Testing of model

We developed an econometric model to analyze the influence of digital economics on green growth in the equation (5).

$$\text{Green\_L}_{it} = c_1 + c_2\text{DGF}_{it} + \sum_{i=1}^{n} \beta_i \chi_{it} + \delta_i + \varphi_i + \varepsilon_{it} \quad (5)$$

When analyzing how digital money affects green development, two important factors come into play. First, we need to discuss the idea of reverse causality. This implies that green development and digital finance are positively correlated, with new developments in green initiatives facilitating the development of digital financial infrastructure and increasing the uptake of digital finance [31]. This reciprocal connection characterizes reverse causality. Second, even though this study takes into account a number of control variables, it is still possible that unanticipated events will affect the results. If such situations are ignored, prejudice may be introduced. Three strategies are used to counteract this: replacing the primary explanatory factors, applying the double-difference method, and using dynamic panel system GMM and differential GMM estimates to prevent indigeneity coming from excluded variables. The goal of these techniques is to make the analysis more robust. Additionally, for thorough testing, the Difference-in-Differences (DID) model is employed, offering further insights into the relationship between digital finance and green development in various contexts of equation (6-8)

$$Green\_L_{it} = c_3 + c_4\gamma_i \times \sigma_t + \sum_{i=1}^{n} \beta_i \chi_{it} + \delta_i + \varphi_i + \varepsilon_{it} \quad (6)$$

$$Volatility_{it} = c_5 + c_6 DGF_{it} + \sum_{i=1}^{n} \beta_i \chi_{it} + \delta_i + \varphi_i + \varepsilon_{it} \quad (7)$$

$$Green\_L_{it} = c_7 + c_8 Volatility_{it} + \sum_{i=1}^{n} \beta_i \chi_{it} + \delta_i + \varphi_i + \varepsilon_{it} \quad (8)$$

If the advancement of digital economics mitigates variations, then the coefficients should have negative values. Thus, equations (6) and (7) will determine whether the advancement of digital banking can aid in promoting green growth by mitigating relevant variations.

Results and discussion

Benchmark regression

Table 3) columns (1) through (5) provide a full breakdown of the estimations' outcomes. The development of digital banking holds the potential for advancing ecologically sustainable economic growth. Political forces heavily influence the results of COP-28. Some countries prioritize economic growth and development, while others push for strict controls and reductions in emissions. Achieving a cohesive approach to climate resilience requires diplomatic finesse and compromise to balance these divergent objectives. At the 1% statistical level, the outcomes of a pooled regression analysis without control variables in Column (1) show a significantly positive coefficient of DGF. The coefficient of DGF shows a modest reduction in value, but it still stays considerably positive at the 1% level in Column (2), which incorporates all control factors and temporal effects. A panel fixed effects model with individual effect controls is presented in Column (3), which displays a statistically significant coefficient for the DGF variable. To compare results with the panel fixed effects regression, we also use Driscoll-Kraay standard error regressions and panel feasible generalized least squares (FGLS). The outcomes show that the DGF coefficients for each of these approaches are almost aligned. A 1% rise in DGF in Column (5) translates into a 0.163% expansion in green development, offering important new information about the connection between green economic growth and digital finance.

Our primary concern regarding the control factors was the outcomes presented in columns (3) through (5). The levels of statistical significance remained largely unchanged despite the observed differences in the sizes of the coefficient values for each variable. Notably, our study revealed a negative relationship between green development and commercial bank default rates. Economic swings were exacerbated by commercial banks' adoption of a more conservative lending approach towards the real sector, resulting from higher default rates. Furthermore, the predicted results for the following variables met our expectations: living environment (Park), education level (Education), economic structure (Economic Structure), external openness (Open), and phone number (Phone Number). This implies that advances in global trade and the spread of information from non-exporting industries support the development of technological innovation and human capital capabilities. In the context of the figure, the model is fit to the data points to determine the relationship between the DGF-FCLS, FDI, and some other variables (Figure 1).

Table 3. Multivariate regression analysis of determinants of green growth performance

VARIABLES	(1)	(2)	(3)	(4)	(5)
	Green_L	Green_L	Green_L	Green_L	Green_L
DGF	0.802***	0.451***	0.148***	0.149***	0.163**
	(0.054)	(0.165)	(0.049)	(0.029)	(0.088)
Default		0.003	−0.065***	−0.089***	−0.044***
		(0.020)	(0.019)	(0.019)	(0.009)
FDI		0.053*	−0.128***	−0.140***	−0.047**
		(0.030)	(0.046)	(0.046)	(0.022)
Open		−0.074	0.442**	1.037***	0.425***
		(0.112)	(0.201)	(0.206)	(0.124)
Eco Structure		0.001	0.003***	0.007***	0.002***
		(0.001)	(0.001)	(0.002)	(0.000)
Education		0.347***	0.561**	0.530***	0.845***
		(0.059)	(0.220)	(0.180)	(0.118)
Park		0.017***	0.059***	0.047***	0.047***
		(0.005)	(0.013)	(0.008)	(0.006)
Phone number		0.004	0.021***	0.014***	0.013***
		(0.004)	(0.006)	(0.004)	(0.001)
Per_gdp		0.382*	−0.161	−0.083	−0.328**
		(0.177)	(0.208)	(0.175)	(0.134)
Per_gdp2		−0.002*	0.000	−0.000	0.001*
		(0.001)	(0.001)	(0.001)	(0.001)
Unemployment		0.013	0.013	0.071	−0.018
		(0.026)	(0.043)	(0.037)	(0.024)
R&D		−0.188***	0.057	0.164***	0.027**
		(0.037)	(0.073)	(0.044)	(0.044)
Government_inter		0.174***	0.061	0.029	0.166**
		(0.048)	(0.060)	(0.044)	(0.061)
Road		−0.002*	0.001	0.005	0.003
		(0.001)	(0.005)	(0.003)	(0.002)

Table 3 continued

VARIABLES	(1)	(2)	(3)	(4)	(5)
	Green_L	Green_L	Green_L	Green_L	Green_L
N	270	270	270	270	270
Adjusted-��2	0.532	0.643	0.567	0.825	0.632
Province fixed effects	NO	NO	YES	YES	YES
Year fixed effects	NO	YES	NO	NO	YES

Note: The symbols *, **, and *** denote significance levels of 10%, 5%, and 1%, respectively.

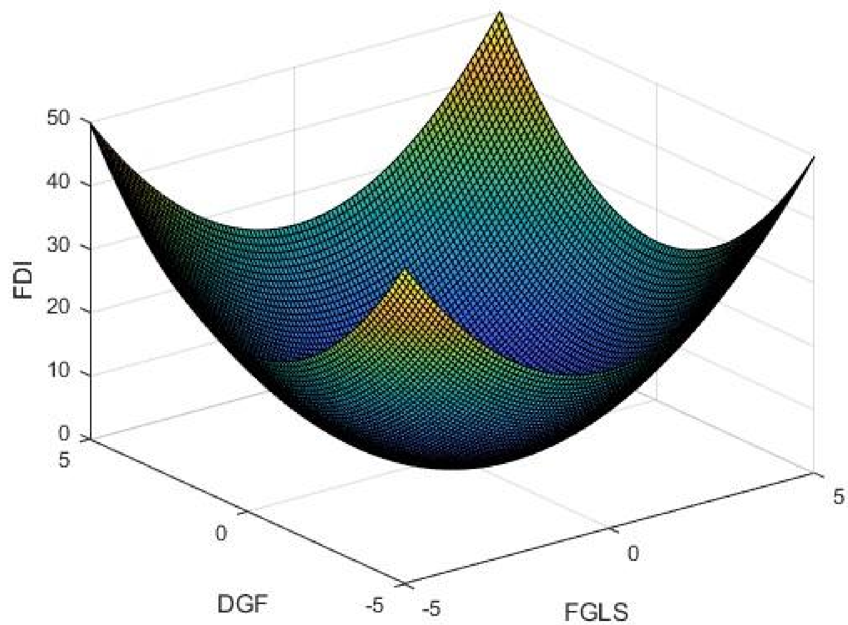

Figure 1. The relation between DGF and FGLS with change in FDI.

Robustness test analysis

While digital banking has a big impact on green growth, it's important to remember that financial technology innovation can also affect green development. Growing green growth will probably mean more attention will be paid to financial technology innovation, which could lead to more advancements in this field. This raises the possibility of an indigeneity problem between the advancement of green growth and the monetary skill revolution. This section uses three techniques to handle potential indigeneity issues in econometric models: changing the control variables and green development level index to alternative variables (Chang et al., 2022) and then regressing the findings to reanalyze the benchmark data. Assessing the causal effects of policy changes pertaining to digital finance on the target variable through the application of the Difference-in-Differences (DID) model.

Table 4. Robustness tests of digital green finance (DGF) and policy impacts on green growth.

VARIABLES	(1)	(2)	(3)	(4)	(5)
	Green L	Green L	Green L	Green L	Green L
POST*TREATED				0.094***	
				(0.019)	
DGF	0.119***	0.166*	0.151***		0.166**
	(0.072)	(0.090)	(0.044)		(0.083)
Digital policy		−0.001			−0.000
		(0.001)			(0.001)
Control variables	YES	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES	YES
Province fixed effects	YES	YES	YES	YES	YES
N	270	269	270	270	270
$Digital\_policy_{t-1}$		0.003***			
		(0.001)			

The symbols *, **, and ***, reflect the significance levels of 10%, 5%, and 1%, respectively.

This research intends to create a meter for digital economic development strategies in order to assess their impact on green economic growth, given the well-established correlations among the expansion of the digital economy, digital finance, and the advancement of Technological Innovation. The study uses Python software to segment text on government job reports. It counts the frequency of terms related to the digital economy to determine how much help the government provides. This collection includes terms like big data, blockchain, cloud computing, smart manufacturing, smart cities, and more (Wei et al., 2021). The results of changing the explanatory factors and control variables in columns (1) and (2), respectively, while maintaining the same DGF coefficients, are shown in (Table 4). Taking into account the possible delayed effects of other policies on the development of the green economy, Column (3) shows the results following the inclusion of the digital economic policy variable. The study improves the analysis in Column (4) by adding a variable of one period behind digital economic policy. The data in (Table 4's) columns (3) and (4) show that, in keeping with the baseline regression results, digital financial development still has a positive effect on green economic growth even after taking into consideration factors related to digital economic policy. Green economic development benefits greatly from the lagged one-period effect of digital economic policy, which is statistically significant at the 1% level. Using a difference-in-differences model for estimate, the results from Column (5) show that the combined effect of temporal and regional dummy factors is represented by the interaction term Post*Treated, which has a coefficient of 0.094 that is statistically significant at the 1% level. This finding implies that the impact of digital finance on environmentally friendly growth in the central and western regions has greatly improved after the G20 High-level Principles for Digital Financial Inclusion were adopted.

Contributory variable regression test

To address indigeneity-related difficulties, we use a variety of panel Generalized Method of Moments (GMM) methodologies in our study, such as 2-step GMM, dynamic panel difference GMM, and system GMM. We use two different kinds of instrumental variables to examine the impacts of digital finance. First of all, recognize that the growth of digital money is mostly due to Internet usage [32]. We take into consideration province Internet penetration rates and provincial per capita postal services as instrumental variables since China's domestic mail service offers fixed telephone services that are closely related to network services. As an additional tool in our study, we use the mean value of digital finance from provinces other than our home province.

Table 5. Results of the robustness checks.

VARIABLES	(1)	(2)	(3)	(4)
	Green_L	*Green_L*	*Green_L*	*Green_L*
Control variables	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES
N	270	270	210	270
AR (2)			0.684	0.791
AR (1)			0.067	0.078
Sargan statistic	0.533		0.363	0.896
Cragg-Donald Wald F statistic	77.290	2684.430		
Anderson canon. corr. LM statistic	98.255	221.516		
Province fixed effects	YES	YES	YES	YES
DGF	0.235***	0.002***	0.468***	0.160***
	(0.083)	(0.000)	(0.056)	(0.052)

For estimation in columns (1) and (2), (Table 5) uses a two-step Generalized Method of Moments (GMM) technique. The results of the statistical analysis indicate that the instrumental variables passed the validity test successfully. At the 1% level of statistical significance, the coefficient of DGF remains considerably positive. The involvement of civil society organizations and young people brings new energy and views to the COP-28 discussions. These stakeholders, ranging from grassroots movements to creative projects, expect international leaders to take responsibility and decisive action to protect the environment for future generations. To somewhat alleviate concerns about indigeneity, the dynamic panel model is also commonly estimated using the differential generalized method of moments (GMM) and systematic GMM, which incorporate lagged terms of the explanatory variables. The results of the dynamic panel difference between the GMM and system GMM estimates are shown in columns (3) through (4). The panel Generalized Method of Moments (GMM) analysis results indicate that the initial regression results remain robust even after considering potential endogeneity issues. As a result, the study's hypothesis H11 has been verified.

The tool used in Column (2) is the mean value of digital finance in provinces other than our own. The difference between the GMM and system GMM estimates, respectively, is shown in Columns (3) to (4), along with Arellano-Bond tests to determine whether autocorrelation is absent in first-differenced errors. There is no significant autocorrelation, as indicated by the p-values of the second-order autocorrelation test (AR(2)), which are 0.684 and 0.791, respectively. Additionally, passing the Sargan test confirms the instrument's legitimacy. The results for the first lagged variable should be included.

Heterogeneity test

Based on several stages of digital finance's expansion, this study examines the evolving relationships between digital finance and green development. This study divides the original sample into four intervals, representing each 25% quantile of the digital finance level. A further criterion for sample division is the average level of digital finance; numbers above the average represent a "high level of digital finance," while values below the average represent a "low level of digital finance. (Table 6's) subsample regressions reveal that digital finance's influence on green development is not statistically significant when its value is below the median. However, the coefficient of DGF is 0.619 and statistically significant at the 1% level when digital finance falls between the median and 75th percentile. These results are consistent with those from the sample that was above the 75th percentile.

Further segmenting the sample into Panel E and Panel F according to the DGF mean yields consistent findings from the quantile analysis. In particular, digital finance shows a strong and favorable impact on economic green development when the DGF exceeds the mean. This result highlights the presence of a threshold effect in the way digital finance influences environmentally sound economic growth. This implies that, at less developed stages, digital finance would only partially capitalize on its advantages in terms of cost and technology.

Table 6. Outcomes of sub-sample reversions.

VARIABLES	Panel A	Panel B	Panel C	Panel D	Panel E	Panel F
	≤ 25%]	(25% 50%]	(50% 75%]	> 75%	≥ median	<median
	Green_L	Green_L	Green_L	Green_L	Green_L	Green_L
Control variables	YES	YES	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES	YES	YES
Province fixed effects	YES	YES	YES	YES	YES	YES
Adjusted-��2	0.633	0.656	0.792	0.793	0.583	0.152
N	67	68	67	68	152	118
DGF	−0.062	0.146	0.619***	0.509***	0.343**	−0.012
	(0.108)	(0.208)	(0.197)	(0.153)	(0.137)	(0.117)

This study conducted a regression analysis after classifying China's 30 provinces into three primary economic zones —East, Central, and West —to examine regional factors. (Table 7) columns (1)– (3) present the results of the regression analysis for the eastern, western, and central regions. The results indicate that the degree of environmentally friendly growth is positively influenced by the development of digital banking in China's central and east areas. Digital money, however, does not statistically significantly affect green development in the Western region [33]. These results suggest that the impact of digital banking on green growth in China may vary by region. Two elements are likely reasons for this variance: First, China's western areas have somewhat less developed initial resource allocation than its central and eastern provinces. China's geographical distribution is defined by rich economic zones in the east, less developed areas in the center region, and impoverished areas in the western region. This distribution was achieved through the implementation of reform and opening-up policies. The Western region is well behind in terms of infrastructural and financial advancement. In addition, the East Coast regions of China constitute the epicenter of digital finance, with the Western regions being located further inland and having relatively lesser levels of advancement in this area. As a result, digital banking has little effect on green growth in the West.

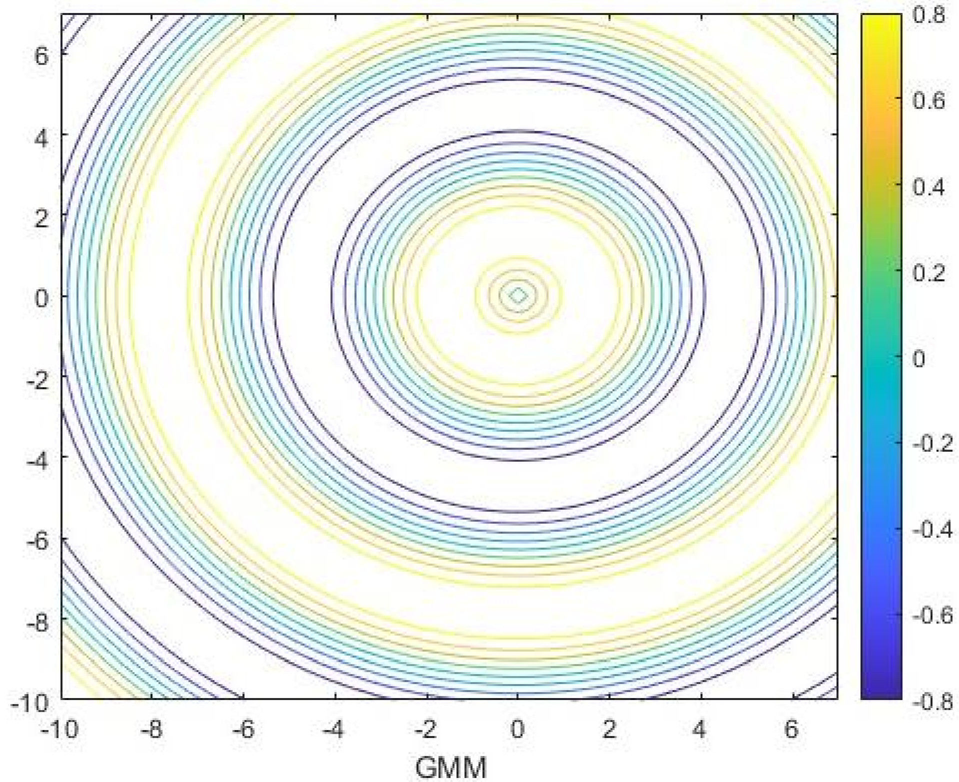

Figure 2. The difference between the GMM and system GMM estimates.

Table 7 displays the impact of digital finance sub-indices on green development in columns (4) through (6). The results indicate that green growth is significantly influenced by the degree of digitization and the breadth of digital financial coverage. The coefficient of DGF_depth, however, shows no discernible change. The DGF_digital index emphasizes the cost and convenience of financial services compared to conventional methods, primarily by measuring the availability of digital financial support services. It emphasizes diversity and the application of financial technologies—such as big data, blockchain, and cloud computing—to advance the digitization of financial infrastructure, enhance market effectiveness, and promote environmentally sustainable growth. However, the ability of digital financial services to reach a wide variety of customers is shown by the digital financial coverage breadth index (DGF_breadth). As a key weapon in the fight against climate change, technological innovation expands the reach of services to a wider range of recipients. The DGF_depth index highlights the relationship between the range of available digital financial goods and services and their actual demand, focusing on the demand side of the industry. There is a clear correlation between this alignment and increased financial literacy. As a result, initiatives should focus on supporting sustainable economic growth, improving the relevance and purposefulness of financial services for consumers, and increasing public knowledge of financial and environmental issues.

Table 7. Regional and dimensional heterogeneity in digital green finance (dgf) impacts on green growth.

VARIABLES	(2)	(6)	(4)	(1)	(5)	(3)
	WEST	Depth	Level	EAST	Breadth	CENTRAL
	Green_L	Green_L	Green_L	Green_L	Green_L	Green_L
DGF	0.154			0.200**		0.302***
	(0.118)			(0.080)		(0.090)
DGF_digital			0.001***			
			(0.000)			
DGF_breadth					0.002***	
					(0.001)	
Control variables	YES	YES	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES	YES	YES
Province fixed effects	YES	YES	YES	YES	YES	YES
Adjusted-��2	0.664	0.551	0.590	0.686	0.564	0.687
N	99	270	270	99	270	72
GDF_depth		−0.000				
		(0.000)				

The symbols *, **, and *** reflect the significance levels of 10%, 5%, and 1% correspondingly.

Evaluation of the mechanism

The integration of fintech into conventional banking has led to a substantial expansion of the financial services portfolio, meeting the diverse needs of both individuals and enterprises while accelerating the digitization of financial information. China's overall objective of attaining sustainable development, which includes both environmental sustainability and economic resilience, is inextricably linked to its pursuit of green growth. We use metrics of green credit volatility (Credit_v) and consumption volatility (Consume_v) to characterize shocks in the green financial sector and the economy. (Table 8's) columns (1) through (2) examine how digital finance might be used to lessen variations in consumption and green credit. The large impact of DGF on Consume_v and Credit_v is highlighted by the findings, which are significant at the 5% level. [34]. These findings suggest that the expansion of digital finance may mitigate the volatility of consumption and green credit.

Additionally, we investigate how volatility affects green development in columns (3) through (4), using the green development index (Green_L) as the dependent variable and the volatility levels of green credit and consumption as predictors. The findings highlight the detrimental effects of Consume_v and Credit_v on green growth, suggesting that reducing consumption and fluctuations in green credit could support China's green development by promoting the emergence of digital finance. Moreover, we rigorously examine the mechanism analysis using the 2-step GMM technique. The consistency of the results in columns (1)–(4) and (5)–(8) highlights how reliable the investigation's conclusions are. The mechanism analysis's findings remain valid and trustworthy even after endogeneity has been taken into consideration, supporting hypotheses H12 and H13.

Table 8. Mediating effects of credit and consumption channels in DGFgreen growth linkages.

VARIABLES	(1)	(2)	(8)	(6)	(7)	(5)	(3)	(4)
	Consume_v	Credit_v	Green_L	Credit_v	Green_L	Consume_v	Green_L	Green_L
DGF	−0.023**	−0.040**		−0.080***		−0.025***		
	(0.006)	(0.006)		(0.012)		(0.007)		
Consume_v					−1.484*		−1.284**	
					(0.803)		(0.472)	
Cragg-Donald Wald F statistic				145.414	171.361	145.414		
Anderson canon. Corr. LM statistic			17.656	50.844	15.547	50.844		
Control variables	YES	YES	YES	YES	YES	YES	YES	YES
Province fixed effects	YES	YES	YES	YES	YES	YES	YES	YES
Adjusted-�� 2	0.191	0.114	0.517	0.076	0.518	0.151	0.525	0.526
N	270	270	270	270	270	270	270	270
Credit_v			−0.669*					−0.746**
			(0.371)					(0.290)

Considering the direct relationship among feasting, credit, and financial cycles, could digital economics have distinct impacts on these two variables as a result of alterations in traditional financial cycles? (Table 9) examines the influence of digital finance on the volatility of green credit in both the economic downturn and upturn cycles, as seen in columns (1) and (2) correspondingly [35]. The findings indicate that the influence of digital finance on the volatility of green credit is negative throughout both periods of financial decline and growth. However, this impact is only statistically significant during the period of financial decline. During an economic downturn, conventional financial institutions typically restrict credit and increase credit requirements. This is not favorable for initiative bankrolling. However, digital finance can enhance the distribution of green credit resources by leveraging big data and low costs. This helps alleviate the limited availability of bank credit caused by information imbalances and minimizes the negative impact on green growth, as observed in old-style monetary downturns. On the other hand, during a period of financial development, when lending policies are relaxed, the influence of digital finance on green credit needs to be clarified, and consequently, it is not substantial.

It is essential to note that the negative impact of digital financial development on consumption fluctuations is considerable during periods of both financial decline and growth. However, the influence of digital economics on consumption instability is more pronounced during economic slumps than during upturns. This implies that digital banking enables individuals better to manage their consumption and financial decisions during economic downturns, resulting in a decrease in the variability of their consumption patterns. In general, digital money has a notable impact on reducing volatility, especially during periods of financial depression.

Table 9. The outcomes of the regular examination.

VARIABLES	(1)	(2)	(3)	(4)
	Credit_v	Credit_v	Consume_v	Consume_v
Control variables	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES
Province fixed effects	YES	YES	YES	YES
Adjusted-��2	0.196	0.257	0.317	0.218
N	129	141	129	141
financial cycle	Down	UP	DOWN	UP
DGF	−0.055***	−0.005	−0.032***	−0.006**
	(0.006)	(0.017)	(0.006)	(0.002)

Discussion

This study departs from earlier research, which has primarily focused on the ways that corporate financing and technological innovation enable digital finance to be integrated into green development. Rather, it examines the viability of green growth and demonstrates how digital finance can effectively mitigate the volatility of green loans and consumption. Furthermore, by reducing the volatility of green lending and consumption, digital finance helps lessen swings in the green economy. Digital finance can lessen these swings because the volatility of green credit and consumption both significantly contribute to the overall volatility of the economy. This viewpoint reaffirms our earlier findings and highlights how digital finance both enhances and hinders environmentally friendly development while providing key decision-makers with a comprehensive foundation for formulating policies. Furthermore, can digital finance offer greater benefits than traditional finance, given its capacity to support green development? Answering this question would support the study's conclusions and provide useful insights that would benefit decision-makers [36]. At the heart of the discussions at COP-28 is the concept of climate justice and equity. Delegates emphasize the importance of justice and solidarity in climate action, recognizing that underprivileged individuals bear the brunt of climate impacts despite contributing the least to global emissions. Using the HP filtering technique, we measured the volatility of green development in each Chinese province by taking the absolute value of the green growth cycle term in Column (1) of (Table 10). With a significance threshold of 1%, the coefficient of DGF is extremely negative, as predicted.

Interestingly, we found a negative association between the coefficients of traditional financial variables when we integrated various conventional economic indicators. This finding suggests that conventional finance can only partially replace digital finance as a means of promoting environmentally responsible growth. In particular, traditional financial mechanisms hurt green development. They appear to say "ECO structure" and "Default education Figure 3. It also underscores the fact that there are other driving forces behind green development besides traditional financing.

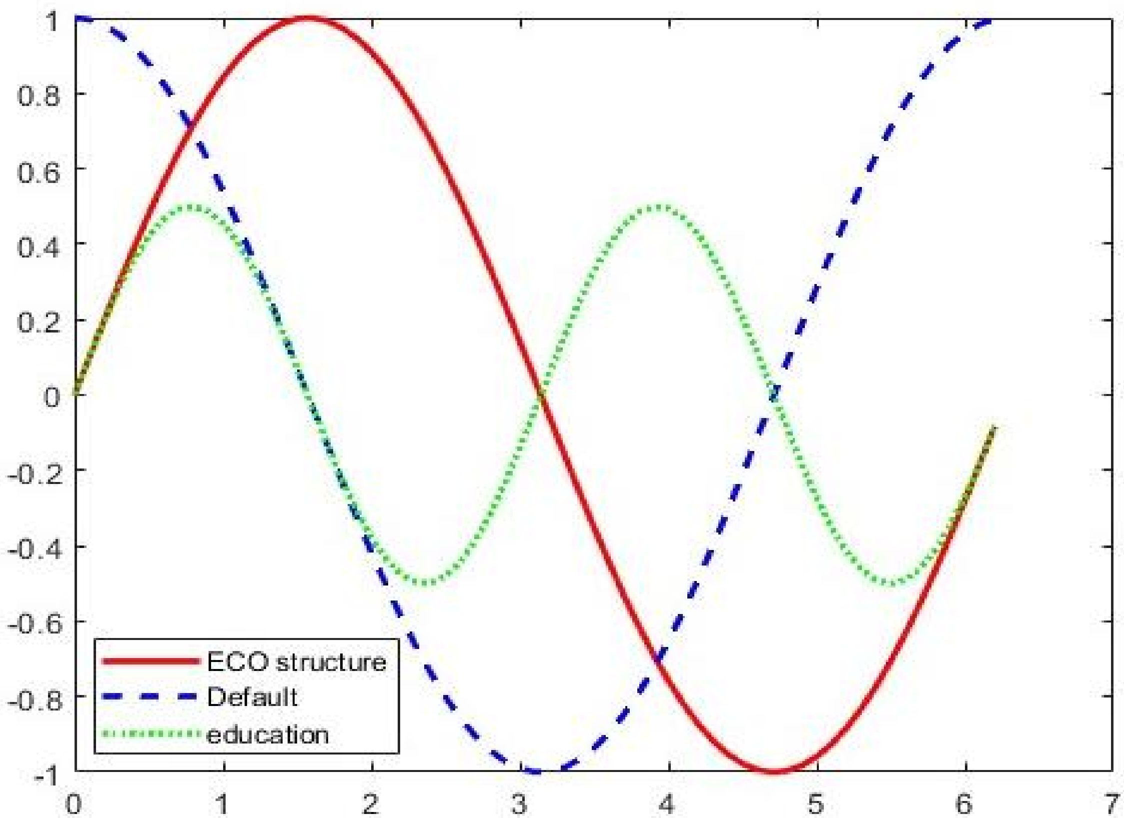

Figure 3. The coefficients of independent variables in the panel Eco-structure.

Additional examination

The shift to a green economy has become a crucial goal for governments and businesses globally in response to urgent global concerns, including climate change and environmental degradation. At the same time, digital finance is revolutionizing traditional financial systems by introducing simplicity, efficiency, and inclusivity. There is a complex and multifaceted relationship between digital finance and the expansion of the green economy. [37]. The application of digital finance in green economic models is encouraged by the correlation between higher education levels, a preference for sustainable development, and increased environmental awareness. Furthermore, the proficient use of digital financial tools requires a certain level of education and skill. Prior research has indicated a relationship between a country's higher educational attainment and lower carbon emissions.

Furthermore, economies that place a high priority on the service and high-technology industries are typically more open to incorporating digital money. It is projected that increased research and development (R&D) spending will accelerate the development of digital financial instruments that support the advancement of green economic growth. However, to fully leverage the potential benefits of digital finance for green economic development, economies that rely heavily on industrial or unsustainable agricultural sectors may require additional support. The effectiveness of digital financial technologies, especially when it comes to funding green initiatives, may be compromised by government actions, particularly those related to fiscal policies, which can lead to market inefficiencies and disruptions in resource allocation.

Table 10. Robustness and sensitivity analysis: Alternative measures and financial channels in DGF-green growth nexus.

VARIABLES	(1)	(3)	(2)
	Green_V	Green_L	Green_L
DGF	−0.076***	0.560**	0.592**
	(0.038)	(0.263)	(0.245)
Finance			−1.078**
			(0.535)
Cragg-Donald Wald F statistic	76.385	14.107	15.140
Control variables	YES	YES	YES
Year fixed effects	YES	YES	YES
Province fixed effects	YES	YES	YES
Sargan statistic （P value）	0.424	0.134	0.141
Anderson canon. corr. LM statistic	97.056	25.807	28.594
N	270	240	240
Loan		−0.606	
		(0.452)	

Table 11 Sectoral interaction effects of digital green finance on green growth performance.

VARIABLES	(1)	(2)	(3)	(4)
	Green_L	Green_L	Green_L	Green_L
DGF_Edu			0.163**	
			(0.074)	
DGF_Structure	0.233*			
	(0.141)			
DGF_R&D				0.017**
				(0.007)
DGF_Government_inter		−0.079***		
		(0.007)		
Observations	270	270	270	270
Province fixed effects	YES	YES	YES	YES

Table 11 continued

VARIABLES	(1)	(2)	(3)	(4)
	Green_L	Green_L	Green_L	Green_L
Year fixed effects	YES	YES	YES	YES
Control variables	YES	YES	YES	YES

We will explore in more detail how government participation, economic structure, research and development (R&D), and educational attainment affect the relationship between digital finance and green economic growth in the following sections. In addition to advancing the use of digital finance in the development of the green economy, this investigation aims to provide policymakers with valuable insights. Moreover, (Table 11's) Column (3) moderating effect is also positive. Column 4, however, shows that the moderating effect of governmental action is negative. Prioritizing economic structural transformation and augmenting technology research and development expenditures are crucial for policymakers to harness digital finance and advance the green economy. To prevent roadblocks to the green economy's sustainable development, they should also thoroughly review and modify their digital finance intervention plans.

At the 5% significance level, the relationship between digital finance and educational attainment is represented by the coefficient of DGF_Edu, which is statistically significant in the positive direction concerning Column (1) of (Table 11). These findings imply that the relationship between digital finance and the growth of ecologically friendly economic development is positively impacted by higher educational attainment. Raising educational attainment improves financial literacy and enhances public understanding of sustainable development. The anticipated coefficients for the moderating effect of the economic structure are shown in (Table 11's) second Column. The association between digital finance and the green economy is positively influenced by economic structure, as indicated by the statistically significant coefficient for Eco structure at the 10% level.

Conclusion

Integrating digital finance, technological innovation, and green development creates a complex environment that is both full of potential and presents challenges, as evident from the insightful information presented in Conclusions 1 and 2. Combining these findings provides a nuanced understanding of how technological innovation-driven digital finance can foster environmentally friendly economic growth. Climate financing challenges persist, with wealthier nations being encouraged to fulfill their promises to provide financial support to poorer countries. Sufficient financing must be mobilized to support technology transfer, capacity development, and adaptation initiatives in vulnerable areas. Studies highlight how technology innovation and digital finance may drive environmentally friendly advancement in a revolutionary way, especially when considering China and the G20 economies. Using an extensive examination of factual data, including provincial data spanning over a decade, we reveal the complex correlation between digital currency and sustainability. Important factors, including economic structure, education, R&D, and government interventions, have become key focus areas for stakeholders and policymakers seeking to enhance the interplay between the digital economy, technological innovation, and green development.

Furthermore, the results clarify the regional differences in the influence of digital finance on green development. The less developed western provinces present particular challenges and opportunities, although the eastern and central areas have a greater degree of influence. To fully realize the promise of digital banking in these areas, tailored regulations and focused actions are necessary to support the growth of infrastructure, financial literacy, and environmentally responsible consumer habits. Our study has led to policy suggestions that support a comprehensive strategy combining sustainable development goals with digital finance. Governments must act swiftly to implement regulatory measures that foster the growth of the digital financial sector while mitigating associated risks. To fully use digital finance for green growth, the economy must be restructured, research and development must be funded, and innovation must be encouraged. Participants from the G20 economies gathered to discuss innovative solutions for the pressing issues of energy transition and climate change. The discussions focused on utilizing digital finance to overcome obstacles that hinder the adoption of technological innovation, such as market fragmentation, regulatory uncertainty, and limited capital availability.

It is recommended that financial institutions, businesses, and professionals utilize digital finance technologies and platforms to optimize the efficiency of green lending programs and mitigate investment risks. Organizations can optimize their methods to achieve effectiveness and ensure long-term sustainability by recognizing regional differences and staying current with digital finance developments. Ultimately, the path to sustainable development must be resilient, inclusive, and intertwined with economic growth. Research provides China with valuable insights and serves as a beacon for other countries undergoing digital and economic transformation. Acknowledging the mutually beneficial connection between digital finance and green development, we can create a path toward a more ecologically sustainable, fair, and resilient future worldwide.

Declaration

Ethics approval/declaration: Not applicable.
Consent to participate: Not applicable.
Consent for publication: Not applicable.
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Conflict of interest: The authors declare no conflict of interest.
Data availability: Data will be available upon reasonable request from corresponding author.
Authors contribution: Fatima Gulzar; Data collection and analysis, supervision. Muhammad Asif; Participated in the idea and design of the research. Maryam Ibrahim; Model creation and interpretation of the findings. Manahil Noor; Composed the text and conducted the literature review. All authors are affiliated with Ghazi University, Dera Ghazi Khan, Punjab, Pakistan.

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