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EDITED BY
Muhammad Zahid Rafique,
Center for Economic Research, Shandong University, China

REVIEWED BY
Kai Liu,
Shandong Normal University, China
Suleman Sarwar,
Jeddah University, Saudi Arabia

*CORRESPONDENCE
Yaqing Han,
hanyaqing306@163.com

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Digital finance, environmental regulation, and green development efficiency of China

Yaqing Han[1,2]*, Yushui Li[1,2] and Qiangqiang Wang[3]

[1]School of Finance, Fujian Jiangxia University, Fuzhou, China, [2]Fujian Social Science Research Base, Financial Risk Management Research Center of Fujian Jiangxia University, Fuzhou, China, [3]College of Economics and Management, Fujian Agriculture and Forestry University, Fuzhou, China

In the context of the increasingly prominent contradiction between economic development and ecological environment, how to promote green development has become the core of sustainable economic development. Digital finance is an innovative financial model with a high degree of integration of finance and digital technology and provides a new opportunity for achieving green development. Based on identifying the mechanisms of digital finance and environmental regulation on green development efficiency, this research uses the directional distance function and Malmquist-Luenberger index to measure the green development efficiency of 30 provinces in China from 2011 to 2020 and then employs a dynamic panel GMM model to empirically analyze the relationships among digital finance, environmental regulation, and green development efficiency. The results of the study show the following. 1) Digital finance contributes to the efficiency improvement of green development. 2) Environmental regulation has not yet crossed the Porter's inflection point and still has a dampening effect on green development efficiency. 3) The synergy between digital finance and environmental regulation has a positive impact on green development. 4) Digital finance alleviates the financing constraints arising from environmental regulation and to some extent weakens the negative effect of environmental regulation on the efficiency of green development. In view of this, the government should give full play to the active role of digital finance in eco-environmental governance, optimize the top-level design of environmental regulation, and promote industrial structure upgrading and optimal allocation of financial resources.

KEYWORDS

digital finance, environmental regulation, green development efficiency, dynamic panel GMM model, Economic Transformation

1 Introduction

It has been more than 10 years since the United Nations proposed the concept of inclusive finance in 2005, and the global practice of inclusive finance has completed the development process of "microfinance—Internet finance—digital inclusive finance". It has made an important contribution to global financial equity and sustainable development. Digital inclusive finance has become a new idea of inclusive financial development and an innovative hot spot in the financial field, which meets the requirements of the digital intelligent era. Currently, the digital wave has largely affected various fields of the traditional economy. In addition, coupled with the sudden outbreak of the new crown pneumonia epidemic, the financial industry has accelerated its transformation to digitalization. Therefore, digital inclusive finance is considered as an important driver for the green transformation of the economy (Ding et al., 2022). The 20th Party Congress report pointed out that promoting green and low-carbon economic and social development is a key link to achieve high-quality development, and achieving green development will certainly put forward higher requirements for ecological and environmental governance. The Global Environmental Performance Index (EPI) report jointly released by Yale University and other research institutions in 2020 showed that China ranks 120th with 37.3 points, and environmental problems are still very serious. In order to reverse the deterioration of the ecological environment and alleviate the outstanding contradiction between the ecological environment and economic development, President Xi Jinping announced at the Climate Ambition Summit on 12 Dec 2020 his solemn commitment to “strive to peak CO_2 emissions by 2030 and strive to achieve carbon neutrality by 2060”, which also means that the intensity of China’s environmental regulations will be further increased (Shi F. et al., 2022). Under the constraints of intensifying environmental pollution and weak transformation of the green economy, how to promote green development has become the core importance of sustainable economic development. Environmental regulation is considered to be an important means to promote the harmonious development of economy and ecology. It encourages enterprises to change their original production methods, strengthen technological innovation, and improve the efficiency of resource factor utilization and environmental efficiency, which requires sufficient funds to ensure technological innovation (Chen et al., 2022a; Chen et al., 2022b; Chen et al., 2022c). As the bloodline of the national economy, finance is an important tool for optimizing resource allocation and macro-control (Zhao and He, 2022). With the widespread application of modern digital technology in the financial sector, the new industry of digital finance has emerged from traditional finance with the empowerment of digital technology and is showing rapid development.

According to the Digital Finance Index Report released by Peking University in 2021, China’s digital inclusive finance has shown a rapid development trend in the past decade with an average annual growth of 29.1% in the Digital Finance Index. Thanks to its advantages of inclusiveness, convenience, and efficiency, digital finance has begun to reshape the pattern of economic development by expanding financing channels and optimizing resource allocation. It has gradually become a new driving force leading scientific and technological innovation, driving economic and social transformation and development, and providing a new opportunity for the improvement of green development efficiency. Green development is a concept with rich connotation. It not only considers energy saving and emission reduction, technological innovation, industrial transformation and other changes in economic growth drivers, but also involves the effect of economic growth. It pursues sustainable growth of environment, resources and economy (Shi Y. et al., 2022; Wang et al., 2023; Zou et al., 2023). In the current macro-level context of tightening environmental regulations, how does digital finance affect green development? What about the synergistic impact of digital finance and environmental regulation on green development efficiency? What is the intrinsic mechanism of interaction between the three? An in-depth exploration of the above topics has important practical value and theoretical significance for exploring the eco-economic and social benefits of digital finance.

Scholars around the world have presented a lot of research results concerning the impact of digital finance and environmental regulation on ecological economy and society, but in the new development pattern, scholars are still at the preliminary stage of exploring the impact mechanism and causal relationship between them. In order to clarify the literature related to digital finance, environmental regulation, and green development, this paper will sort out the existing papers from the following aspects.

First, from the perspective that digital finance affects green development efficiency, some scholars stated that digital finance improves the financing environment, enhances corporate green technology innovation, and supports green development. Technological innovation of enterprises can improve production efficiency and reduce environmental pollution, but enterprises need long-term and stable capital investment to carry out green innovation activities (Yu et al., 2021). However, many enterprises’ technological innovation activities are constrained by financing (He et al., 2022), and traditional financial institutions are unable to provide them with sufficient financial support (Bo, 2021). Other scholars considered that digital finance has greatly reduced the threshold and cost of financial services by using digital technologies such as the Internet, big data, and cloud computing to provide financial services to enterprises (Ozili, 2018) and expanding the coverage of financial services (Liu et al., 2021). In addition, digital finance can promote the upgrading of industrial structure by regulating the economy and optimizing resource allocation (Shofawati, 2018), thus enhancing the level of green development (Ding et al., 2022). Some other scholars found that digital finance can facilitate the innovation of financial instruments, such as green funds and green bonds (Antimiani et al., 2017; Cui and Huang, 2018), to promote green development. Digital finance improves the efficiency of green development by creating new financial markets that reduce the risks faced by enterprises and the social environment (Turski, 2018). Digital finance, driven by information technologies such as big data, block chain, and cloud computing, breaks through time and space limitations, enables resource sharing and interoperability, and facilitates economic green transformation and green development with the advantages of low cost, high efficiency, and wide coverage (Sun, 2020).

Second, from the perspective of the impact of environmental regulation on green development, the impact mechanism is complex, and there is no unified conclusion on the relationship between the two in the academic community. The first view sees a positive role for environmental regulation in promoting green development. Environmental regulation promotes advanced industrial structure and low carbon energy consumption through the technological innovation effect, innovation compensation effect, and investment screening effect (Huang and Lei, 2021; Behera and Sethi, 2022; Fan et al., 2022), while attracting high-end green production technology of good quality to realize green the spillover effect, thus promoting green development. Technological innovation has been shown to be effective in mitigating environmental degradation (Chien et al., 2021). The second view is that environmental regulations have a negative impact on the efficiency of the green economy, that stronger environmental regulations lead to higher environmental protection and governance costs, which affect output efficiency and economic development (Cai and Ye, 2020; Li and Ma, 2022), and that stronger environmental regulations lead to the allocation of financial resources to the secondary sector, thus inhibiting the improvement of green development efficiency. The third view argues that the impact of environmental regulation on the efficiency of the green economy is stage-specific and non-linear (Zhao and He, 2022). Porter and van der Linde (1995) proposed the

Porter hypothesis, which states that moderate environmental regulation can stimulate firms to innovate in R&D and improve their output efficiency through technological innovation to compensate for the increased compliance costs of environmental regulation (Porter and van der Linde, 1995). As the topic progressed, scholars further subdivided the study in terms of industries, regions, and environmental regulatory tools (Yin et al., 2022) and explored the differences in the impact of various environmental regulatory tools and types of industries and regions on green technology innovation (Feng et al., 2022).

In summary, scholars have presented rich findings on digital finance, environmental regulation, and green development, but few of them have included the interactions among digital finance, environmental regulation, and green development into a unified analytical framework, have not yet responded positively to the synergistic impact and intrinsic correlation between digital finance and environmental regulation on the efficiency of green development, and have not reached a unanimous conclusion on the environmental and economic effects of digital finance. Compared with existing studies, this paper tries to contribute in the following three aspects: 1) to identify theoretically the mechanism of digital finance, environmental regulation, and their synergistic effects on green development, enriching the literature on digital finance and environmental regulation; 2) to explore mainly how the synergistic effects of digital finance and environmental regulation affect regional green development in the context of the current situation of tightening environmental regulation by local governments and to enrich relevant literature on understanding the relationship between them. Specifically, the directional distance function and Malmquist-Luenberger productivity index are used to measure green development efficiency in China, and the composite index method is used to construct a comprehensive index of environmental regulation intensity, and a dynamic panel GMM model is applied to empirically analyze the effects of digital finance and environmental regulation on green development efficiency.; and 3) to examine the heterogeneous effects of the three dimensions of digital finance on promoting green development. The above research provides a basis for government departments to formulate environmental regulatory policies that are appropriate to the level of development of digital inclusive finance.

The research arrangement of this paper is as follows: Section 2 is the Theoretical Mechanism and Research Hypotheses, Section 3 is Methodology, Section 4 is the empirical analysis, and Section 5 is the conclusions and policy recommendations.

2 Theoretical mechanism and research hypotheses

2.1 The impact of digital finance on green development efficiency

Digital finance has strong green attributes and plays an important role in the process of promoting green development. Different from traditional finance, digital finance has the advantages of low cost, universality, and high efficiency with the empowerment of digital technology such as big data and artificial intelligence, providing a new engine to promote green development and improve economic quality. Specifically, digital finance has an impact on green development in the following ways. First, it promotes the upgrading of industrial structure to promote green development (Pai, 2016). On the one hand, modern digital technology can be used to accurately identify green innovation projects, guide the flow of funds to low-carbon green and high-tech industries, and promote the optimization and upgrading of industrial structure. On the other hand, it can stimulate green consumption demand through differentiated financial products and services, further force the transformation and upgrading of enterprises, accelerate the layout of green industry chain, and thus promote green development.

Second, digital finance helps improve the efficiency of optimal resource allocation and promote green development efficiency. Digital finance has broken the “two-eight law” of the traditional financial system, reshaped the financial system to a certain extent, improved the accessibility of financial resources, enabled financial services to reach the long tail of small- and micro-size enterprises and other groups discriminated against by capital (Gomber et al., 2018; Li et al., 2020), optimized the distribution system, and thus enhanced the efficiency of green development. At the same time, the digital platform is used to continuously innovate financial products and services, broaden the boundary of financial services, establish a bridge of interconnection between the two sides of financial services, break through time and space restrictions, accurately match the demand side of the industry chain, improve financing efficiency, reduce costs, effectively alleviate the problem of resource mismatch (Kshetri, 2016; Dendramis et al., 2018), and provide strong financial support for the overall enhancement of green development.

Finally, digital finance promotes technological innovation and improves green development efficiency. Innovation is the endogenous driving force of green development. Digital finance makes up for the shortcomings of traditional finance through modern technologies such as big data and artificial intelligence (Cao et al., 2021) and provides financing services for some clean energy development, environmental protection, and other technology enterprises with its highly informative and inclusive features, reducing the R&D costs of small- and medium-size enterprises (SMEs). The promotion and application of new technologies by enterprises can reduce environmental pollution at the source and alleviate damage to the ecological environment caused by their production activities, while also opening up new ways to develop green production factors. Therefore, we propose Hypothesis 1.

Hypothesis 1. Digital finance has a facilitating effect on the improvement of green development efficiency.

2.2 The impact of environmental regulation on green development efficiency

Green development is oriented to resource conservation and environmental protection and takes environmental benefits into account on the basis of measuring economic growth. It enhances green development efficiency by reducing pollution emissions and energy inputs, and environmental regulation is an important policy tool to achieve green development (Chen et al., 2022c; Zou et al., 2022). The impact of environmental regulation on the efficiency of green development can be explained in the following ways. First, environmental regulation impacts its efficiency through the effect of technological improvement. The Porter hypothesis suggests that strengthening environmental regulations will bring about an increase in compliance costs, but in the long run, environmental regulations force enterprises to innovate in technology, to improve their production processes and technologies, to enhance the optimal allocation of resources, to reduce pollution emissions, and to enhance green development (Ye et al., 2021; Yang, 2022).

Second, environmental regulations affect the efficiency of green development through the capital screening effect. When environmental regulations are gradually strengthened, financial institutions will gradually tend to support green enterprises or projects in the supply of funds and reduce investments in high pollution and high energy consumption enterprises or projects. This forms a fund screening effect to gradually optimize the industrial layout and promote green development efficiency (Guo et al., 2018; Song et al., 2022).

Third, environmental regulation affects green development through the input appropriation effect. The increased intensity of environmental regulations forces the government and enterprises to invest more resources in environmental protection to reduce pollution emissions, which in turn crowd out productive and profitable investments of enterprises, forming the encroachment effect of environmental protection inputs. This inevitably weakens enterprises' green innovation and R&D efforts, reduces resource allocation efficiency, and affects the improvement of green development efficiency (Song et al., 2019). However, studies have found that the improvement of green development efficiency is mainly caused by technological progress (Chen et al., 2020), and the negative effects of environmental regulation can be fully compensated by the technological improvement effect (Ouyang et al., 2020). Therefore, we propose Hypothesis 2.

Hypothesis 2. Environmental regulation has a facilitating effect on the improvement of green development efficiency.

2.3 Digital finance, environmental regulation, and green development efficiency

The key to achieving green development is to improve environmental policies and systems. Local governments should not only promote green technological innovation through environmental regulation means and force the green transformation and upgrading of high pollution and high energy consumption industries, but also promote financial innovation, guide the green development of the local economy through green credit and green finance, and support green technological innovation and application (Zhang et al., 2022). The implementation of environmental regulations has placed higher demands on production activities. In order to meet environmental regulations, companies have to increase investment into research and development (R&D) of environmental protection and pollution control technologies and improve production processes and efficiency. While endogenous financing can alleviate some of the financial pressure, the need for a continuous supply of funds for technological innovation R&D and the uncertainty of short-term output make it particularly important for companies to seek more external sources of financing.

The development of digital finance provides financial support for environmental regulation to better promote green development and technological innovation. Relying on modern digital technologies such as the Internet, big data, and cloud computing, digital finance brings together idle funds in society through digital platforms, and under the joint action of the "visible hand" of the government and the "invisible hand" of the market it promotes the flow of financial resources to more long-tail groups, breaks the restriction of exogenous financing, and provides financial support for technological innovation and green development. At the same time, environmental regulation can significantly improve environmental information disclosure, provide information screening for financial institutions, and promote green credit placement. Therefore, digital finance can alleviate the financing constraints arising from environmental regulations and weaken the negative impact of environmental regulations on green development efficiency to a certain extent, while environmental regulations promote the development of digital finance to a certain extent and guide financial institutions to explore the environmental blue ocean market. In summary, we propose Hypothesis 3.

Hypothesis 3. The interactive effect of digital finance and environmental regulation has a catalytic effect on the improvement of green development efficiency.

The influence mechanism of digital finance, environmental regulation and green development efficiency is shown in Figure 1.

3 Methodology

3.1 Model setting

In order to test the intrinsic connections among digital finance, environmental regulation, and green development efficiency and to better analyze the impact of the synergy between digital finance and environmental regulation on green development efficiency, this paper adds the interaction term of digital finance and environmental regulation to the model and centralizes this. The econometric model is set in the following form.

$$GTFP_{it} = \alpha_0 + \rho_1 GTFP_{i,t-1} + \rho_2 GTFP_{i,t-2} + \beta_1 lndf_{it} + \beta_2 er_{it} + \beta_3 lndf_{it} \times er_{it} + \sum_{i=1}^{4} \omega_i control_{it} + \mu_i + \varepsilon_{it} \quad (1)$$

In Eq. 1, $GTFP$ is green development efficiency, df is digital finance development index, er is environmental regulation, $control$ is control variables, $lndf_{it} \times er_{it}$ is the interaction term between digital finance and environmental regulation (interaction term centralized treatment), i is provincial cross-sectional unit, t is year, μ is individual fixed effect, ε is random disturbance term, and $\alpha, \beta,$ and ω are parameters to be estimated. $GTFP_{i,t-1}$ and $GTFP_{i,t-2}$ are the green development efficiency at lag one and lag two, respectively, and are put into the model as explanatory variables. However, this creates endogeneity problems among the model variables and also leads to autocorrelation in the model.

To solve the above problem, we use the GMM method for estimation, and the endogeneity problem can be effectively solved by introducing the lagged terms of the explanatory variables as instrumental variables. First, the individual effects of the model are eliminated by doing a first-order difference for Eq. 1.

$$\Delta GTFP_{it} = \rho_1 \Delta GTFP_{i,t-1} + \rho_2 \Delta GTFP_{i,t-2} + \beta_1 \Delta lndf_{it} + \beta_2 \Delta er_{it} + \beta_3 \Delta lndf_{it} \times er_{it} + \sum_{i=1}^{4} \omega_i \Delta control_{it} + \Delta\varepsilon_{it} \quad (2)$$

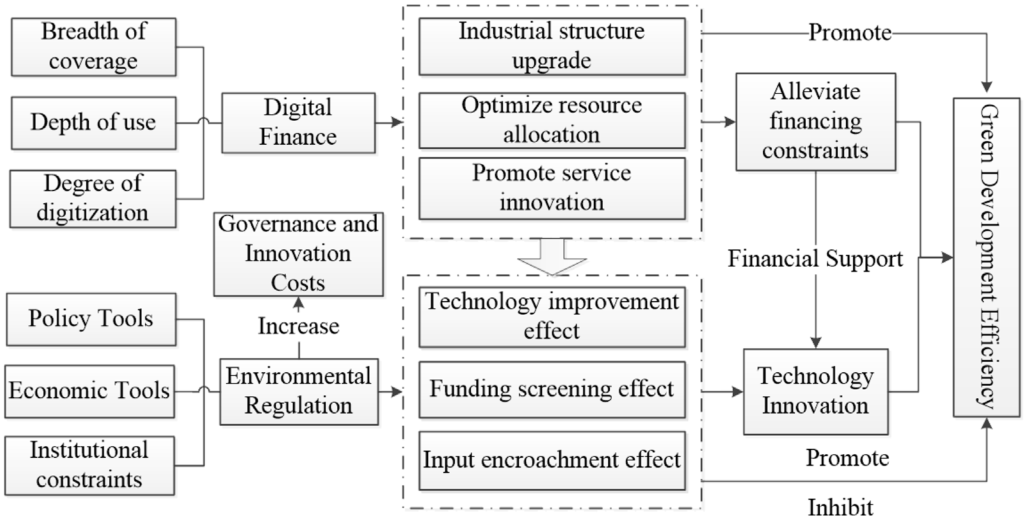

FIGURE 1
Influence mechanism of digital finance, environmental regulation and green development efficiency.

The lag term still correlates with $\Delta\varepsilon_{it}$, the endogeneity problem of model (2) still exists, and so further instrumental variables can be sought to obtain consistent estimates. Arellano and Bond (1991); Blundell and Bond (1998) propose two types of methods, differential GMM and systematic GMM, for regressing dynamic panel models, which can effectively solve the endogeneity problem (Arellano and Bond, 1991; Blundell and Bond, 1998). However, the premise of using this method is that the perturbation terms are not autocorrelated. Therefore, we choose the differential GMM model for testing.

3.2 Green development efficiency measurement

Green development is a new model to achieve sustainable development by protecting the ecological environment under the constraints of ecological and environmental capacity and resource carrying capacity. Green development requires economic growth while reducing the impact on the ecological environment, emphasizing the mutual unity and coordinated development of the two (Zhao and He, 2022; Chen et al., 2022b). The existing methods on measuring green development efficiency mainly include Data Envelopment Analysis (DEA), Stochastic Frontier Analysis (SFA), Total Factor Productivity (TFP), and other efficiency measurement methods. In this paper we use the directional distance function by considering the undesirable output and the Malmquist-Luenberger productivity index to measure green development efficiency (Chen et al., 2022a). This method, proposed by (Chung et al., 1997), applies the directional distance function containing non-desired outputs to the Malmquist model to obtain the Malmquist-Luenberger index (ML index for short). The directional distance function is defined as follows:

$$\overrightarrow{D_0}\left(x, y, b; g_y, -g_b\right) = sup\left\{\beta:\ \left(y + \beta g_y, b - \beta g_b\right) \in p(x)\right\} \quad (3)$$

In Eq. 3, $\overrightarrow{D_0}$ is the distance function, $x, y,$ and b are the input vector, desired output vector and non-desired output vector, respectively, g is the direction vector, $g = (g_y, -g_b)$, and β is the distance function value.

$$\overrightarrow{D_0^t}\left(x_k^t, y_k^t, b_k^t; y_k^t, -b_k^t\right) = max\,\beta \quad (4)$$

$$s.t.\begin{cases} \sum_{k=1}^{k} z_k^t y_{km}^t \geq (1+\beta) y_{km}^t, \ m = 1,2\ldots,M \\ \sum_{k=1}^{k} z_k^t b_{ki}^t = (1-\beta) b_{ki}^t, \ i = 1,2\ldots,I \\ \sum_{k=1}^{k} z_k^t x_{kn}^t \leq x_{kn}^t, \ n = 1,2\ldots,N \\ z_k^t \geq 0, \ k = 1,\ldots,K \end{cases} \quad (5)$$

In Eq. 5, z_k^t is the k th observation weight, $M, I,$ and N are desired output, non-desired output, and types of input factors, respectively, t is the period, and so the ML index from period t to period $t+1$ can be expressed as follows:

$$ML\_TFP_t^{t+1} = \left[\frac{\left(1 + \overrightarrow{D_0^t}\left(x^t, y^t, b^t; y^t, -b^t\right)\right)}{\left(1 + \overrightarrow{D_0^t}\left(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1}\right)\right)} \times \frac{\left(1 + \overrightarrow{D_0^{t+1}}\left(x^t, y^t, b^t; y^t, -b^t\right)\right)}{\left(1 + \overrightarrow{D_0^{t+1}}\left(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1}\right)\right)}\right] \quad (6)$$

In Eq. 6, $ML\_TFP_t^{t+1}$ greater than 0 indicates productivity growth and efficiency improvement; $ML\_TFP_t^{t+1}$ less than 0 indicates productivity decline. The measurement of ML productivity index requires comprehensive consideration of environmental, energy, resource, and other constraints. Therefore, we include the above elements in setting the input and output indicators, and the indicator selection and interpretation are explained as follows.

TABLE 1 Descriptive statistics of variables.

Variable type	Variable	Mean	Standard error	Min	Max
Explained variables	*GTFP*	0.815	0.116	0.485	1.123
Core explanatory variables	*er*	0.896	0.100	0.433	1.000
	df	217.246	96.968	18.330	431.930
	cov	198.010	96.334	1.960	397.000
	deep	212.036	98.106	6.760	488.680
	cov	290.238	117.644	7.580	462.230
Control variables	*gdp*	5.370	2.696	1.591	16.493
	indus	0.410	0.081	0.158	0.620
	innov	58602.22	8936.55	502	709725
	green	0.396	0.035	0.279	0.491
	open	0.254	0.272	0.007	1.359

1) Input indicators. Labor force, capital stock, and energy input are used as input indicators for green development efficiency, where labor force input is measured by the total number of employed persons at the end of the year. Capital stock is calculated by referring to the measurement method of Shan Haojie (Shan, 2008), using the perpetual inventory method, and the annual capital stock of each province is calculated by using 2010 as the base period with a depreciation rate of 10.96%. The amount of energy input is expressed in terms of comprehensive energy consumption—that is, the eight kinds of energy consumed by each province each year—which is converted into a uniform unit according to GB2589-2008T General Rules for Calculating Comprehensive Energy Consumption to sum up the total energy consumption of each province. The energy consumption is converted into million tons standard coal.
2) Output indicators. Output includes desired output and non-desired output, where desired output is expressed as the real GDP *per capita* of each province calculated in 2010 at constant prices; non-desired output is measured by the total annual carbon emissions and industrial triple waste emissions (i.e., three major pollution emission indicators of wastewater, waste gas and solid waste) of each province, where carbon emissions are calculated according to the formula of energy in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The formula for calculating carbon dioxide emissions provided as below.

$$E(CO_2) = \sum_{i=1}^{8} E(C) = \frac{\sum_{i=1}^{8} Q_i \times NCV_i \times CEF_i \times COF_i \times 44}{12} \quad (7)$$

In Eq. 7, $E(CO_2)$ is the total carbon emissions of eight energy consumptions, $E(C)$ is the carbon emission of energy i, Q_i is fuel consumption, NCV_i is the net heat of energy fuel i, CEF_i is the carbon emission factor of energy fuel i, COF_i is the carbon oxidation factor of energy fuel i, 44 indicates the molecular weight approximation of CO_2, and 12 represents the approximate atomic weight of carbon.

3.3 Selection of indicators

3.3.1 Explained variables

The explanatory variable in this paper is *GTFP* as measured by MaxDEA software; i.e., green development efficiency expressed as the Malmquist-Luenberger productivity index.

3.3.2 Core explanatory variables

Digital Finance (*df*). We choose the Peking University Digital Inclusive Finance Index, jointly compiled by the Digital Finance Research Center of Peking University and Ant Financial Services, to measure the level of digital finance development. The index constructs an evaluation system of digital inclusive finance in three dimensions: breadth of coverage (*cov*), depth of use (*deep*), and degree of digitization (*dig*) (Guo et al., 2020), which can comprehensively reflect the level of digital finance development in each province.

Environmental regulation (*er*). Due to the diverse characteristics of environmental regulation tools and government intervention patterns, the measures of environmental regulation by domestic and foreign scholars also differ significantly. We summarize two types of approaches. One type is measured by using a single index, including the number of inspections on the number of times enterprises discharge (Brunnermeier and Cohen, 2003), the share of pollution control investment in industrial value added, or the share of pollution control investment in GDP (Berman and Bui, 2001). Another type is to measure the intensity of environmental regulation using a composite index, which combines the aspects of managing wastewater, solid waste, and exhaust gas (Wang et al., 2022), using the entropy value method. We choose the second method to measure the intensity of environmental regulation by replacing the single index method with the comprehensive index method, consider the three wastes treatment, select the investment amount completed in wastewater treatment, investment amount completed in waste gas treatment, and investment amount completed in solid waste treatment as a proportion of industrial GDP, and use the entropy method to calculate the comprehensive

TABLE 2 Regression results of the dynamic panel GMM model.

Variables	1)	2)	3)	4)	5)
L.GTFP	—	0.186***	0.276***	0.156***	0.0389***
	—	(0.0203)	(0.0138)	(0.0197)	(0.0726)
L2.GTFP	—	−0.334***	−0.612***	−0.335***	−0.358***
	—	(0.0165)	(0.0164)	(0.0368)	(0.0736)
lndf	0.0640***	0.0362***	0.0262***	0.0168**	0.057***
	(0.0178)	(0.0030)	(0.0053)	(0.0073)	(0.0534)
er	−0.0472**	—	−0.0623***	−0.0602***	−0.121***
	(0.0641)	—	(0.0054)	(0.0079)	(0.0117)
lndf × er	0.253**	—	—	0.693***	0.520***
	(0.103)	—	—	(0.0336)	(0.0818)
lnpgdp	0.0984**	—	—	—	0.0480**
	(0.0705)	—	—	—	(0.0688)
indus	0.498**	—	—	—	1.206***
	(0.216)	—	—	—	(0.288)
lninnov	0.115***	—	—	—	0.225***
	(0.0231)	—	—	—	(0.0196)
green	0.992**	—	—	—	1.454**
	(0.455)	—	—	—	(0.694)
open	−0.233***	—	—	—	−0.276***
	(0.0675)	—	—	—	(0.0936)
_cons	1.916***	1.438***	2.034***	1.337***	1.830***
	(0.243)	(0.0319)	(0.0194)	(0.0287)	(0.383)
AR(1)-P	—	0.042	0.033	0.043	0.031
AR(2)-P	—	0.386	0.549	0.536	0.793
Sargan-P	—	0.845	0.973	1.000	1.000
N	300	210	210	210	210

Note: Values in parentheses are standard errors. $^{*}p < 0.1$, $^{**}p < 0.05$, and $^{***}p < 0.01$.

10.3389/fenvs.2023.1131058

environmental regulation index (*er*), which avoids the bias of the single indicator method.

3.3.3 Control variables

To mitigate the estimation bias caused by omitted variables, this paper combines macroeconomic theory and the variables considered by relevant scholars in the research process (Wu et al., 2020; Zhao and He, 2022; Zhao et al., 2022a; Zhao et al., 2022b), then selects five indicators of economic development level (*gdp*), industrial structure (*indus*), technological innovation level (*innov*), greening level (*green*), and openness to the outside world (*open*) as control variables. Economic development and green development are closely related, and this paper expresses the level of regional economic development in terms of real GDP *per capita* calculated in constant prices in 2010. Numerous studies have shown that industrial structure is one of the important factors affecting green development. Therefore, this paper uses the ratio of the output value of secondary industry to GDP to indicate the status of industrial structure. Technological innovation can effectively improve the production efficiency of traditional industries, promote the progress of environmental protection technology, improve the green manufacturing capability of enterprises (Liu et al., 2022), and thus promote green development. This paper selects the number of domestic patent applications granted to measure the level of technological innovation. The greening level reflects the green development level of the region to a certain extent, and this paper measures the greening level of the region by the proportion of the greening coverage area of the built-up area to the total area of the built-up area. The level of external openness directly reflects the degree of connection between a country or region and foreign regional markets, which is conducive to promoting exchanges and cooperation among enterprises, and thus improving production efficiency and technological innovation. In this paper, we use the proportion of total import and export trade to GDP to measure the level of external openness. In order to narrow the scale between variables and improve the accuracy of the test results, the values of economic development level and technological innovation level are treated as logarithms in this paper.

3.3.4 Data sources

Given that the Peking University Digital Financial Inclusion Index has been measured since 2011, a total of 10 years of data from 2011–2020 is selected based on data availability. Since Tibet, Hong Kong, Macao, and Taiwan statistics are more seriously missing, we use the provincial panel data of 30 provinces as the basis for testing and analysis. The data are obtained from EPS database, CSMAR database, China Statistical Yearbook, and China Environmental Statistical Yearbook. Table 1 shows the definition and description of each variable.

4 Empirical analysis

4.1 Impact of digital finance and environmental regulation on green development efficiency

In this paper we adopt Arellano-Bond's approach, the dynamic differential GMM model, use the lagged terms of the explanatory variables as instrumental variables to solve the model endogeneity problem, and use STATA16.0 to estimate the impact relationship between digital finance, environmental regulation, and green development efficiency. Two conditions are required for the application of the two-step differential GMM model: first, there is first-order autocorrelation in the random disturbance terms, but not second-order or higher-order autocorrelation; second, there is no over-identification of instrumental variables. The estimation results are in Table 2. AR 1) is significant at the 5% level, but AR 2) is not significant, which is consistent with condition one. The Sargan test results show that the *p*-value is greater than 0.1, which is not significant, indicating that all instrumental variables are valid, which is consistent with condition two.

Table 2 reports the estimation results for the full sample, where column (1) shows the estimation results using the fixed effects model and columns (2) to (5), using the differential GMM estimation method and adding variables column by column. The results in Table 2 denote that digital finance and environmental regulation have a significant

TABLE 3 Sub-dimensional regression results.

Variable	(1)*GTFP*	(2)*GTFP*	(3)*GTFP*
	cov	*deep*	*dif*
L.GTFP	0.0293	0.0433	0.0909
	(0.147)	(0.0512)	(0.112)
L2.GTFP	−0.452***	−0.248**	−0.219*
	(0.110)	(0.0967)	(0.132)
er	−0.204***	−0.0601***	−0.264***
	(0.0421)	(0.0221)	(0.0291)
lncov	0.197***	—	—
	(0.0350)	—	—
lncov × *er*	0.326**	—	—
	(0.166)	—	—
lndeep	—	0.0767***	—
	—	(0.0163)	—
lndeep × *er*	—	0.678***	—
	—	(0.0458)	—
lndig	—	—	0.126***
	—	—	(0.0120)
lndig × *er*	—	—	0.724***
	—	—	(0.159)
controls	Yes	Yes	Yes
_cons	2.795***	3.984***	2.938***
	(0.461)	(0.219)	(0.343)
AR(1)-P	0.018	0.036	0.040
AR(2)-P	0.432	0.903	0.449
Sargan-P	1.000	1.000	1.000
N	210	210	210

Notes: Values in parentheses are standard errors. $^{*}p < 0.1$, $^{**}p < 0.05$, and $^{***}p < 0.01$.

TABLE 4 Endogeneity test: IV-2SLS.

Variable	First stage	Second stage
	df	*GTFP*
Internet penetration rate	0.0265***	—
	(0.0031)	—
df	—	0.0994***
	—	(0.0314)
controls	Yes	Yes
Adj-R^2	0.714	0.821
N	300	300

Notes: Values in parentheses are standard errors. *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$.

TABLE 5 Robustness tests.

1) System GMM		2) Substitution of explanatory variables	
L.GTFP	0.289***	*L.GTFP*	0.558***
	(0.099)		(0.062)
L2.GTFP	−0.768***	*L2.GTFP*	−0.660***
	(0.074)		(0.067)
lndf	0.194***	*lndf*	0.184***
	(0.029)		(0.045)
er	−0.174***	*er1*	−0.044***
	(0.016)		(0.008)
lndf × *er*	0.582***	*lndf* × *er1*	0.331***
	(0.142)		(0.081)
controls	Yes	*controls*	Yes
_cons	0.103***	*_cons*	3.111***
	(0.273)		(0.820)
AR(1)-P	0.037	*AR(1)-P*	0.005
AR(2)-P	0.278	*AR(2)-P*	0.178
Sargan-P	1.000	*Sargan-P*	1.000
N	240	*N*	210

Notes: Values in parentheses are standard errors. *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$.

impact on green development efficiency, indicating that digital finance and environmental regulation play an important role in the green development process.

Considering the problem of "tightening 1 year and loosening the other" in the implementation of environmental regulatory policies and institutions, the model is estimated using the lagged one-period and lagged two-period green development efficiency as instrumental variables, as shown in Table 2. The coefficient of green development efficiency of the first lag is significantly positive in the current period, which means that the green development efficiency of the previous period has a significant effect on the green development efficiency of the current period. In contrast, the green development efficiency of the second-period lag has a significantly negative impact on the green development efficiency of the current period, which means that the green development efficiency of the second-period lag inhibits the green development efficiency of the current period. This indicates that the improvement of green development efficiency in the previous period improves the ecological environment. However, due to the implementation of environmental regulation policies with a certain lag, environmental regulation has not yet shown its impact effect, and the government chooses to continue to implement the environmental regulation policies in the previous period. Moreover, green development efficiency in the second lag has a suppressive effect on the current period, which means that the high intensity of environmental regulation suppresses the green development efficiency, and due to the competitive pressure, the government has to choose to relax the intensity of environmental regulation and increase economic output, so as to win the competition among governments.

The effect of digital finance (*df*) on green development efficiency is significantly positive, which indicates that the development of digital finance has a significant contribution to local green development efficiency. Thus, Hypothesis 1 is supported. Digital finance has strong green attributes, and its natural advantages of inclusiveness, efficiency, and convenience play a positive role in the process of enhancing green development efficiency. On the one hand, digital finance expands the boundary of financial services with modern digital technology, improves resource allocation efficiency, accurately identifies green projects through technical screening function, and directs resources to high-tech and innovative environment-friendly enterprises, thus increasing environmental benefits as a "blood transfusion" for enterprises. On the other hand, it stimulates green consumption demand and promotes the transformation and upgrading of green industries. Green consumption and green credit stimulate residents' demand for environmentally friendly products, spur industries to upgrade to green and environmental protection, improve the virtuous cycle of economy and environment, and promote green development.

The effect of environmental regulation (*er*) on green development efficiency is significantly negative, which implies that environmental regulation has a negative effect on the improvement of green development efficiency, which runs contrary to Hypothesis 2. The empirical findings indicate that the impact of environmental regulation has not yet crossed the Porter's inflection point; i.e., the negative effect of compliance cost brought by environmental regulation to enterprises has not yet jumped to the technological innovation compensation positive effect. The possible reason is that China's environmental regulations are mostly based on emission constraints and pollution control, forcing enterprises to increase pollution treatment and ecological protection expenditures, but China is also mainly a heavy industry and manufacturing economy that is subject to high levels of environmental regulations and large compliance costs. Only proper environmental regulations can promote enterprises to improve energy efficiency, innovate production processes and environmental protection technologies, and continue to play the innovation compensation effect in order to enhance the efficiency of green development.

The synergistic effect of digital finance and environmental regulation (digital finance and environmental regulation interaction term *df*er*) on green development efficiency is significantly positive, which indicates that the interactive effect of digital finance and environmental regulation has a positive impact on green development efficiency improvement. Thus, Hypothesis 3 is supported. Digital finance can alleviate the financing constraints arising from environmental regulations and to a certain extent weaken the negative impact of environmental regulations on green development efficiency. Local governments also need to use digital finance to guide the flow of resources and support the innovation and application of production technology and pollution control technology when using environmental regulations to push enterprises to green transformation and upgrading. Therefore, the synergy between digital finance and environmental regulation can effectively improve the efficiency of regional green development.

4.2 Analysis of the impact of interaction between sub-dimensions of digital finance and environmental regulation on green development efficiency

To further explore the impact of the interaction between the dimensions of digital finance and environmental regulation on the efficiency of green development, this paper estimates the three sub-dimensions of digital finance. The results appear in Table 3. As can be seen from the table, all three dimensions of digital finance are significant at the 1% level with positive coefficients, indicating that the breadth of coverage, depth of use, and digitization of digital finance significantly enhance green development efficiency. In terms of the magnitude of the coefficients, the degree of influence of the three sub-dimensions on green development efficiency is: breadth of coverage > digitalization > depth of use. The intensity of environmental regulation has a negative effect on green development efficiency, but its interaction with the digital finance sub-dimension has a significant positive effect on green development efficiency.

4.3 Endogenous discussion

An underlying assumption of the above analysis is the premise that digital finance is an exogenous variable. Although this paper uses a dynamic panel GMM model to reduce the problem of endogeneity among variables, there is still reverse causality leading to endogeneity bias in the model estimation process. Therefore, this paper uses the Durbin-Wu-Hausman test for endogeneity of the core explanatory variables. The test results show that the p-value is less than 0.05, and digital finance is considered as an endogenous variable. In order to avoid the reverse causality of "the higher the efficiency of green development, the higher the degree of access to green financial resources and even digital financial development," in this paper we use the Internet penetration rate as an instrumental variable and adopt the 2SLS method to correct for the endogeneity of the model.

After controlling for the level of regional economic development, industrial structure, technological innovation, greening level, and openness to the outside world, there is no direct correlation between Internet penetration rate and green development, which satisfies the requirement of exogeneity. The use of instrumental variables needs to be tested for validity. First, the Keilbergen-Paap rk LM statistic is used for the non-identifiability test, and the result shows that the value of the statistic is 51.639 (p = 0.000), indicating that the instrumental variables can be effectively identified. Furthermore, the Keilbergen-Paap rk LM statistic is used to test the validity of the instrumental variables. In the Keilbergen-Paap rk Wald F-statistic for weak instrumental variables test, the results show that the value of the statistic is greater than the critical value of 19.93 for Stock-Yogo at the 10% significance level, indicating that there are no weak instrumental variables. The results in Table 4 indicate that digital finance can still significantly improve the efficiency of green development after accounting for endogeneity issues.

4.4 Robustness test

To test the robustness of the model estimation results, this paper uses the systematic GMM estimation method and substitution of core explanatory variables to test the robustness of the above findings.

1) Systematic GMM method. Compared with differential GMM, the advantage of systematic GMM is that it can improve the efficiency of estimation and reduce the estimation error. Therefore, this paper uses the systematic GMM model to conduct robustness tests on the data, as shown in Table 5(1). The test results are consistent with those of the differential GMM model.
2) Replacement of core explanatory variables. In order to test the robustness of the results, this paper adopts another method to measure environmental regulation and selects the proportion of industrial pollution control investment to GDP to measure the intensity of environmental regulation in each province. The results of the robustness test by the above method are basically consistent with a previous paper, which indicates that the empirical results of this study are robust and reliable.

5 Conclusion and policy recommendations

Based on identifying the mechanisms of digital finance and environmental regulation on green development efficiency, this research measures green development efficiency using the directional distance function and Malmquist-Luenberger index based on 30 provinces' panel data in China from 2011 to 2020. The relationship among digital finance, environmental regulation and green development efficiency is empirically analyzed through a dynamic panel GMM model. The main findings are as follows. 1) Digital finance and its three sub-dimensions have a catalytic effect on the improvement of green development efficiency. 2) Environmental regulation has not yet crossed Porter's inflection point and still has a suppressive effect on green development efficiency. 3) The interaction between digital finance and environmental regulation has a positive effect on the improvement of green development efficiency. 4) The interaction between digital finance and environmental regulation has a positive impact on the improvement of green development efficiency, indicating that digital finance can alleviate the financing constraints arising from environmental regulation and to some extent weaken the negative effect of environmental regulation on green development efficiency.

Based on the above research findings, we propose the following policy recommendations.

1) Give full play to the active role of digital finance in ecological and environmental governance. First, the government should rely on modern digital technology to accurately screen green, clean, and environmental protection enterprises and projects, guide financial resources to high technology, high value-added, and other green industries, appropriately finance high pollution and high energy consumption enterprises, accelerate the layout of the green industry chain, and force the green transformation and upgrading of industries. Second, the relevant authorities should pus to build a diversified digital financial platform, carry out digital financial service model innovation, integrate social idle funds, give full play to the optimal allocation of resources in environmental protection, break the stratification of financial resources mobility, and make reasonable use of the government's "visible hand" and the market's "invisible hand". Third, efforts should be geared to giving full play to the optimal allocation of resources in environmental protection, breaking the stratification of financial resource liquidity, building a government-market dual-track parallel mechanism, and promoting the synergy of digital finance and environmental regulation to promote green development.
2) Optimize the top-level design of environmental regulation and establish a reasonable, scientific, and flexible environmental regulation system. First, China should formulate differentiated and diversified environmental regulation policies according to local conditions. There are significant regional differences in the impact of environmental regulation on the efficiency of green development, and the country should combine the characteristics of economic and environmental resource endowments of each region to formulate environmental regulation policies that are compatible with the characteristics of industries. Second, the government should improve every detail of environmental regulations from their introduction to their implementation to avoid the phenomenon of "loud thunder but little rain" in their implementation. At the same time, the process of implementing environmental regulation policies should also avoid brutal policy implementation methods such as "one size fits all" and "one stop". Third, to reduce the frequency of environmental regulation policy adjustment, some regions in the pursuit of economic development of environmental regulation have implemented a policy of "a year tight and a year loose", resulting in serious slowdown of the green development process. Thus, local governments should develop a long-term environmental regulation system and implement strict and appropriate intensity of environmental regulation, in order to play a positive role of environmental regulation on green development efficiency. Only in this way can environmental regulations really exhibit a positive role in the efficiency of green development.
3) Actively encourage and support the R&D and application of green innovative technologies in enterprises to provide endogenous drive for green development. The authorities should tighten the direction of green and low-carbon development, set up advanced green and low-carbon technology R&D teams, break down technical barriers, increase support for R&D of key core technologies, promote the output and application of low-carbon technology achievements, and promote the process of green development. The global trend is low-carbon transition, low-carbon development capability, and advanced low-carbon technology, which represent international competitiveness. Therefore, supervising the R&D and application of low-carbon technologies is beneficial for China to seize the high point of future world green market competition and lead the trend of low-carbon economic development in the world.

Data availability Statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

YH: conceptualization, software, resources, writing—original draft preparation, conceptualization, methodology, data curation; YL: validation, investigation; QW: validation, validation, writing—reviewing and editing, supervision. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest

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

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