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Urban Economic Efficiency, Environmental Factors, and Digital Finance: Impacts on Sustainable Development in Chinese Cities

Yuling Yuan [1] and Dukangqi Li [2,*]

[1] School of Economics, Xiamen University, Xiamen 361000, China; 15620180155365@stu.xmu.edu.cn
[2] School of Economics and Management, Fujian Polytechnic Normal University, Fuqing 350300, China
* Correspondence: lidukangqi@126.com

Abstract: This study investigates the potential of digital finance to mitigate the environmental impact of economic development. Utilizing panel data from 290 Chinese cities between 2011 and 2019, we employ a two-way fixed effects model to control for unobservable city characteristics and time-invariant macro factors. Our findings reveal that cities with higher proportions of value-added tax and secondary industries (mainly for manufacturing) tend to experience increased air pollution. Conversely, cities characterized by higher economic efficiency exhibit better air quality, underscoring the significance of prioritizing technology-intensive sectors during economic development. Pollution control technologies, such as centralized wastewater treatment systems and harmless treatment systems for household waste, also play positive roles. Moreover, technological and educational investments correlate with increased urban green coverage and lower air pollution, highlighting the pivotal role of technology development and residents' literacy in fostering sustainable practices. Although we initially observed a positive association between the index of digital financial technology and air pollution, which could be attributed to the influence of economic growth, our study employs instrumental variable regression to unveil their true correlation. The results suggest the application of digital financial technology may enhance environmental awareness, contributing to the mitigation of air pollution.

Keywords: digital technology; digital inclusive finance; sustainable economy; urban governance

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1. Introduction

Digital innovation, characterized by the integration of digital and physical components facilitated by digital technology, has been driving profound changes in both organizational and societal development [1–3]. In the face of rapid digital innovation reshaping organizational and societal landscapes, digital finance, often referred to as Fintech, has emerged as an important technological innovation in traditional financial industries, and combines banking expertise, modern management science technology, and computers [4]. In short, digital finance is a combination of digital technology and finance [5]. Combining banking expertise with modern technology, digital finance as a new technology-driven business model shortens the distance between borrowers and lenders [6]. In recent years, digital finance has gained considerable attention due to its ability to improve financial inclusion, foster economic growth, and facilitate efficient resource allocation. The integration of digital technologies into financial systems has revolutionized the way financial services are delivered, accessed, and utilized [7]. Digital transformation has become an influential force in shaping economic landscapes, infrastructure development, and the sustainable development of cities [8]. Digital finance has facilitated the rapid growth of eco-friendly industries such as bike-sharing and car-sharing. These digitally driven eco-industries help conserve energy and materials and promote material recycling, all of which are undeniably essential for the sustainable development of urban economies [9]. While this digital innovation has garnered attention for its potential to enhance financial inclusion and stimulate economic growth, its environmental implications remain underexplored.

In recent years, China has undergone a significant economic transformation, shifting from a manufacturing-centric economy to one that encompasses manufacturing, services, technology, and finance. This transformation has triggered mounting concerns, particularly regarding air pollution in many Chinese cities. However, while there is substantial research on the environmental impact of traditional industries, there is limited empirical evidence regarding the environmental implications of digital finance. This study aims to contribute to discussions on sustainable development and inform policy decisions that balance economic growth and environmental protection. Specifically, we seek to explore the role of digital finance in urban air pollution within the context of China's evolving economy, offering a fresh perspective on China's economic transformation.

Moreover, though it might seem intuitive that financial industries create less pollution than secondary industries, people may observe a counter-intuitive phenomenon that sometimes cities with advanced digital finance infrastructure have higher levels of air pollution. An empirical challenge emerges when applying conventional empirical methods to assess the environmental implications of digital finance, because regions with advanced digital finance typically exhibit higher levels of urban industrial development, which may cause more air pollution. Although a two-way fixed effect model in this paper shows that digital finance is significantly positively correlated with urban air pollution, we need to explain this result very carefully based on the reasons mentioned above.

This study embarks on a comprehensive exploration of the multifaceted relationship between digital finance, economic growth, and environmental preservation. We seek to clarify the intricate dynamics and uncover insights that reconcile this apparent paradox. By examining key factors such as economic efficiency, technological development, and educational investments, we aim to elucidate the role of digital finance in mitigating urban air pollution. To analyze the role of digital finance in balancing economic growth and environmental protection, this article first seeks to illustrate the positive environmental impact of digital finance by demonstrating that higher economic efficiency, technological development, and education levels can reduce urban air pollution. This is because economic efficiency, technological development, and education are all crucial components in developing digital finance. To further investigate the environmental impacts of digital finance, this study examines the relationship between digital finance and urban environmental protection measures. Finally, this paper tries to utilize an instrumental variable approach to minimize potential endogeneity issues within the model, and uncover the true effects of digital finance on urban air pollution.

This paper sheds light in its comprehensive analysis of the multifaceted relationship between digital finance, economic growth, and the environment, addressing the counter-intuitive observation that advanced digital finance infrastructure may lead to higher air pollution in urban areas. It innovatively navigates the challenge of empirically assessing digital finance's environmental implications in regions with advanced digital finance and high industrial development. This study can supplement the existing literature on the environmental impacts of digital finance within the broader context of China's economic transformation. In doing so, it opens up a new perspective for the study of digital finance while providing actionable insights for investors, policymakers, and international markets.

In the baseline results, this paper uses a two-way fixed effects model to analyze panel data from 290 cities in China spanning from 2011 to 2019 to account for unobservable city characteristics and some time-invariant macro factors. To ensure robustness, standard errors are clustered at the city level, allowing for potential correlations within the same city.

From an economic perspective, baseline results show that cities with a higher proportion of value-added tax (mostly applied for the secondary industry before 2016 in China) and a larger share of the secondary industry (including manufacturing, mining, and construction) face more severe air pollution, indicating that urban air pollution is associated with traditional and energy-inclusive industries in developing countries. However, cities with a higher proportion of public profits to GDP and higher public finances over GDP exhibit better air quality, suggesting that higher economic efficiency leads to less air pollution. Furthermore, effective sewage treatment systems and sustainable municipal solid waste management systems significantly reduce air pollution. These results indicate that technology may be important to reconcile the conflict between urban economic growth and environmental protection.

To achieve digital transformation, a city heavily relies on the advancement of technology [10] and the improvement of residents' digital literacy and learning ability [11]. Therefore, to study the impact of digital transformation on the environment, this paper first examines the impacts of urban technological and educational investments on the environment.

Advancements in technology increase productivity and efficiency in industries, leading to higher output and profitability, and also less pollution [12]. For example, technological advancements contribute to smart city management, promoting urban sustainability [13]. Automation, digitalization, and innovation enable companies to streamline operations, reduce costs, and improve resource utilization. Meanwhile, technological development enables the adoption of cleaner processes and pollution control technologies.

Education is also important in promoting economic growth, urban digitalization, and environmental protection. Educated individuals possess the knowledge and skills necessary for innovation and productivity improvement, leading to enhanced economic performance [14]. At the same time, higher levels of education enable residents to better understand the importance of environmental protection and the consequences of pollution, so they are more likely to adopt environmentally friendly behaviors, support sustainable practices, and demand cleaner technologies [15].

Together, higher investments in technology and education in a city may contribute to higher economic efficiency, efficient waste disposal, and reduced air pollution, creating a healthier urban environment [16,17]. As mentioned above, this paper shows that cities with higher economic efficiency and more efficient waste treatment systems experience lower levels of air pollution. Empirical results show that cities with higher technological and educational investments experience lower levels of air pollution and higher urban green coverage.

After showing the importance of education and technology, this paper now tries to investigate the role of digital finance in reconciling the conflict between urban economic growth and environmental protection. Technologies such as electronic payments, blockchain, and big data analysis promote economic development and also offer more efficient environmental solutions at the same time. Due to the rapid development of the Internet, and other information technologies, digital finance has expanded dramatically in China [18]. As urban economic development relies heavily on the support of financial industry [19], with the development of digital technology, digital finance is no longer confined to the optimization of traditional lending processes [20]. The rapid advancement of digital finance presents novel opportunities and solutions for environmental protection [21]. It has also emerged as a supporter of numerous environmental initiatives in cities, including bike-sharing, car-sharing, and power-bank-sharing in the sharing economy. These initiatives not only contribute to the promotion of sustainable urban development but also imbue environmental consciousness among urban residents, fostering a greater inclination towards eco-friendly behaviors [22]. Therefore, this study investigates the impacts of urban digital transformation on the environment from a financial perspective.

The baseline results show a positive correlation between digital financial development and air pollution. However, it is important to interpret this result with caution. As we know, urban digitization is often correlated with cities' economic and industrial development. Moreover, advanced economies usually necessitate the development of digital finance to provide the required financial infrastructure to support industrial growth. As a result, air pollution is more likely a consequence of urban economic development rather than urban digitization per se.

Given the challenges in addressing the complicated endogeneity issues among digital financial transformation, economic growth, and environmental pollution, this paper turns to investigate the role of digital financial transformation from another angle. Since there is no necessary connection between urban greening and economic growth, and urban greening certainly is beneficial for urban air quality, this study turns to examine the impact of digital financial development on urban greening. The results demonstrate a positive correlation between digital finance and urban greening. This paper further uses urban greening coverage and urban greening as instrumental variables for digital finance in the regression analysis of air pollution, and finds that the relationship between digital finance and air pollution becomes negative, although statistically insignificant. While no direct evidence suggests that the digital transformation of the financial sector reduces urban air pollution, digital finance seems to play a role in alleviating the conflicts between urban economic development and the environment, which can be attributed to the inclusive nature of digital finance.

The findings contribute to the burgeoning field of digital technology for sustainable development, illuminating the transformative potential of digital finance to address pressing environmental challenges. Furthermore, this research delves into the realm of urban environmental protection measures, aiming to discern how digital finance interfaces with sustainability initiatives. Our investigation employs an instrumental variable approach to address potential endogeneity issues, providing a more nuanced understanding of digital finance's true effects on urban air quality. Thus, this study not only navigates the complexities of empirical analysis but also contributes to the broader discourse on sustainable development in the context of China's economic transformation.

2. Literature Review

Rapid urbanization and industrialization may accelerate urban air pollution [23], which has emerged as a critical global issue, posing significant risks to human health and the environment [24–27]. Specifically, air pollution has both acute and chronic effects on human health, affecting a number of different systems and organs, resulting in disease like chronic respiratory, heart disease, lung cancer, and acute respiratory infections [28]. Consequently, pollution control and environment management has drawn considerable attention [29–35].

Many studies investigate the impacts of finance on the environment. Some studies find that financial development promotes energy innovation and improves environmental quality [36–42]. Using data from 1990–2020, Rahman et al. (2022) use the augmented Dickey-Fuller test, Phillips-Perron test, Autoregressive Distributed Lag (ARDL) bounds test and the pairwise Granger causality test, and find that financial development reduces CO_2 emissions in Australia [36]. Baloch (2021) utilizes a Pooled Mean Group Autoregressive Distributed Lag (PMG/ARDL) estimator that counters the issue of heterogeneity and cross-sectional dependence and finds that financial development promotes energy innovation and improves environmental quality [37]. Khan and Ozturk (2021) employ a system-generalized method of moments for a large sample of 88 developing countries during the 2000–2014 period, and finds that financial development inhibits pollution based on five different indicators of financial development [38]. Shahbaz et al. (2021) use a Fully Modified OLS (FMOLS) approach to analyzes the impact of financial development on renewable energy consumption in 34 upper-middle-income developing countries from 1994 to 2015, and finds that financial development increases demand for environmentally friendly energy sources [39]. Iqbal et al. (2021) use a common weight DEA composite indicator to develop a green finance index to measure the combined effects of energy, environment, and financial variables, and find that green finance can reduce environmental pollution [40].

Yang et al. [6] use a dynamic panel data model and find that the development of digital finance damages the environment. However, after incorporating a threshold effect into a kink model, Yang et al. (2022) determine that digital finance reduces pollution when its development exceeds a certain level, suggesting that a high level of digital finance development not only increases economic growth but also improves air quality [6]. Their baseline conclusion is very similar to our research. By using a two-way fixed effect model, we find that the development of digital finance damages the air quality. Different from the kink model they use, this paper tries to find a proper instrumental variable for digital finance, and finds that digital finance is negatively correlated with air pollution, which is consistent with Yang et al.'s (2022) final conclusion [6].

Shah and Solarin (2013) apply the bounds testing approach and find that while energy consumption and economic growth add in CO_2 emissions, financial development reduces CO_2 emissions in Malaysia [41]. Their findings seems to suggest that the development of financial industry can mediate the conflicts between economic growth and environmental protection, which is consistent with our findings: that the development of digital finance promotes environmentally friendly measures and reduces air pollution. However, they did not analyze the reason why financial development reduces CO_2 emissions in detail. In our paper, the one of the innovations lies in its systematic investigation of the multifaceted relationship between digital finance, economic growth, and environmental protection, providing valuable insights into a complex and previously unexplored area.

Using a standard reduced-form modeling approach and controlling for country-specific unobserved heterogeneity, Tamazian et al. (2009) find that higher degree of economic and financial development decreases the environmental degradation, suggesting that financial liberalization and openness are essential factors for the CO_2 reduction [42]. Their modeling approach is similar with ours. However, as well as controlling for area-specific unobserved heterogeneity, we also control for year fixed effects to account for some time-invariant macro factors. Moreover, Tamazian et al. (2009) find that a higher degree of economic development decreases the environmental degradation; this seems to be a little counter-intuitive [42]. For example, Shah and Solarin (2013) suggest that economic growth increases CO_2 emissions [41]. Considering the endogeneity issue in a reduced-form modeling approach, we also use an instrumental variable approach to reveal the true effects of digital finance.

On the contrary, other studies find that financial development contributes to carbon emissions and increases environmental degradation [43–46]. Shah et al. (2019) select a sample of 101 countries from 1995 to 2017 and utilize cross-section dependence test, panel unit root test, and Westerlund test to ascertain the long-run affiliations, FMOLS to extract the long-run coefficients, and the Dumitrescu and Hurlin test to find out about the causal nature of the panel series; they find that financial development has a positive relationship with CO_2. However, after considering economic intuitions, the negative impact of financial development on the environment is reduced [43]. Sehrawat et al. (2015) implement the Autoregressive Distributed Lag bounds testing approach and co-integration, error correction method (ECM) to examine the short-run dynamics, VECM framework to check the direction of the causality, and variance decomposition to predict exogenous shocks of the variables, and find that financial development appears to increase environmental degradation in India [44]. Carratù et al. (2019) find that fiscal consolidation policies, while facilitating the achievement of macroeconomic stability within European countries, might have negative effects on the environment [46].

Some other researchers believe that financial development may have more complicated impacts [47,48]. Yin et al. (2019) use the Seemingly Unrelated Regression (SUR) model to analyze the city level data over the period 2007–2014, and find that financial development improves the water quality while resulting in more SO_2 emissions in China [47]. Seetanah et al. (2019) select 12 small island developing states for the period 2000–2016, use a panel vector autoregressive model which accounts for the issue of dynamism and endogeneity, and find that a higher degree of economic development decreases the emissions. Although they find no significant impact of financial development on CO_2 emissions, they believe that financial development may have a positive influence on the environment [48].

There are many articles researching digital technological innovation [49–51]. Digital technologies contribute to urban environmental sustainability in many ways [49]. Specifically, the application of digital technology in finance enables broad and unhindered access to financial services for all segments and groups of society [51]. Therefore, digital finance provides a large amount of savings, investment, and capital aggregation opportunities for economic agents [20]. Fu et al. (2022) apply the Bootstrap ARDL model for empirical analysis and find that digital trade in goods and services, financial development, and green innovation are conducive to long-term environmental sustainability [49]. Notice that digital trade in financial development is similar with digital finance, so their findings are consistent with ours.

Many researchers find that digital finance is environmentally friendly [52–56]. Ma et al. (2023) investigate the impact of Fin-tech development on air pollution using a two-factor fixed effects model based on data for prefecture-level cities in China from 2011 to 2017, and show that Fin-tech development effectively reduces air pollution emissions [52]. Their model is similar with ours. However, using the two-way fixed effects model, we find that digital financial development is significantly positively correlated with air pollution in the baseline result. After using the IV regression approach, the relationship of digital finance and air pollution changes to be negatively correlated, which is consistent with Ma et al. (2023) [52]. We suggest that this difference in the baseline results is because the data are different.

Elheddad et al. (2020) use fixed and random effects models of panel data to control for the possible heterogeneity between countries, and also use an instrumental variable estimation approach and a panel quantile regression as a robustness check, and find that electronic finance reduces CO_2 emissions in OECD countries [53]. Yuan et al. (2022) use a panel threshold regression model to estimate the nonlinear association between financial agglomeration and environmental pollution, and find that financial agglomeration reduces environmental pollution through financial scale, financial structure, and financial technology innovation [54]. Since digital finance is also a kind of financial technology innovation, their findings are consistent with ours. Shi et al. (2022) use the spatial econometric model and the panel threshold model and find that digital finance in the central area has a governance function for the environment [55]. Du et al. (2022) discuss the spatial spillover effect and transmission mechanism between digital finance and environmental pollution, and find that digital finance has a significant positive spatial spillover effect on environmental pollution to the nearby areas [56].

While there is substantial research on the environmental impact of traditional industries, there is limited empirical evidence regarding the environmental implications of digital finance. The study may supplement the literature on the environmental impacts of digital finance within the broader context of China's economic transformation, thereby opening up a new perspective for the study of digital finance.

3. Research Hypothesis

While it might seem intuitive that financial industries create less pollution than traditional industries, people may observe a counter-intuitive fact that sometimes cities with advanced digital finance infrastructure have higher levels of air pollution. An empirical challenge emerges when applying conventional empirical methods to assess the environmental implications of digital finance because regions with advanced digital finance typically exhibit higher levels of urban industrial development, which may cause more air pollution.

To analyze the role of digital finance in balancing economic growth and environmental protection, this article first seeks to illustrate the positive environmental impact of digital finance by demonstrating that higher economic efficiency, technological development, and education levels can reduce urban air pollution. This is because economic efficiency, technological development, and education are all crucial components in developing digital finance. To further investigate the environmental impacts of digital finance, this study examines the relationship between digital finance and urban environmental protection measures. Finally, this paper tries to utilize an instrumental variable approach to minimize potential endogeneity issues within the model, and uncover the true effects of digital finance on urban air pollution.

The framework shown in Figure 1 can be obtained by considering the above studies on the impact of environmental regulation, digital financial inclusion, and environmental pollution. Based on this fact, the following assumptions are proposed in this paper:

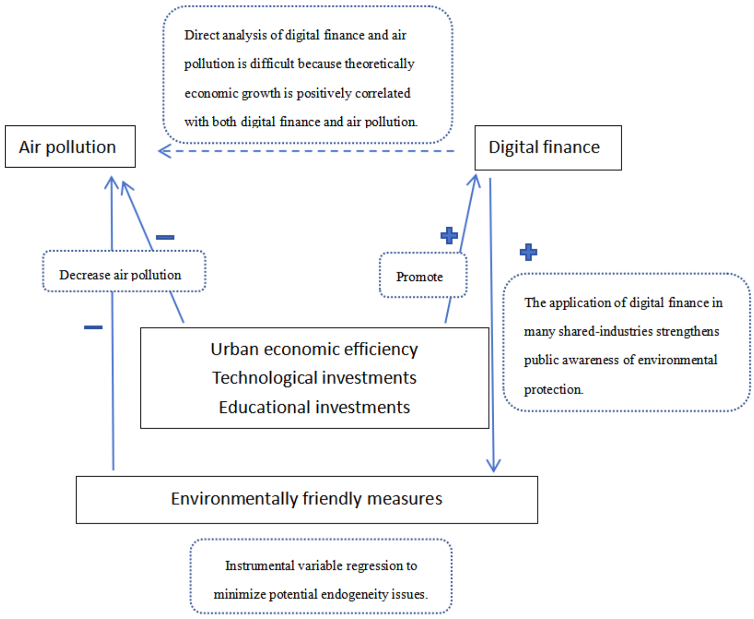

Figure 1. Theoretical framework of digital finance, economic efficiency, urban technological, and educational investments and environmental pollution.

3.1. Economic Efficiency and Air Pollution

The manufacturing industry typically emits more pollutants and consumes more energy compared to agriculture and the service industry. Consequently, regions heavily reliant on manufacturing may experience more severe air pollution [57]. Given that value-added tax primarily targeted the manufacturing sector before 2016 in China, and the secondary industry is predominantly manufacturing-oriented [58], regions with a higher proportion of value-added tax to GDP may face more significant air pollution challenges.

Hypothesis 1. *Cities with a higher proportion of value-added tax to GDP experience more severe air pollution.*

Similarly, compared to the service and agriculture sectors, the waste emissions produced by the secondary sector are evidently higher [59]. For example, CO_2 emissions from the secondary industry make up a large proportion of total CO_2 emissions in China, corresponding to 78.55% [60]. The proportion of the secondary industry in GDP will significantly increase PM2.5 emissions [61]. Therefore, a higher proportion of employment in the secondary industry, specifically in manufacturing, mining, and construction, signifies a greater dependence on manufacturing development, potentially leading to elevated levels of environmental pollution.

Hypothesis 2. *Cities with a higher proportion of employment in the secondary industry experience more severe air pollution.*

3.2. Urban Waste Treatment Efficiency and Air Pollution

Regions prioritizing pollution prevention and control tend to exhibit lower levels of air pollution [62]. Thus, cities with a higher centralized treatment rate for sewage treatment plants and a higher rate of harmless treatment for domestic waste demonstrate more efficient and effective waste management practices. This, in turn, reduces pollutant emissions and improves air quality.

Hypothesis 3. *Regions with a higher centralized treatment rate for sewage treatment plants and a higher rate of harmless treatment for domestic waste have better air quality, resulting in lower PM2.5 concentrations in the air.*

3.3. Technological and Educational Investments and Air Pollution

Technological advancements play a crucial role in mitigating air pollution [63]. Cleaner energy sources, improved industrial processes, and enhanced pollution control technologies have emerged as outcomes of technological development [64]. For instance, the implementation of advanced wastewater treatment systems and solid waste management techniques, driven by technological innovations, effectively reduces pollutants discharged into the environment [65], thereby minimizing air pollution.

Furthermore, higher levels of education among individuals contribute to increased environmental awareness and understanding [17]. Educated individuals are more likely to adopt environmentally friendly practices, support sustainable initiatives, and demand cleaner technologies [13]. Additionally, their involvement in sustainable development efforts can lead to reduced air pollution in cities.

Hypothesis 4. *Cities with higher technological and educational investments experience lower levels of air pollution and exhibit higher urban green coverage*.

3.4. Impacts of Digital Finance on the Environment

While the development of digital finance often coincides with the growth of urban economies and the manufacturing industry, it is important to note that regions with more developed economies and manufacturing industries tend to consume more energy and emit more pollutants, resulting in higher levels of air pollution [66]. However, this does not necessarily imply that the development of digital finance exacerbates urban environmental pollution. On the contrary, some studies suggest that capital markets react to environmental events, signaling a potential positive influence of digital finance on environmental performance [67,68].

Digital finance not only streamlines the lending process [69] but also extends its support to various environmental initiatives in urban areas, such as bike-sharing and car-sharing within the sharing economy [70]. These initiatives foster sustainable urban development and integrate environmental awareness into residents' daily lives, promoting greater adoption of eco-friendly behaviors [22]. Moreover, digital financial development will alleviate the financing constraints faced by enterprises in green technology innovation, thereby promoting green technology innovation [71]. Consequently, the development of digital finance has the potential to mitigate urban environmental pollution and enable cities to progress in a more sustainable manner. Inclusive digital finance plays a pivotal role in urban development by improving the environmental awareness of city governments and residents and allocating more resources to urban greening [72].

Hypothesis 5. *Cities with more advanced digital finance development exhibit higher urban green coverage.*

4. Research Design

4.1. Model Construction

This study employed a fixed effects model to investigate the relationship between variables while controlling for unobservable factors specific to each city and accounting for time-specific effects. This approach is commonly used in panel data analysis and allows for the examination of relationships across both time and individual entities, with individual fixed effects accounting for the variation between cities and year fixed effects controlling for common time trends.

The fixed effects model used in this study can be specified as follows:

$$PM2.5_{it} = \alpha_i + \gamma_t + \beta X_{it} + Control_{it} + \varepsilon_{it} \quad (1)$$

where $PM2.5_{it}$ denotes PM2.5 particles in the air ($\mu g/m^3$) for city i in year t. We focused on PM2.5 for several reasons. First, PM2.5 is a widely recognized and extensively studied air pollutant with well-documented adverse health effects [73]. In China, coal is used both industrially and domestically, and coal burning produces lots of PM2.5 every year, which may cause serious air quality problems [74]. When Chinese people or mainstream media discuss urban air pollution, they often refer to the PM2.5 indicator. Second, PM2.5 is often a major contributor to poor air quality in urban areas in China [75], making it a relevant and meaningful parameter to study. Third, there are more comprehensive and reliable data available for PM2.5, allowing us to conduct a robust analysis. Finally, the literature on the health and environmental impacts of PM2.5 is extensive, providing a strong foundation for our study [76–78].

X_{it} denotes the independent variables, including Value-Added Tax Ratio, Secondary Industry Employment Ratio, Profit over GDP, Public Fiscal Revenue over GDP, Centralized Treatment Rate of Sewage Plants, Harmless Treatment Rate of Household Waste, Technological Investment over GDP, Educational Investment over GDP, and the Digital Inclusive Finance Index (%). Detailed definitions of these variables are in Section 4.2.3 Variables. $Controls_{it}$ denote economic and environmental control variables described in Section 4.2.3, Variables; α_i denotes the individual fixed effect capturing city-specific unobserved heterogeneity; γ_t represents the year fixed effect capturing common time trends; β represents the estimated coefficients; and ε_{it} represents the error term. By including the city fixed effects, the model controls for time-invariant factors that may influence the relationship between the variables of interest.

All data processing and empirical analysis in this paper were conducted using the economics-specific statistical software, Stata 16. In this study, rigorous data cleaning and standardization processes were meticulously carried out to ensure the utmost reliability and consistency of the dataset. These processes involved a comprehensive examination of the data for outliers, missing values, and inconsistencies, which were subsequently addressed using established data cleaning techniques. Most variables were standardized as ratios to a common scale, facilitating meaningful comparisons and analysis across different measures. To ensure robustness, standard errors are clustered at the city level, allowing for potential correlations within the same city.

However, this reduced-form model still has some endogeneity issues: in cities with more advanced digital finance, the level of economic development and industrialization is typically higher, which can lead to higher levels of air pollution. However, it is important to note that this is not directly caused by the development of digital finance itself. Therefore, this paper use urban green coverage as an instrumental variable of digital finance.

Generally speaking, there is no direct relationship between urban green coverage and economic development. In addition, there is no doubt that urban greening is conducive to improving air quality. In recent years, digital finance has been applied in many environmentally friendly industries, like the bike-sharing industry, car-sharing industry, and so on; thus, the inclusive nature of digital finance can easily increase the environmental awareness of urban residents. Therefore, the development of digital finance may increase urban green coverage. Thus, it is appropriate to use urban greening as an instrumental variable for digital finance.

Before the IV regression, this paper first estimates the relationship of digital finance and urban greening. Then, this paper uses the green coverage rate in urban built-up areas as an instrumental variable for the Digital Inclusive Finance Index. The control variables are the same as model 1's.

4.2. Data

4.2.1. Sample Selection Criteria

The dataset used in this study comprises information on 290 prefecture-level cities in China over the period of 2011–2019. To make this analysis more robust and applicable to a broader range of urban settings, we selected 290 prefecture-level cities which represent a diverse cross-section of urban areas in China. Note that the 290 prefecture-level cities in our study already cover the vast majority of regions in China. A few cities had to be excluded from our analysis due to data limitations. We selected the majority of city samples based on the following reasons:

Geographic Diversity: To ensure a representative sample, cities were selected from different regions of China, including eastern, western, central, and northeastern regions. This geographic diversity was essential to capture variations in economic development, environmental conditions, and urbanization levels.
Economic Significance: We included cities that are economically significant and diverse, ranging from large metropolises to smaller urban centers. This allowed us to analyze a broad spectrum of urban economic activities and development patterns.
Availability of Data: Data availability was a crucial factor in city selection. We focused on cities for which comprehensive data on economic variables, environmental indicators, and digital finance development were accessible and consistent over the study period.
Socioeconomic Diversity: To account for socioeconomic diversity, we considered factors such as population size, income levels, and industrial composition when selecting cities. This ensured that our sample covered a wide range of urban characteristics.
Digital Finance Development: Given the focus on digital finance, cities with varying degrees of digital finance development were included, allowing us to explore its impact across different contexts.

4.2.2. Data Source

The data for this study were primarily obtained from the City Statistical Database of the China Research Data Services Platform (CNRDS-CCSD). This database provides comprehensive data on various aspects of Chinese cities, including economic, environmental, and social indicators. The data used in this study focused on the level of air pollution (PM2.5 concentration) and covered the time period from 2011 to 2019.

The digital inclusive finance index data used in this study were developed by Peking University to reflect the development of digital finance since 2011. The index was compiled by the joint research group composed of the Institute of Digital Finance of Peking University, Shanghai Finance Institute, and Ant Financial Services Group, based on the big data on digital inclusive finance from Ant Financial Services. This index system covers three dimensions of digital financial services: coverage breadth, use depth, and digital support services. Under the total index, there are six categories of sub-index: payment, insurance, monetary funds, investment, credit investigation and, credit. The index has three levels: province, municipality, and county. This paper mainly used the data at municipal level for regression analyses and used county level data for the robustness check. In addition, in the regression analyses, the digital finance development index that lagged two periods were adopted and all indexes were divided by 100.

4.2.3. Variables

1. Dependent Variable

We use the Annual Average PM2.5 Concentration ($\mu g/m^3$) to measure air pollution. The PM2.5 concentration data obtained from CNRDS-CCSD, were collected from atmospheric monitoring stations, meteorological bureaus, and other relevant institutions. The data underwent quality control and standardization processes, ensuring their reliability and accuracy. Annual average PM2.5 concentration data were used in this study, measured in micrograms per cubic meter ($\mu g/m^3$).

2. Independent Variables

Digital Finance: In this paper, digital finance refers to the Digital Inclusive Finance Index (%), which is measured by the Digital Finance Group of Peking University. The data contain three categories, which are as follows: digital inclusive finance coverage, usage depth, and digitization degree. In this article, the digital inclusive financial coverage and depth of use are the indicators reflecting its inclusive characteristics, and the degree of digitalization is the indicator reflecting its digital characteristics. The digital financial data used in this study covered the period from 2011 to 2019.

Economic Variables: Economic-related variables include the following: the proportion of annual profit income to GDP (Profit over GDP), the proportion of annual public fiscal revenue to GDP (Public Fiscal Revenue over GDP), the proportion of annual value-added tax revenue to GDP (Value-Added Tax Ratio), the proportion of employment in the secondary sector to total employment (Secondary Industry Employment Ratio), the proportion of annual technological investment to GDP in a city (Technological Investment over GDP), and the proportion of annual educational investment to GDP in a city (Educational Investment over GDP). These data, obtained from CNRDS-CCSD, originated from official statistical agencies such as the National Bureau of Statistics and local statistical bureaus.

Environmental Variables: Environmental governance-related data primarily include the centralized treatment rate of sewage treatment plants (%) and the harmless treatment rate of household waste (%). The centralized treatment rate of sewage plants refers to the proportion of urban sewage that is centrally processed by sewage treatment plants. The harmless treatment rate of household waste refers to the proportion of urban household waste that undergoes harmless treatment. These data are typically collected and reported by city environmental protection departments or relevant agencies, and they can be sourced from local government statistical yearbooks, environmental protection reports, and environmental monitoring data. Environmentally friendly measures includes urban green coverage area (hectare) and green coverage rate (%).

3. Control Variables

The control variable data encompassed various factors such as the comprehensive utilization rate of general industrial solid waste, the proportion of agricultural insurance premium income, the proportion of agricultural insurance claim expenditures, industrial smoke and dust emissions, the proportion of urban construction land to urban area, the proportion of tertiary sector employment, the proportion of enterprises with investments from Hong Kong, Macao, and Taiwan, the proportion of foreign-invested enterprises, the proportion of wholesale and retail trade sales profit from enterprises above a certain threshold, the proportion of total retail sales of consumer goods, the proportion of public fiscal expenditure, per capita regional GDP, regional GDP growth rate, and the proportion of the tertiary sector to regional GDP. These data were sourced from the National Bureau of Statistics, local statistical bureaus, and other relevant statistical institutions.

All data used in this study were publicly accessible official statistical data and were provided by research institutions, ensuring their credibility and accuracy. The specific data collection methods and statistical procedures can be referenced in the relevant documentation and explanations provided by the China Research Data Services Platform and the City Statistical Database. Before conducting the analysis, all data underwent preprocessing, cleaning, and standardization processes to ensure their reliability and consistency.

4.3. Descriptive Statistics

Descriptive statistics of the data are presented in Table 1. Table 1 shows that there is significant variation in PM2.5 concentration levels across different cities. There is also a regional imbalance in the development of digital inclusive finance in different cities. This is because of the regional imbalance of economic development in the country. Since the Digital Inclusive Finance Index starts from 2011, this variable has fewer observations.

Table 1. Statistical results.

	Variable Name	Obs	Mean	SD	Min	Median	Max
Dependent Variable	PM2.5 Annual Concentration (μg/m^3)	2367	38.471	16.433	3.210	36.090	86.740
Independent Variables	Value-Added Tax Ratio	2314	0.046	0.026	−0.005	0.041	0.550
	Secondary Industry Employment Ratio	2314	0.455	0.133	0.086	0.456	0.844
	Profit over GDP	2367	0.092	0.068	−0.185	0.081	1.221
	Public Fiscal Revenue over GDP	2367	0.070	0.026	0.021	0.066	0.238
	Centralized Treatment Rate of Sewage Plants	2232	75.928	20.011	0.160	82.725	100.000
	Harmless Treatment Rate of Household Waste	2181	86.231	21.480	0.440	95.320	362.000
	Technological Investment over GDP	2314	0.002	0.002	0.000	0.002	0.041
	Educational Investment over GDP	2314	0.030	0.013	0.003	0.027	0.097
	Digital Finance Index (%)	1349	131.482	48.977	23.100	134.740	246.919
Control Variables	Comprehensive Utilization Rate of Industrial Solid Waste	2314	81.658	21.330	0.490	90.795	100.000
	Emissions of Industrial Particulate Matter (Tons)	2314	33,625	0.001	49.000	19,730	5,168,812
	Agricultural Insurance Premium Income over GDP	2367	0.051	0.259	0.000	0.011	8.510
	Agricultural Insurance Payout over GDP	2367	0.030	0.154	0.000	0.006	5.366
	Urban Built-up Land Ratio to City Area	2367	9.070	9.795	0.120	5.590	97.180
	Secondary Industry Employment Ratio	2367	0.454	0.132	0.086	0.455	0.844
	Tertiary Industry Employment Ratio	2367	0.516	0.123	0.099	0.518	0.870
	Percentage of Hong Kong, Macau, and Taiwan Investment Enterprises	2367	0.046	0.068	0.001	0.022	0.540
	Percentage of Foreign Investment Enterprises	2367	0.045	0.046	0.002	0.031	0.326
	Wholesale and Retail Trade Profit Ratio for Above-Quota Goods	2367	0.354	0.322	0.000	0.256	3.497
	Total Retail Sales of Social Consumer Goods Ratio	2367	0.359	0.097	0.026	0.350	0.826
	Public Fiscal Expenditure Ratio	2367	0.162	0.076	0.044	0.147	1.485
	Per Capita Gross Regional Product (CNY)	2367	38,501	27,075	99	31,010	290,477
	Gross Regional Product Growth Rate	2367	11.474	4.532	−12.300	11.800	109.000
	Percentage of Tertiary Industry in Gross Regional Product (GRP)	2367	36.714	8.253	11.800	35.850	76.350

5. Empirical Results and Analysis

5.1. Urban Economic Efficiency and Air Pollution

The empirical analysis in Table 2 provides insightful results regarding the relationship between economic efficiency and urban air pollution. Firstly, cities with a higher proportion of value-added tax to GDP and a greater share of employment in the secondary sector demonstrate higher levels of air pollution, as shown in Columns 1–2 of Table 2. Notice that value-added tax primarily targets the manufacturing sector before 2016 in China, and the secondary industry is predominantly manufacturing-oriented. This association suggests that cities heavily reliant on manufacturing, known for its higher pollution emissions, tend to experience more severe air pollution.

Conversely, regions with higher economic efficiency, as indicated by higher annual urban profit and fiscal revenue over GDP, tend to have better air quality, as shown in Columns 3–4 of Table 2. This improvement can be attributed to a lower presence of low-efficiency manufacturing industries and a greater emphasis on technology-intensive industries, which often produce fewer pollutants. Additionally, the increased focus on environmental protection in high-income cities contributes to lower pollution levels. This finding highlights the potential for sustainable development strategies to mitigate air pollution.

Table 2. Urban economic efficiency and air pollution.

	(1)	(2)	(3)	(4)
	PM2.5 (μg/m^3)	**PM2.5 (μg/m^3)**	**PM2.5 (μg/m^3)**	**PM2.5 (μg/m^3)**
Value-Added Tax Ratio	14.962 ** (6.778)			
Secondary Industry Employment Ratio		8.850 * (4.843)		
Profit over GDP			−5.947 *** (2.283)	
Public Fiscal Revenue over GDP				−32.225 *** (11.925)
Comprehensive Utilization Rate of Industrial Solid Waste	0.003 (0.006)	0.006 (0.006)	0.004 (0.006)	0.005 (0.007)
Agricultural Insurance Premium Income over GDP	0.691 (0.951)	0.522 (0.957)	0.573 (0.963)	0.622 (0.946)
Agricultural Insurance Payout over GDP	−1.828 (1.723)	−1.665 (1.753)	−1.802 (1.768)	−1.862 (1.758)
Emissions of Industrial Particulate Matter (Tons)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)
Urban Built-up Land Ratio to City Area	0.013 (0.020)	0.015 (0.019)	0.013 (0.019)	0.014 (0.019)
Tertiary Industry Employment Ratio	2.899 (2.061)	10.671 ** (5.044)	1.887 (2.150)	1.966 (2.058)
Percentage of Hong Kong, Macau, and Taiwan Investment Enterprises	22.929 *** (5.923)	22.585 *** (6.186)	22.061 *** (6.100)	22.677 *** (6.299)
Percentage of Foreign Investment Enterprises	−27.490 ** (10.998)	−25.042 ** (11.102)	−28.448 ** (11.155)	−30.285 ** (11.746)
Wholesale and Retail Trade Profit Ratio for Above-Quota Goods	−0.516 (0.420)	−0.657 (0.410)	−0.721 * (0.415)	−0.729 * (0.401)
Total Retail Sales of Social Consumer Goods Ratio	4.885 ** (2.282)	5.358 ** (2.419)	4.554 * (2.321)	4.637 * (2.386)
Public Fiscal Expenditure Ratio	1.202 (2.220)	1.180 (2.119)	1.173 (2.083)	2.938 * (1.633)
Per Capita Gross Regional Product	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)
Gross Regional Product Growth Rate	−0.038 (0.034)	−0.043 (0.035)	−0.041 (0.034)	−0.040 (0.033)
Percentage of Tertiary Industry in Gross Regional Product	0.013 (0.038)	0.007 (0.045)	−0.012 (0.044)	0.005 (0.045)
Cons	39.027 *** (2.215)	30.963 *** (5.262)	41.225 *** (2.287)	41.619 *** (2.430)
City fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
N	2339	2339	2339	2339

Significance levels are * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$, indicating statistical significance at the 5%, 1%, and 0.1% levels, respectively.

In conclusion, our analysis of Table 2 highlights the intricate relationship between urban economic efficiency and air pollution. While manufacturing-intensive cities tend to experience higher pollution levels, economically efficient regions exhibit better air quality. This underscores the need for targeted pollution control measures in manufacturing-heavy areas and presents opportunities for sustainable development strategies to mitigate air pollution.

5.2. Urban Waste Treatment Efficiency and Air Pollution

The results in Table 3 demonstrate that cities with higher rates of centralized treatment for wastewater and harmless treatment for household garbage have lower PM2.5 concentrations in the air. This indicates that more effective measures in sewage and waste management lead to lower levels of environmental pollution. The findings support the conclusion that stronger pollution control efforts, as reflected in higher rates of wastewater and household waste treatment, result in lower air pollution levels. This highlights the importance of sustainable urban development and the need for effective pollution control measures. This also indicates that the application of waste treatment technology is important, and certainly will improve the efficiency of the waste treatment system.

Table 3. Urban waste treatment efficiency and air pollution.

	(1)	(2)
	PM2.5 (μg/m^3)	**PM2.5 (μg/m^3)**
Centralized Treatment Rate of Sewage Plants	−0.016 ** (0.007)	
Harmless Treatment Rate of Household Waste		−0.010 * (0.005)
Cons	41.486 *** (2.143)	40.603 *** (2.405)
Control Variables	Yes	Yes
City fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
N	2256	2206

Significance levels are * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$, indicating statistical significance at the 5%, 1%, and 0.1% levels, respectively.

To sum up, the results in Table 3 underscore the pivotal role of effective waste management in reducing air pollution. Cities with robust wastewater and household garbage treatment systems experience lower PM2.5 concentrations. This emphasizes the importance of pollution control efforts and sustainable urban development, supported by advanced waste treatment technology.

5.3. Technological and Educational Investments and Air Pollution

Advancements in technology increase economic efficiency and waste treatment efficiency in cities, leading to higher output and profitability, and also less air pollution [12]. Education is also important in promoting economic growth, urban digitalization, and environmental protection, because educated individuals possess the knowledge and skills necessary for innovation and productivity improvement, leading to enhanced economic performance [14]. In Table 4, technological and educational investments are both significantly negatively correlated with urban air pollution. These results are consistent with Hypothesis 4.

Notice that urban digital transformation heavily relies on the advancement of technology and the improvement of residents' digital literacy and learning ability. Thus, the findings about urban technological and educational investments are very important for us to understand the role of digital finance in coordinating economic development and environmental protection.

In summary, Table 4's findings highlight the positive influence of technological and educational investments on curbing urban air pollution. Technological advancements enhance economic efficiency and waste treatment, leading to reduced pollution. Concurrently, education fosters economic growth, digitalization, and environmental protection. These outcomes align with Hypothesis 4 and underscore the role of technology and education in achieving a balance between economic development and environmental protection.

Table 4. Technological and educational investments and air pollution.

	(1)	(2)
	PM2.5 (μg/m^3)	**PM2.5 (μg/m^3)**
Technological Investments	−122.070 * (70.062)	
Educational Investments		−107.375 *** (27.021)
Cons	37.560 *** (1.997)	39.573 *** (2.115)
Control Variables	Yes	Yes
City Fixed Effects	Yes	Yes
Year Fixed Effects	Yes	Yes
N	2346	2346

Significance levels are * $p < 0.05$, and *** $p < 0.001$, indicating statistical significance at the 5% and 0.1% levels, respectively.

5.4. *Digital Financial Development and Air Pollution*

The inclusion of digital finance in this study is motivated by its increasing importance and its potential role in shaping urban development. To explore the potential effects of digital finance in protecting the environment without sacrificing economic growth, this paper first analyzes the relationship between digital finance and urban area pollution.

As shown in Column 1 of Table 5, digital financial development is positively associated with air pollution. However, this result should be interpreted carefully. It does not imply that digital transformation in finance causes pollution in cities. It is often observed that, compared with cities in mountainous areas, agricultural regions, and tourist areas, cities with relatively advanced economies and manufacturing sectors, which are conducive to developing digital finance, tend to have more significant pollution. These cities possess the necessary industrial infrastructure and financial demand for developing digital finance. In other words, the air pollution is more likely to be driven by economic development, rather than digital financial development. This implies that this baseline result, though controlled for city and year fixed effects, still has a serious endogeneity issue. Therefore, further research is needed to establish a causal relationship.

Table 5. Digital financial development and the environment.

	Baseline Regression	**IV: First-Stage Regression**	**IV: Second-Stage Regression**
	(1)	**(2)**	**(3)**
	PM2.5 (μg/m^3)	Green Coverage Rate in Urban Built-up Areas	PM2.5 (μg/m^3)
Digital Inclusive Finance Index	0.136 *** (0.028)	0.159 *** (0.059)	0.029 (0.032)
Cons	32.856 *** (3.969)	22.091 *** (6.841)	- -
Control Variables	Yes	Yes	Yes
N	1374	1550	1362
Cragg-Donald F Statistic (Weak Identification Test)	-	-	39.532

Significance level is *** $p < 0.001$, indicating statistical significance at the 0.1% levels, respectively.

Generally speaking, there is no direct relationship between urban green coverage and economic development, but there is no doubt that urban greening is conducive to improving air quality. As the application of digital finance in many environmentally friendly industries, like the bike-sharing industry, car-sharing industry, and so on, demonstrates the inclusive nature of digital finance can easily increase the environmental awareness of urban residents. Therefore, the development of digital finance may increase urban green coverage. Therefore, it is appropriate to use urban greening as an instrumental variable for digital finance.

Before the IV regression, this paper first estimates the relationship of digital finance and urban greening. As shown in Column 2 of Table 5, digital financial development is significantly positively associated with green coverage rate in urban built-up areas. Then, this paper uses green coverage rate in urban built-up areas as an instrumental variable for the Digital Inclusive Finance Index. The IV regression result is shown in Column 3 of Table 5. After considering the endogeneity issue of digital finance, economic growth and air pollution, the relationship between digital finance and air pollution becomes negative, although statistically insignificant.

The empirical results in Table 5 suggest that the development of digital inclusive finance has a positive impact on the sustainable development of the urban environment: digital finance enhances residents' environmental awareness, promotes an increase in greening coverage, and therefore may contribute to the improvement of the urban environment.

In conclusion, our exploration of digital finance's impact on air pollution reveals a complex relationship. Although Column 1 of Table 5 suggests a positive link, this should be interpreted cautiously. Digital finance's association with economic development, rather than causing pollution, likely explains this result. Addressing endogeneity concerns, our analysis with urban green coverage as an instrumental variable suggests that digital inclusive finance may contribute to urban environmental sustainability by enhancing environmental awareness and increasing greening coverage. However, further research is essential to establish causal relationships accurately.

In summary, the empirical results of this study support Hypotheses 1 to 5, providing valuable insights into the potential effects of digital finance in protecting the environment without sacrificing the economic growth. These empirical findings provide valuable insights into the potential of digital finance to protect the environment while fostering economic growth.

6. Discussion

In previous sections, we have strived to enhance the reliability of our empirical results through a meticulous methodology, transparent discussions, and sensitivity analyses. While acknowledging the limitations, we believe that the empirical findings presented in this study offer insights into the relationships between various economic factors and urban air pollution. The following aspects were taken into consideration in this research:

Data Processing: We have provided detailed insights into our data collection and validation processes. This includes a description of the sources of our data and the measures taken to ensure data accuracy and consistency.
Robust Methodology: To ensure the reliability of our empirical results, we adopted robust methodological approaches. By employing a two-way fixed effects model and the instrumental variable regression, we aimed to mitigate potential endogeneity issues that could affect the causal interpretation of the relationships under examination.
Sample Representativeness: The robustness of our empirical findings is enhanced by the careful selection of our sample of Chinese cities. These cities represent a diverse range of economic and industrial characteristics, contributing to the generalizability of our results to similar urban contexts.
Variable Definitions and Measurement Units: We have elucidated the definitions of key variables in the "Data Source" subsection, ensuring the clarity and reliability of our measurements.
Discussion of Potential Biases: We acknowledge that certain biases might influence our empirical results. Notably, the positive correlation between digital financial development

and air pollution presented in the fixed effects model requires careful interpretation. Our analysis indicates that economic development, rather than digital finance itself, may be a driving factor behind air pollution in cities with advanced economies and manufacturing sectors. We tried to correct this bias by using an instrumental variable regression, and found that the correlation between digital financial development and air pollution became negative.

Comparison of Empirical Findings with Existing Research:

Our findings, as summarized in the empirical results section, offer valuable insights into the impact of digital finance on urban air pollution. Specifically, we find that digital financial development is significantly positively correlated with air pollution in our baseline results. However, when addressing endogeneity concerns through an instrumental variable (IV) approach, the relationship becomes negatively correlated, aligning with the conclusions of Ma et al. (2023) [52].

Moreover, our findings resonate with research by Fu et al. (2022) [49], who find that digital trade in goods and services, financial development, and green innovation contribute to long-term environmental sustainability. This synergy between digital finance and environmental improvement underscores the potential of digital finance to promote environmentally friendly measures and reduce air pollution.

The existing literature also presents diverse viewpoints on the environmental impact of financial development. While some studies, such as Tamazian et al.'s (2009) [42], suggest that higher degrees of economic and financial development decrease environmental degradation, others, including Shah et al.'s (2019) [43], Sehrawat et al.'s (2015) [44], and Carratù et al.'s (2019) [46], argue that financial development may contribute to increased carbon emissions and environmental degradation.

Notably, the relationship between financial development and environmental outcomes is intricate, as highlighted by Yin et al. (2019) [47] and Seetanah et al. (2019) [48]. These studies emphasize the need to consider various factors and dynamics, including the type of pollution and the specific context, when assessing the environmental impact of financial development.

Our study bridges this gap in the literature by systematically investigating the multifaceted relationship between digital finance, economic growth, and environmental protection. By utilizing an IV regression approach and accounting for time-invariant macro factors, we offer valuable insights into the complex and previously unexplored area of digital finance's environmental implications.

In summary, while there is a spectrum of opinions in the existing literature regarding the environmental consequences of financial development, our study contributes to this discourse by focusing on digital finance and using rigorous empirical methods. It underscores the potential of digital finance to align economic growth with environmental protection, emphasizing the importance of considering data quality and endogeneity concerns in empirical assessments. Our findings, though specific to the analyzed sample of Chinese cities, provide a valuable foundation for further research in this evolving field.

Limitations and Future Research: Despite our efforts to ensure the reliability of our empirical results, we acknowledge certain limitations inherent in our study. As with any empirical study, endogeneity concerns and potential unobserved factors might affect the causality interpretation of our findings. Therefore, further research using advanced methodologies, possibly incorporating longitudinal data and natural experiments, could shed additional light on the causal mechanisms at play.

We have strived to enhance the reliability of our empirical results through a meticulous methodology, transparent discussions, and sensitivity analyses. While acknowledging the limitations, we believe our study contributes insights into the potential impacts of digital finance on urban environmental protection. The specificity of our results to Chinese cities underscores the relevance of our findings in addressing the complex interplay between economic growth and environmental sustainability.

In addition, since our study primarily focused on Chinese cities, we must acknowledge that the political environment may have some influence on the issue of urban air pollution in Chinese cities. China is a vast and diverse country, with varying regional policies in politics, economy, and the environment. Therefore, some of our research results may be partially influenced by the local political context. For instance, in certain regions, the government may place a stronger emphasis on environmental protection policies, leading to lower levels of air pollution. Conversely, in other areas, economic development may take precedence, potentially resulting in higher pollution levels.

However, despite the potential influence of the political environment in some aspects, we emphasize that certain results are more universal and politically independent. For example, we observe a consistent positive correlation between economic efficiency and waste treatment efficiency with air quality. These findings may not only apply to China and may also have relevance to other countries and regions.

In addition, some of the results may possess broader applicability and serve as references for research and policymaking in other countries and regions. For instance, our findings indicate that effective wastewater and waste management measures can lead to reduced air pollution, which could be relevant to cities worldwide. Additionally, investments in technology and education have a positive impact on reducing air pollution, offering potential strategies for other nations to improve environmental quality.

However, it is crucial to note that each country and region faces unique environmental challenges influenced by various factors, including geography, politics, and economics. Therefore, when applying our research results to different contexts, further analysis and adaptability adjustments are necessary.

7. Conclusions

This empirical study embarked on a comprehensive exploration of the multifaceted relationship between digital finance, economic growth, and environmental preservation. We aimed to clarify the intricate dynamics and uncover insights that reconcile the apparent paradox where cities with advanced digital finance infrastructure sometimes experience higher levels of air pollution.

While it may seem logical that financial industries produce less pollution compared to secondary industries, our research unveiled a puzzling trend. In cities equipped with advanced digital finance infrastructure, we discovered that air pollution levels sometimes rise unexpectedly. This counter-intuitive phenomenon poses significant challenges when using conventional methods to assess the environmental impact of digital finance. This puzzling trend may largely be attributed to the fact that regions with advanced digital finance often have more significant urban industrial development, which can lead to increased pollution.

Since direct analysis of the environmental impacts of digital finance is challenging using standard economic model, we first try to show that the above factors can lower air pollution because economic efficiency, technological, and educational investments play essential roles in the development of digital finance [7,10,11]. To analyze how digital finance balances economic growth and environmental protection, we initially highlighted its positive environmental impact by demonstrating that higher economic efficiency, technological development, and education levels can reduce urban air pollution. Then we showed that, with the distraction of economic growth, which can increase air pollution and promote the development of digital finance at the same time, the relationship between digital finance and air pollution could be positive in our sample.

Lastly, it is important to address the initial positive correlation between digital financial development and air pollution. This association, which could be largely attributable to concurrent economic growth, necessitates a nuanced interpretation. To mitigate this apparent contradiction, we introduced urban greening as an instrumental variable for digital financial development. We used the instrumental variable model to try to reveal the real relationship between digital finance and air pollution, and found that they were negatively correlated in our sample.

In addition, the first-stage result of the instrumental variable regression reveals a positive association between digital financial development and greening coverage, indicating the potential of digital inclusive finance to enhance environmental awareness among residents. Although the second-stage regression did not achieve statistical significance, it indicated a negative correlation between digital financial development and air pollution. This implies that digital finance plays a role in alleviating the tensions between urban economic growth and environmental preservation, attributed to its inclusive nature.

Our findings provide substantial contributions and implications for various stakeholders:

Investors: Our research offers insights into the complex interplay between digital financial development and environmental factors. This knowledge is crucial for making informed and sustainable investment decisions in the evolving digital finance landscape.
Policymakers: Policymakers can use our insights to develop strategies and regulations that promote technology-driven, environmentally friendly economic growth. This can contribute to both economic prosperity and environmental protection.
International Markets: As digital finance transcends national boundaries, our study highlights the importance of considering the environmental footprint of international investments in regions with advanced digital finance. It encourages international markets to engage in dialogue and collaboration for responsible and sustainable economic development.

This study significantly contributes to the evolving field of digital technology for sustainable development by empirically evaluating the environmental impact of digital finance in regions characterized by advanced digital finance and high industrial development. Our research opens up new avenues for further exploration within the realm of digital finance's environmental implications.

In summary, our findings provide valuable insights into the intricate relationship between digital finance and environmental concerns. They align with the broader discourse on digital technology, which aims to harness both incremental and radical digital innovations to offer solutions for sustainable development in organizations and society as a whole. Policymakers and stakeholders should acknowledge the potential of digital financial development as a catalyst for sustainable practices and allocate resources accordingly to safeguard our environment for future generations.

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