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How Digital Finance Empowers Polluting Enterprise Green Innovation

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Abstract. Using data from A-share listed companies in the heavy polluting industries in Shenzhen and Shanghai from 2011 to 2020, matched with the Peking University Inclusive Finance Index, this paper empirically investigates the impact of digital finance on the green innovation of heavy polluting enterprises and its mechanism of action. According to the study, substantially polluting businesses' adoption of green innovation was significantly facilitated by digital financing. The mechanism path analysis found that digital finance promoted green innovation in heavy polluting enterprises by reducing internal financing constraints and financing costs. Further analysis found that firms' internal leverage and financial risk strengthened the impact of digital finance on green innovation of heavy polluting firms. Following a number of robustness tests, the conclusions still hold. The preceding conclusions have ramifications for policy. First, the development of digital finance should be further deepened and financial instruments should be used to promote green development. Second, heavy polluting enterprises should be guided to aim for green innovation and give full play to the advantages of digital finance.

Keywords. Digital finance, enterprises' green innovation, financing constraints

1. Introduction

The rapid emergence and growth of emerging market economies (EME) have greatly contributed to the world's economic development over the past few decades, however this has also caused significant ecological harm and environmental contamination, which has negatively impacted people's daily lives [1]. As environmental degradation becomes one of the world's greatest challenges, more and more companies are adopting novel measures to attain the objective of long-term revenue growth [2]. Heavy polluters have been criticized as a major source of environmental degradation because they increase environmental issues include global warming, the decreasing quantity of natural resources, the production of garbage and the weak environmental commitment of businesses, and therefore have a greater responsibility for environmental protection and a greater need for innovative development [3].

Domestically, China's economic development achievements have attracted world attention, however, behind the impressive achievements lies an environmental crisis. The long-standing rugged economic development approach has been squeezing the ecological environment, with the ecological imbalance and other problems becoming increasingly apparent and the environmental carrying capacity gradually reaching its

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upper limit. As a large industrial country, China's economic growth is marked by high levels of pollution, emissions, and energy use, and the conflict between economic growth and environmental degradation is becoming increasingly prominent. The 2014 Global Environmental Performance Indicators Report indicates that, China ranked only 118th out of 178 countries in the ranking, with an extremely low score of 43 points. This unquestionably reflects the serious global pollution problem in China and the country's generally lax environmental controls. So, the key to long-term prosperity is to improve environmental management and balance economic expansion with environmental protection [4]. Being a significant cause of environmental contamination, companies need to make a green technology transition in order to advance healthy financial growth. Green innovation is steadily growing in significance as a means of competitive advantage for businesses [5]. Among the many different types of technological innovation, green innovation often takes longer and carries higher risks, in the course of implementing green innovation, businesses must pay higher costs, have greater constraints in terms of capital and other resources, and have more demanding projects, more uncertainty and more financial needs [6].

Among the elements required for green technology in highly polluting industries, finance is one of the very important elements. This means that a good financing channel or access to capital is essential for green innovation, but under the standard systems for finance, it is difficult for companies to obtain financial assistance, and banks are often too poor for different companies. Therefore, the current lack of innovation capacity of many enterprises and their failure to meet the financial conditions required for technological innovation are in many cases related to the incomplete and insufficient development of the traditional financial system.

Reference [7] is based on conceptualization and empirical research, it is concluded that financial technology has the ability to increase both the number and quality of green technology innovation, which is a key driver of green innovation in China. Using information from 30 Chinese provinces, municipalities or autonomous regions, reference [8] reveal digital finance's effects on innovative green technologies, empirical research suggests that more advanced digital finance levels are usually associated with better green innovation. Reference [9] focuses on the effect of enhancing the financial climate for corporate green technology innovation through digital finance, and how this process is mediated by financing costs and financial flexibility. However, little literature is available that focuses on and examines the effect of digital affordable financing on environmental innovation in polluting businesses, which are a key source of pollution and are desperate for green innovation. Secondly, there is little research on the transmission pathways between the two.

2. Sample Selection and Data Sources

This study chooses data from A-share listed firms between 2011 and 2020, screens out companies belonging to 16 heavy pollution industries according to the Ministry of Environmental Protection's delineation of heavy pollution industries, matches companies according to their city of incorporation from 2011 using the prefecture-level digital finance index to construct a panel data set for 2011-2020, and refers to previous literature to do the following on the data. The data were screened as follows: (i) to exclude ST or *ST or PT stocks that occurred during the fiscal year or lasted until the end of the fiscal period; (ii) to exclude companies that had been listed for less than one

year, delisted or suspended; (iii) to further match the resulting data with corporate green innovation data and other financial data and to exclude companies missing key variables; (iv) to Winsorize the continuous variables by 1%. (iv) to Winsorize the continuous variables at 1%. A sample of 6947 observations was obtained. In the sample, the CSMAR database was used to get financial and green patent information for businesses, the Digital Inclusive Finance Index of Peking University served as the source for the digital finance index, and the industrial value added data, regional industrial upgrading and regional resource factor allocation efficiency were gathered from the China Statistical Yearbook.

3. Measurement Model Construction

A two-way industry-year fixed effects model is used in this paper, because there is heterogeneity among different heavy polluting industries, and the results of data analysis vary greatly, if not fixed industry effects will make the results more biased.

Based on this, we first test digital finance's direct influence of heavily polluting businesses on green innovation. The model formula is as follows:

$$GP_{it} = \alpha + \beta index_{it} + \sum \lambda Controls_{it} + \sum year + \sum ind + \varepsilon_{it} \quad (1)$$

where i stands for the company, t for the year, and the explanatory variable GP stands for a company's capacity for green innovation. The core explanatory variable *index* is regional digital finance development, *Controls* denotes control variables, *ind* and *year* represent industry and year fixed effects, and ε is the residual term.

To further verify the transmission path of digital finance indirectly influencing green innovation of heavy polluting firms *t*, this study develops a mediating influence model that appears to be this:

$$M_{it} = \alpha + \beta index_{it} + \sum \lambda Controls_{it} + \sum year + \sum ind + \varepsilon_{it} \quad (2)$$

$$GP_{it} = \alpha + \beta_1 index_{it} + \beta_2 M_{it} + \sum \lambda Controls_{it} + \sum year + \sum ind + \varepsilon_{it} \quad (3)$$

where M includes two mediating variables, including financing constraints (SA) and financing costs (FY), to test whether digital finance can indirectly promote green innovation among heavy polluters by reducing firms' financing constraints and financing costs.

The following moderating effect model is then created to see if different intra-firm variables have an impact on how digital financing affects green innovation in highly polluting firms.

$$GP_{it} = \alpha + \beta_1 index_{it} + \beta_2 M_{it} + \beta_3 index_{it} \times M_{it} + \Sigma \lambda Controls_{it} + \Sigma year + \Sigma ind + \varepsilon_{it} \quad (4)$$

where M includes two moderating variables, including firm leverage (Lev), and firm financial risk (ZScore). index × M is the phrase for the connection between online financing and the moderating variable after it has been centralised.

4. Variable Descriptions and Statistics

Corporate Green Innovation (GP). The number of green patent applications and the

number of issued patents are two ways to evaluate corporate green innovation. According to some academics, it is very unpredictable how many green patent applications will be submitted, time-consuming and only reflects a company's willingness to make a green transition, but does not necessarily reflect the company's green innovation capability, while some scholars believe that a company has already started to enjoy the dividends and benefits of a patent when it makes a green transition application, which is more stable than a patent grant, and that the grant of a patent is subject to interference from various sources and There is great uncertainty. For this reason, this paper uses the number of green innovation patent applications by heavy polluters to measure green innovation.

The Digital Inclusive Finance Index (2011-2020), which was introduced by the Digital Finance Centre of Peking University in collaboration with Ant Financial Services, is the source for the Digital Financial Index (index), which has three dimensions: breadth of coverage (breadth), depth of use (depth), and digitization (digitization). The index is divided into provincial and municipal data. The primary explanatory variable in this study is the prefecture-level digital financial index. For measurement purposes, the financial index is divided by 100.

Financing Constraint (SA). The SA index's absolute value is used to gauge the firm's level of financial restrictions. The firm's financial limitations are more severe the higher the absolute value.

Financing cost (FY). This index uses the enterprise finance cost instead of operating income to measure the financial cost that the enterprise needs to consume in the business process, which can reflect the various costs required by the enterprise to carry out financing from the side.

Corporate leverage (Lev). A balance sheet ratio is used to measure corporate leverage.

Financial risk (ZScore). Referring to Altman [10], the risk Z-score method is used to measure the risk because the smaller the Z-score, the higher the financial risk of the enterprise and the more likely it is to fall into operational difficulties. For ease of observation, the opposite number is taken for the Z-score, then the larger the Z-score the higher the risk of the enterprise.

We choose the following control variables. Size, measured as the logarithmic of the company's total assets; Age, expressed as the current year minus the year the firm was founded and taken as the logarithm; Ltime, taken as the logarithm of the current year divided by the year the company began public; Equity, expressed as the proportion of the company's shares held by the largest shareholder; Management expense ratio (Mgee), expressed as the ratio of current overheads to operating income; TobinQ, expressed as the market capitalisation of a firm compared to its total assets.

The descriptive statistics for the variables are shown in Table 1.

5. Regression Results and Analysis

Table 2's columns (1) through (4) show the effects of the overall digital finance index (index) and its three sub-indicators, namely, the breadth of coverage (breath), the depth of usage (depth), and the digitization (digitization), on the adoption of green technologies by highly polluting businesses. The coefficient of digital finance on green innovation, according to the regression results in column 1, is 7.534, and at a 1% importance level, it encourages significantly polluting businesses to innovate greenly.

Hypothesis H1 is verified. The regression findings from columns (2) to (4) demonstrate that, at a 1% level of significance, the indicators of the depth and breadth of use of digital finance both favorably support green innovation of highly polluting businesses, while the indicator of digitisation has no significant impact on green innovation of heavily polluting enterprises, in which the coefficient of the impact of the indicator of breadth of coverage is greater than the other two indicators, which shows that the inclusive nature of digital finance is the strongest in empowering green innovation of heavily polluting enterprises. It can significantly lower the barriers to financing for enterprises, reach thousands of households, and provide lower barriers to entry for a large number of SMEs than traditional finance.

Table 1. Detailed statistics for important variables.

Variable	N	Mean	Sd	Min	Max
Gp	6947	4.706	34.00	0	991
Index	6947	2.031	0.711	0.213	3.345
Sa	6947	3.795	0.254	2.120	4.830
Fy	6947	0.0241	0.0569	-0.708	1.547
Lev	6947	0.424	0.210	0.00708	2.123
Zscore	6947	-5.398	10.33	-329.7	5.805
Size	6947	22.35	1.361	17.81	28.64
Age	6947	2.823	0.357	0.693	3.738
Ltime	6947	2.137	0.886	0	3.332
Equity	6947	0.355	0.153	0.00290	0.900
Mgee	6947	0.0818	0.0858	0.00154	2.987
Tobinq	6947	2.056	2.442	0.701	102.4

To be able to verify the robustness of the intermediation effect, the Sober and bootstrap intermediation effect tests were conducted on the above intermediation paths. The results of the Sober test showed that the *Z*-value of the financing constraint was 6.076, with a *p*-value of 0.00, and the intermediation effect accounted for 43.9%; the Z-value of the financing cost was 4.412, with a *p*-value of 0.00, and the intermediation effect accounted for 10%.

The test's outcomes are displayed in Table 3 for the mediating effects of the internal financing constraints (SA) and financing costs (FY) of the heavily polluting firms. Column 2 displays the results of a regression analysis on the financial restrictions faced by highly polluting businesses. It is clear that digital banking has a considerably negative impact on financing limitations, indicating that it can ease those limits for businesses, and the increase in financing constraints in column (3) will significantly inhibit enterprises' green innovation. The coefficients of digital finance and financing constraints in columns (1), (2) and (3) are all significant and the coefficient of digital finance decreases after adding mediating variables, which demonstrates that the financial limitations faced by businesses act as a partial mediating factor. In column (4), digital finance significantly reduces the cost of corporate finance, while in column (5), the increase in the cost of finance inhibits corporate green innovation and the coefficient of digital finance is smaller than column (1), indicating that the cost of corporate finance partially mediates the connection between large polluters' green innovations and digital financing.

Table 2. The benchmark regression results of corporate green innovation and digital finance.

Variables	GP	GP	GP	GP
Index	7.534***			
	(0.972)			
Breadth		4.481***		
		(0.662)		
Depth			8.090***	
			(1.095)	
Digitization				2.006
				(1.261)
Size	6.530***	6.558***	6.557***	6.656***
	(0.674)	(0.680)	(0.673)	(0.686)
Age	-2.678**	-2.640*	-2.655*	-2.566*
	(1.363)	(1.363)	(1.360)	(1.362)
Ltime	-0.945***	-1.053***	-0.828***	-1.210***
	(0.273)	(0.279)	(0.268)	(0.284)
Equity	7.840***	8.000***	7.896***	8.652***
	(2.301)	(2.315)	(2.297)	(2.350)
Mgee	11.70***	11.60***	12.20***	11.59***
	(3.894)	(3.909)	(3.856)	(3.899)
Tobinq	0.713***	0.723***	0.713***	0.752***
	(0.177)	(0.181)	(0.175)	(0.190)
Constant	-149.6***	-148.9***	-150.5***	-149.6***
	(16.31)	(16.27)	(16.38)	(16.38)
Industry fixed	√	√	√	√
Year fixed	√	√	√	√
Observations	6,947	6,947	6,947	6,947
R-squared	0.302	0.301	0.303	0.300

Note: indicators of statistical significance at the 10%, 5%, and 1% levels include *, **, and ***. Statistical significance is indicated by the symbols *, **, and *** at the 10%, 5%, and 1% levels. Robust standard errors are in brackets.

Columns (1) and (2) of Table 4 group regressions of firm leverage by median into two groups of low and high leverage levels, and columns (4) and (5) group regressions of firm financial risk levels by median into two groups of low and high risk levels. It can be seen that both high and low numerical finance significantly promote green innovation in heavily polluting firms, and both high and low numerical financial risk. The regressions in column (2), however, show that the regressions in column (3) and column (4) are not significant. The regression coefficient in column (2), however, is noticeably greater than that in column (1), while the regression coefficient in column (5) is noticeably larger than that in column (4), indicating that in enterprises with high leverage level and high financial risk, digital finance is equivalent to sending charcoal in snow, which can increase the extent of green innovation in highly polluting businesses; while in enterprises with low leverage, which are in good financial condition and have low financial risk, the enterprises themselves are in a certain condition to carry out green innovation, digital finance has a smaller effect on enhancing green innovation in heavily polluting enterprises. Columns (3) and (6) include the cross-products of corporate leverage and financial risk and the cross-products of digital finance centralized with corporate leverage and financial risk

in the regressions, respectively, and it can be seen that both cross-products significantly and positively affect green innovation of heavily polluting enterprises, thus indicating that both corporate leverage and the association between digital finance and green innovation of highly polluting firms is positively moderated by corporate financial risk.

Table 3. Analysis of the internal mechanisms by which digital finance influences corporate green innovation.

Variables	GP	SA	GP	FY	GP
Index	7.534***	-0.0441***	4.230***	-0.0205***	6.777***
	(0.972)	(0.00703)	(0.786)	(0.00381)	(0.912)
Sa			-74.92***		
			(10.80)		
Fy					-37.05***
					(9.480)
Rd					
Constant	-149.6***	3.428***	107.2***	-0.186***	-156.5***
	(16.31)	(0.0679)	(23.41)	(0.0276)	(17.35)
Control variables	√	√	√	√	√
Industry fixed	√	√	√	√	√
Year fixed	√	√	√	√	√
Observations	6,947	6,947	6,947	6,947	6,947
R-squared	0.302	0.746	0.381	0.172	0.305

Note: indicators of statistical significance at the 10%, 5%, and 1% levels include *, **, and ***. Statistical significance is indicated by the symbols *, **, and *** at the 10%, 5%, and 1% levels. Robust standard errors are in brackets.

Table 4. Regression results on the moderating effect of corporate leverage and financial risk.

Variables	GP	GP	GP	GP	GP	GP
Index	1.936**	14.14***	7.151***	2.431**	9.820***	7.526***
	(0.912)	(1.831)	(0.943)	(1.047)	(1.380)	(0.970)
Index×Lev			5.719***			
			(1.473)			
Lev			-9.417***			
			(2.028)			
Index×zscore						0.0772***
						(0.0287)
Zscore						-0.0503**
						(0.0243)
Constant	-54.27***	-195.3***	-159.6***	-101.7***	-223.4***	-151.0***
	(7.400)	(23.22)	(17.49)	(27.09)	(27.12)	(16.48)
Control variables	√	√	√	√	√	√
Industry fixed	√	√	√	√	√	√
Year fixed	√	√	√	√	√	√
Observations	3,578	3,369	6,947	3,522	3,425	6,947
R-squared	0.134	0.361	0.305	0.362	0.296	0.302

Note: indicators of statistical significance at the 10%, 5%, and 1% levels include *, **, and ***. Statistical significance is indicated by the symbols *, **, and *** at the 10%, 5%, and 1% levels. Robust standard errors are in brackets.

Table 5 displays the outcomes of this paper's robustness tests. First, the model was replaced. Regression was substituted with the Toti model since the explanatory variable for this study, the number of green innovation patent applications, had more issues with zero value stacking [11]. The outcomes are displayed in column 1 of Table 5. Second, the significant factors were changed. (i) Substitute green invention patents for the explanatory variable in the regression. The outcomes are displayed in Table 5's column (2). (ii) The provincial-level data on digital finance was chosen to replace the prefecture-level data with matched firm data for regression, and the outcomes are displayed in Table 5's column (3). (iii) Due to the time lag effect of digital finance influencing corporate green innovation, regressions were conducted by replacing two and three periods of digital finance lagged values, and the outcomes are displayed in Table 5's columns (4) and (5). The regression results demonstrate that heavy-polluting companies' adoption of green innovation is still considerably and favorably impacted by digital finance, further confirming the findings of this study. Together with the previous endogeneity tests, they indicate that the findings of this research are quite reliable.

Table 5. Robustness test regression results.

Variables	Gp	Gi	Gp	Gp	Gp
Index	2.999***	4.071***	9.586***		
	(0.628)	(0.638)	(1.368)		
L2. index				8.591***	
				(1.094)	
L3. index					9.322***
					(1.261)
Constant	-149.636***	-79.23***	-148.6***	-162.9***	-179.5***
	(8.865)	(13.43)	(16.16)	(18.38)	(22.25)
Control variables	√	√	√	√	√
Industry fixed	√	√	√	√	√
Year fixed	√	√	√	√	√
Observations	6,947	6,947	6,947	4,822	3,980
R-squared		0.263	0.306	0.421	0.444

Note: indicators of statistical significance at the 10%, 5%, and 1% levels include *, **, and ***. Statistical significance is indicated by the symbols *, **, and *** at the 10%, 5%, and 1% levels. Robust standard errors are in brackets.

6. Conclusion

With the aid of developing technology, digital finance has grown quickly in recent years, successfully making up for the flaws in traditional finance and encouraging businesses to engage in green technology. This study empirically examines the impact of digital finance on the ecological innovation of heavy-polluting enterprises and its mechanism, using the research sample of A-share listed businesses operating in the highly polluting sector from 2011 to 2020. The study draws the following conclusions. First, digital finance greatly encourages heavy-polluting companies' green innovation, and the conclusions still hold following a number of tests for durability dealing with endogeneity issues. Secondly, by easing financial restrictions and business costs, digital

finance encourages ecological innovation, which further encourages ecological innovation in heavy polluters. Third, corporate leverage and financial risk positively moderate the effect of digital financing on environmentally friendly innovation in extremely harmful businesses.

This article develops the following policy recommendations after analyzing the aforementioned findings. First, expanding the use of financial instruments to support green growth and the advancement of digital finance. On the one hand, regions and governments should utilize cutting-edge tools like big data and artificial intelligence to speed up the construction of supporting infrastructure for digital finance and introduce corresponding protection policies for the development of digital finance, so as to provide a solid foundation for digital finance to feed sustainable development in extremely harmful businesses. On the other hand, encouraging traditional financial institutions like banks to quickly upgrade their digital infrastructure and accelerate their digital transformation. Following that, lowering the financing requirements for businesses and fostering the mutual integration and complementarity of traditional and digital finance. The next step is to develop top-notch finance services and support green innovation for businesses that produce a lot of pollution.

Second, harness heavily polluting companies' social duty to the fullest, encourage their interest in green innovation, and fully exploit the benefits of digital finance. Firstly, actively mobilizing the green innovation enthusiasm of enterprise management and guide them to use the information effect brought by digital finance to correct the short-sighted behaviour of the leadership and promote their green innovation investment. Secondly, guiding heavily polluting enterprises to pay full attention to the role of digital finance and develop green patents. Then paying attention to environmental protection and adopting government subsidies and other means to alleviate the pressure of green upgrading of heavily polluting enterprises, and actively using digital finance to stabilise their own financial situation when the internal financial problems of enterprises lead to insufficient support for innovation activities, thus creating a good environment for green innovation of enterprises. In addition, when enterprises are faced with heavy leverage and poor financial conditions, they are guided to actively relax the demand of ecological innovation by using digital finance, fully mobilise benefits of electronic financing, play the effect of sending charcoal in snow while reducing unnecessary leverage needs and alleviating the financial risks of enterprises.

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