



Digital Technology Innovation and High-Quality Economic Development in China's Resource-Based Cities: A Panel Data Analysis

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Abstract. Urban economy has gained rapid traction following the rise of digital technology innovation with its “green technology attribute”. However, leveraging such innovation has remained a critical challenge for resource-based cities that heavily rely on a single industrial structure and consume significant resources for energy. The current study empirically examined the relationship between digital technology innovation and the high-quality economic development using the panel data of 111 resource-based cities in China from 2012 to 2021. Heterogeneity analysis was also performed to examine how the hypothesized impact affect different city types. Empirical analyses confirmed that the high-quality economic development of resource-based cities was significantly and positively impacted by digital technology innovation. Results also showed significant heterogeneity of impact at different development stages from declining and growing cities to regenerating and mature cities, and the substantial positive moderating role of investment in science and technology(S&T). The robustness and absence of potential endogeneity issues of the derived results were validated accordingly. This study proposed several evidence-based policy recommendations for high-quality economic development: (1) leverage digital technology innovation to promote differentiated green transformation; (2) optimize policy support mechanisms with increased investment in science and technology; (3) implement differentiated digital technology development strategies according to local conditions.

Keywords: Digital Technology Innovation; Resource-based cities; high-quality economic development; investment in S&T

1 Introduction

Resource-based cities mainly function to produce and export products based on their available resources. The resource development and utilization, land use characteristics, and evolution patterns distinguish these cities from non-resource-based cities. Resource-based cities are crucial parts of the urban ecosystem and largely reliant on the availability of natural resources like coal, forests, and oil. This has unfortunately led to the overexploitation of these valuable resources, resulting in their continuous decline

[1]. Natural resource extraction and processing activities are highly prevalent in these cities for industrial development, putting them at prominent risks of imbalanced industrial structure, slow economic growth, and deteriorating environmental quality [2]. The development of mines, depletion of natural resources, and diminishing marginal benefits have significantly affected their socioeconomic development. Critical environmental pollution and energy resource depletion would greatly hamper the cities' economic development—and China is a prominent case of this.

With the global transformation of economy towards digitalization and intelligence, digital technology innovation has recently emerged as a significant breakthrough for resource-based cities. These cities are propelled to leverage digital technology innovation, which can help to optimize traditional industrial processes, promote efficient resource consumption, and facilitate the rise of new industries [3]. With that goal in mind, a regional coordinated development strategy was proposed in the report of the 19th National Congress of the Chinese Communist Party (CCP). Resource-based industries are mostly at the lower end of the industrial chain, possessing low profit margins, inadequate capital returns, and stagnant economic performance. Moreover, most of these resource-based cities encounter talent recruitment problems and weak labour force innovation due to their remote locations .

With the same goal of realizing high-quality economic development, the subsequent report in the next annual congress underscored the combination of digital economy and real economy by highlighting digital technology as a technical means to boost China's digital economy, which is now ranked second globally. Despite that, unlike Western developed countries like the United States, China encounters certain limitations in its core digital innovation fields, such as chip manufacturing, high-end Computer Numerical Control (CNC) machine tools, and quantum information. The inclusion of China's leading digital corporations, such as Huawei and iFlytek, in the United States' list of technological embargoes since 2019 has severely impacted the country's development of digital economy. Addressing this technological blockade in key areas, there have been several initiatives launched to promote digital technology innovation in China. In February 2023, the CCP Central Committee and State Council issued the "Overall Layout Plan for the Construction of Digital China" as part of the country's efforts to level up and become the world's forefront in digitalization development by 2035 through the formation of Digital China.

There are varied interpretations to what high-quality development reflects, which typically includes socioeconomic growth. Resource-based cities feature unique economic development given its dependence on conventional energy sources like coal and oil. As a result, these cities experience critical environmental pollution. The increase in coal consumption in resource-based cities further aggravates environmental pollution. Considering this critical period for China, these cities should consider leveraging digital technology innovation to address the issues and challenges encountered in terms of resource consumption and environmental quality.

Numerous studies focused on the impact of digital transformation, instead of digital technology innovation, on economic growth. Wu et al. (2021) highlighted the conceptual difference between both aspects of digitalization [4]. Digital transformation fea-

tures digital technology implementation, whereas digital technology innovation emphasizes new technological breakthroughs. Digital development process offers conducive infrastructure and digital platforms that allow the sharing of information, resources, and technology, boosting the economic resilience of the neighbouring regions [5]. Besides that, corporations can enhance their core competitiveness and R&D investment through digital transformation, which subsequently strengthen digital technology innovation [6]. Additionally, digital policies can benefit the urban economy by propelling the digital transformation of traditional industries [7]. Studies have also observed significantly lower green innovation costs and enhanced green innovation capacity for resource-based cities due to digital economic growth [8]. Hence, digital technology technically supports digital transformation, with digital innovation process driving the positive impacts of digital transformation.

Despite the extensive empirical studies on digital technology innovation, only a few studies explored its impact within the context of resource-based cities. Unlike general technology innovation, digital technology innovation features more distinct attributes, such as significant investment and risk and long cycle. Digital technology innovation holds promising prospects for resource-based cities in China to realize their high-quality economic development. This has raised several pertinent questions, particularly in regards of the role of digital technology innovation in facilitating high-quality economic development for cities with a single development structure and high energy consumption and emissions [9], which was addressed in this study. Focusing on these resource-based cities, the current study empirically examined the impact of digital technology innovation on high-quality economic development and the moderating role of investment in Science and Technology (S&T) on this relationship. This study also examined this relationship at different stages of development. Findings would significantly enriched the literature and benefit policymakers and other key stakeholders in resource-endowed regions.

2 Literature Review

2.1 Digital Technology Innovation And Economic Development of Resource-Based Cities

Research on the impact of digital technology innovation on resource-based cities' economic development and environmental quality remains inconclusive. A majority of studies, including Balsalobre-Lorente et al. (2023), Wang et al. (2023), Zhu et al. (2023), and Peng and Anthony (2024), confirm that digital technology innovation promotes energy efficiency, reduces carbon emissions and resource consumption, empowers traditional industries (e.g., smart mining, smart manufacturing), and fosters new industries (e.g., big data, cloud computing), thereby driving economic growth and green transformation of resource-based cities [8][10][11][12]. Liu et al. (2024) further verified that industrial robots, a typical digital technology application, significantly improve energy efficiency and reduce carbon emissions. At the industrial and energy levels, digital technology innovation provides resource-sharing platforms and promotes renewable energy application, respectively, further reinforcing its positive effects.

However, opposing views exist: Xue et al. (2022) found that new digital infrastructures (e.g., 5G base stations, big data centres) increase carbon emissions and energy consumption, deteriorating environmental quality [13]. Additionally, despite its economic advantages, digital technology innovation faces weak coordination with resource-based cities' economic development [14].

Heterogeneity in the impact of digital technology innovation across different development stages of resource-based cities has also been highlighted. Si et al. (2024) noted that digital technology innovation drives green economic growth in growing and mature resource-based cities, serves as a "rescue transformation" for declining ones, and differs in application focus across stages (e.g., emerging industries for growing cities, traditional industry empowerment for mature ones) [15]. Zhou et al. (2024) and Xu and Cai (2024) supplemented that digital infrastructure investment and digital platform economy alleviate economic contraction in declining cities and promote transformation in regenerative ones, respectively [16][17]. Yang et al. (2024) further clarified the driving factors for each city type, while differences in digital infrastructure, talent mobility, and policy support lead to varying degrees of digital dividend release across cities [18].

2.2 Digital Technology Innovation, Investment in Science and Technology, and Economic Development of Resource-Based Cities

Investment in science and technology (S&T) is indispensable for digital technology innovation and the economic development of resource-based cities. R&D investment and human capital accumulation positively drive S&T innovation and enhance the innovation capacity of resource-based cities [19]. Governmental expenditures on education and science optimize innovation resource allocation and improve regional technology supply capacity in these cities. Regions with advanced S&T capabilities (equipped with complete R&D institutions, talent training systems, and innovation platforms) better absorb and transform digital technologies into economic growth engines [20], while regions with insufficient S&T investment often experience weakened innovation effects. Xu and Cai (2024) found that S&T input exerts the most significant positive direct and indirect impacts on regenerating resource-based cities [13], and empirical evidence confirms that high S&T investment strengthens the relationship between digital technology innovation and urban economic development [14].

3 Model Construction, Variable Selection, and Data Description

3.1 Baseline Models

With respect to the objectives of this study, a time and region two-way fixed effects model was constructed for the panel data of 111 resource-based cities between 2012 and 2021:

$$HQD_{it} = \alpha_0 + \alpha_1 DTI_{it} + \sum \alpha_j CONTROL_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (1)$$

where HQD_{it} denotes the city's high-quality economic development; α_0 , α_1 , and α_j represent parameters to be estimated; DTI_{it} denotes digital technology innovation; $CONTROL_{it}$ denotes a series of control variables; μ_i represents the region fixed effects; δ_t represents the time fixed effects; ε_{it} refers to the random disturbance terms.

Investment in S&T in this study was examined as a moderator using the following constructed model:

$$HQD_{it}=\beta_0+\beta_1DTI_{it}+\beta_2SCI_{it}+\beta_3DTI_{it}*SCI_{it}+\sum\beta_jCONTROL_{it}+\mu_i+\delta_t+\varepsilon_{it} \tag{2}$$

where β_2SCI_{it} denotes the level of investment in S&T; $\beta_3DTI_{it}*SCI_{it}$ denotes the interaction term between investment in S&T and digital technology innovation; $\beta_0,\beta_1,\beta_2,\beta_3,\beta_j$ denotes the parameters to be estimated.

3.2 Variable Selection

Referring to Han and Wei (2024) and Ran et al. (2024), DTI_{it} , which served as this study's explanatory variable, was measured in terms of the number of digital patent applications [21] [22]. This study first determined the industry to which each digital patent belongs to by referring to the Reference Relationship Table of International Patent Classification and National Economic Industry Classification (2018) issued by the State Intellectual Property Office of the People's Republic of China. Following that, the relevant digital economy patents were matched to the Statistical Classification of the Digital Economy and its Core Industries 2021 issued by the National Bureau of Statistics of the People's Republic of China. The calculation step ultimately involved obtaining the original digital economy patents (invention and utility model patents) through the described steps and statistically determining the application and authorization of the city's digital economy patents.

The comprehensive index of high-quality economic development of resource-based cities HQD_{it} served as this study's core explained variable. Given the absence of a unified measurement standard to measure this variable, this study referred to the study of Liu et al. (2021) to develop a comprehensive evaluation indicator system (Table 1)[23]. The entropy method for measurement was adopted.

Table 1. Evaluation Indicator System for High-Quality Economic Development of Resource-Based Cities

Target Layer	Level 1 Indicators	Level 2 Indicators	Level 3 Indicators	Property
Index of high-quality economic development	Innovative development	Investment in S&T	Investment of science and education (in %)	Yes
			Investment in education (in %)	Yes
	Coordinated development	Patent level	Patent acquisition (in number)	Yes
		Financial growth	Balance of financial deposits/loans (in %)	Yes
			Unit per capita income (in RMB)	Yes
		People's livelihood		

Target Layer	Level 1 Indicators	Level 2 Indicators	Level 3 Indicators	Property
			Non-real estate investment/fixed assets (in %)	Yes
		Industrial structure	Share of tertiary sector (in %)	Yes
		Foreign investment	Foreign capital utilization (in USD billions)	Yes
	Open development		Gross output of foreign-owned enterprises (in billions)	Yes
		Foreign enterprises	Number of foreign-owned enterprises (in number)	Yes
			Industrial wastewater discharge (in tonnes/million)	No
		Waste emissions	Industrial SO ₂ emissions (in tonnes/million)	No
	Environmental development		Industrial fume (dust) emissions (in tonnes/million)	No
			Comprehensive general industrial solid waste utilization rate (in %)	Yes
		Pollutant treatment	Centralized sewage treatment plant rate (in %)	Yes
			Non-hazardous domestic waste treatment rate (in %)	Yes
			Number of physicians (per 10,000 people)	Yes
	Shared development	Social welfare	Wages (in RMB)	Yes
			Urban greening ratio (in %)	Yes
		Consumption	Social retail goods consumption (in %)	Yes
		Government burden	Fiscal expenditure (in %)	Yes

Meanwhile, the level of investment in S&T represented this study's moderator. Referring to Jiang et al. (2024), this moderator was measured in terms of the proportion of expenditure for S&T investment to the expenditure for the general public budget[5]. Additionally, this study incorporated several control variables, including the degree of government intervention (Govtin), which was measured in terms of the share of local government fiscal expenditure to GDP [24]. Secondly, openness to the outside world (Openw), which was measured as the ratio of regional exports to GDP, served as one of this study's control variables. Openness to the outside world fosters the sharing of knowledge and technology and stimulates digital technology innovation [21]. Another control variable in this study was the urbanisation level (Urban), which was measured as the ratio of urban population to the total population [2]. Besides that, human capital (Humanc) served as a control variable given the significance of highly skilled and innovative talents in shaping China's high-quality economic development, supported by the accumulation of human capital. This variable was measured as the ratio of students enrolled in colleges and universities in each region to the total number of students in

that region[21]. The final control variable included in this study involved the Internet penetration rate (Intr). It was measured as the ratio of the number of Internet users to the number of resident population, reflecting the capacity and level of informatisation [21].

3.3 Data Description

Data from the National Sustainable Development Plan for Resource-Based Cities were obtained. It should be noted that, in December 2018, the administrative division adjustment adjusted Laiwu City to Laiwu District and Gangcheng District in Jinan City. The former name (Laiwu City) was employed in this study.

This study included the following mature resource-based cities ($n = 59$): Anshun, Baise, Baoji, Baoshan, Benxi, Bozhou, Changzhi, Chengde, Chenzhou, Chifeng, Chizhou, Chuzhou, Datong, Daqing, Dazhou, Dongying, Ezhou, Ganzhou, Guang'an, Guangyuan, Handan, Hebi, Hechi, Heihe, Hengyang, Huainan, Huzhou, Jilin, Jincheng, Jining, Jinzhong, Jixi, Linfen, Longyan, Loudi, Lüliang, Mudanjiang, Nanping, Panzhihua, Pingdingshan, Pingliang, Sanmenxia, Sanming, Shaoyang, Suzhou, Tai'an, Qujing, Weinan, Xingtai, Xinzhou, Xuancheng, Ya'an, Yangquan, Yichun, Yuncheng, Yunfu, Jinan, Zhangjiakou, and Zigong.

The following regenerating resource-based cities ($n = 15$) were included in this study: Anshan, Baotou, Huludao, Lijiang, Linyi, Luoyang, Ma'anshan, Nanyang, Panjin, Suqian, Tangshan, Tonghua, Xuzhou, Zhangye, and Zibo.

Selected growing resource-based cities ($n = 14$) that were included in this study are as follows: Hezhou, Hulunbeier, Liupanshui, Nanchong, Ordos, Shuozhou, Songyuan, Qingyang, Wuwei, Xianyang, Yan'an, Yulin, Longnan and Zhaotong.

Finally, this study included the following declining resource-based cities ($n = 23$): Baishan, Baiyin, Fushun, Fuxin, Hegang, Huaibei, Huangshi, Jingdezhen, Jiaozuo, Liaoyuan, Luzhou, Pingxiang, Puyang, Shaoguan, Shizuishan, Shuangyashan, Tongchuan, Tongling, Qitaihe, Wuhai, Xinyu, Yichun, and Zaozhuang.

3.4 Data Source

The National Sustainable Development Plan for Resource-Based Cities (2013–2020) listed 262 resource-based cities in China, including 126 prefectural-level administrative districts. However, there were critically insufficient data for the Daxinganling region, Altay region, and eight autonomous regions. Laiwu City was part of Jinan City in 2019, while the former county-level Bijie City was renamed as Qixingguan District under the new prefecture-level Bijie City in 2011. There were also critically insufficient data for Longnan. Thus, Laiwu City, Longnan City, Bijie City, and Tongling City were not part of the analysis. The final list only contained 111 resource-based prefectural-level cities for analysis. China's Statistical Yearbook, Urban Statistical Yearbook, National Bureau of Statistics, regional statistical yearbooks, Industrial Statistical Yearbook, Tertiary Industry Statistical Yearbook, Environmental Statistical Yearbook, as well as the official website of the Ministry of Industry and Information Technology (MIIT) and the China Data Service Platform (CNRDS) were referred to for the main data. Considering the

aspect of data availability, this study only included data of 111 resource-based prefecture-level cities between 2012 and 2021. In addition, linear interpolation method was employed for individual missing data. The descriptive results are summarised in Table 2.

Table 2. Descriptive Results of Variables

Variables	Number of Observations	Mean	Standard Deviation	Minimum Value	Maximum Value
HQD	1221	0.0013447	0.0007989	0.0002043	0.0053727
DTI	1221	7.161989	1.948839	3	13.74252
Openw	1221	0.0148844	0.0167422	$1.85e^{-06}$	0.1343093
Urban	1221	0.5383283	0.1381006	0.1815	0.9588
Humanc	1221	127.8133	128.3878	2	1141
Govtin	1221	0.2214491	0.1045735	0.0438815	0.7410996
Intr	1221	224.9134	1271.247	1.82926	35517.96

4 Results and Discussion

4.1 Regression and Heterogeneity Tests

Referring to Table 3, DTI significantly and positively influenced HQD in Model (1). Model (2) incorporated control variables. The results revealed the statistically significant increase in the composite index of HQD by 0.0000893 with every 1% increase in DTI. With that, H1 was supported.

Table 3. Baseline Regression Model Results

Variables	Model (1) (HQD)	Model (2) (HQD)
DTI	0.000107*** (6.02)	0.0000893*** (5.16)
Openw		0.00749*** (7.35)
Urban		0.000187 (0.92)
Humanc		$5.78e^{-08}$ (0.37)
Intr		$4.44e^{-09}$ (0.58)
Govtin		-0.00125*** (-5.52)
_cons	0.000801*** (7.85)	0.000919*** (6.26)
N	1221	1221
R ²	0.4997	0.5215
CITY-Fixed Effects	YES	YES
YEAR-Fixed Effects	YES	YES

Notes: *t*-statistics in parentheses; * denotes < 0.05 ; ** denotes < 0.01 ; *** denotes < 0.001 .

Moreover, DTI in Model (1) recorded significantly higher regression coefficient at 0.000107 than Model (2), which implied the overestimation of its positive impact in the absence of the control variables. In Model (2), the statistically insignificant but positive

effects of Openw, Urban, Humanc, and Intr indicated their strong contributions to DTI. The insignificant outcomes further implied their limited effects on the HQD. It may require a longer period of time or a combination of other salient factors to exert more pronounced impact. On the other hand, Govtin recorded statistically significant, negative coefficient, which suggested its dampening effect on the impact of DTI on HQD. This may be attributed to the dependence of these cities on the utilization of natural resources and excessive government interventions, distorting the allocation of these resources. The government may have invested substantial financial capital and human capital in certain resource development projects through administrative means but overlooked other more promising industries or technology innovation domains. As a result, resources are not optimally utilized, inhibiting the impact of DTI on HQD.

As previously noted, these resource-based cities are at different development stages with different resource reserves, industrial structures, and development challenges. These resource-based cities were first classified into growing, mature, declining, and regenerating types based on the issued National Sustainable Development Plan for Resource-Based cities (2013-2020). These development stages were combined, and group regression and other relevant tests were performed. Results in Table 4 showed statistically significant and positive impact of DTI on HQD in all four models representing different city types. The impact was the strongest in declining resource-based cities, followed by growing, regenerating, and mature resource-based cities. Thus, H2 was supported. The reason for this may be that declining cities usually face the problems of population loss, industry shrinkage and resource depletion, and digital technology innovation can activate new economic growth points, such as artificial intelligence or software development to empower digital industries and replace traditional resource-based industries. Growing cities may face rapid population growth, insufficient resources and management pressure in the process of development. Digital technology innovation can lead high-end industrial agglomeration and accelerate the transformation of growing cities into innovation-driven economies. Regenerative cities are usually in the process of transitioning from resource-based or industrial to green and service-oriented, and digital technology can be realised to promote the reuse of resources, optimise the efficiency of urban operations and achieve the goal of a circular economy. The key task for mature cities is to maintain competitive advantage and innovation vitality, and digital technology innovation can further consolidate their position in the global high-end industrial chain.

Table 4. Heterogeneity Test Results

	(Growing) Model (1) HQD	(Mature) Model (2) HQD	(Declining) Model (3) HQD	(Regenerating) Model (4) HQD
DTI	0.0000443** (2.72)	0.000205*** (14.89)	0.0000602*** (4.00)	0.000206*** (5.90)
Openw	0.00636** (2.96)	0.0113*** (8.20)	0.00849*** (4.46)	0.00111 (0.47)
Urban	0.0000747 (0.40)	-0.00101*** (-4.63)	0.000191 (1.11)	-0.00259*** (-5.65)
Humanc	0.000000355	0.000000840***	-0.000000133	0.00000273***

	(Growing)	(Mature)	(Declining)	(Regenerating)
	(1.90)	(5.32)	(-0.49)	(4.40)
Intr	-5.52e ⁻⁰⁹	-9.27e ⁻⁰⁸	3.15e ⁻⁰⁹	-0.000000236
	(-0.71)	(-1.95)	(0.12)	(-1.67)
Govtin	-0.000528**	-0.00225***	-0.00158***	-0.00658***
	(-2.88)	(-8.95)	(-6.25)	(-8.54)
_cons	0.000764***	0.000588***	0.000899***	0.00255***
	(5.75)	(4.20)	(5.47)	(5.77)
N	168	708	276	180
R²	0.2444	0.5070	0.3630	0.6223

Notes: *t*-statistics in parentheses; * denotes < 0.05; ** denotes < 0.01; *** denotes < 0.001.

Besides that, the model incorporated the interaction term of DTI and SCI (SCI*DTI) to determine the moderating effect of the level of investment in S&T on the relationship between digital technology innovation and high-quality economic development of resource-based cities. As shown in Table 5, DTI recorded positive coefficient at 0.000107 and SCI*DTI recorded positive coefficient at 0.00102. SCI*DTI recorded statistically significant and positive coefficient, reflecting its significant and positive moderating effect. With that, H3 was supported. Higher investment in S&T offers more financial and resource support, boosting the R&D of digital technology innovation. Drawing more investment in R&D, particularly in frontier digital technology fields like artificial intelligence, big data, and Internet of Things, would further accelerate the process of digital technology innovation, optimizing and upgrading the industrial structure of resource-based cities. Through digital technology innovation, traditional resource-based industries can gain intelligent and green transformation with lower resource consumption and environmental pollution without compromising production efficiency.

Table 5. Moderating Effect of Level of Investment in S&T

	Model (1) (HQD)
DTI	0.0000703*** (4.09)
Interaction (SCI*DTI)	0.00102*** (6.84)
Openw	0.00696***((6.95)
Urban	0.000220 (1.10)
Humanc	5.24e ⁻⁰⁸ (0.34)
Intr	5.75e ⁻⁰⁹ (0.76)
Govtin	-0.000989*** (-4.38)
_cons	0.000905*** (6.30)
N	1221

Notes: *t*-statistics in parentheses; * denotes < 0.05; ** denotes < 0.01; *** denotes < 0.001.

These results may have been contributed by population loss, industry shrinkage, and resource depletion in declining resource-based cities. Through digital technology innovation, new economic growth points, such as artificial intelligence or software development, are stimulated, empowering digital industries and revolutionizing traditional resource-based industries in these cities. Meanwhile, growing resource-based cities often encounter rapid population growth, lack of resources, and management pressure.

Digital technology innovation stimulates high-end industrial agglomeration and accelerate the transformation of these cities into innovation-driven economies. In contrast, regenerating resource-based cities are often in the transition from resource-based (or industrial) to green and service-oriented. With digital technology innovation, the resources in these cities can be optimized for reuse. The efficiency of their urban operations can be optimized as well. This drives their goal of achieving a circular economy. Lastly, mature resource-based cities can reestablish their position in the global high-end industrial chain through digital technology innovation, maintaining their competitive advantage and innovation vitality.

4.2 Endogeneity and Robustness Tests

Considering the possible occurrence of endogeneity issues, this study opted for the instrumental variable method. Referring to Hong et al.(2024), digital technology innovation lagged by one period (IV-DTILAG) served as one of the key variables. In addition, surface and terrain feature variables were identified as another key variables. This selection was due to the distinctiveness of surface and terrain features, as exogenous variables, from the economic system, satisfying the exogeneity requirement and relevance of these key variables—the construction of digital infrastructure is more convenient in regions with lower topographic relief, contributing to the development of digital technology innovation [5].

Table 6 presents the endogeneity test results through the two-stage least squares (2SLS) method for two key variables, which reaffirmed the statistically significant and positive impact of DTI on HGD. The results also confirmed the robustness of the results, as the instrumental variables passed the under-identification and weak key variable tests. Based on the regression coefficients, the statistically significant and positive outcomes in the second stage of regression (inclusion of key variables) validated the prior results. The results of Kleibergen-Paap rk LM and Cragg-Donald Wald F statistics also confirmed the feasibility of these key variables.

Table 6. Endogeneity Test Results

	Instrumental Variable 1		Instrumental Variable 2	
	(1) First Stage	(2) Second Stage	(3) First Stage	(4) Second Stage
DTI	0.000115** (3.21)	0.000190*** (17.70)	0.000179*** (17.26)	0.000401*** (4.84)
Control variables	YES	YES	YES	YES
IV-DTILAG	0.0000709* (1.98)			
IV-STCV			2.06e-09** (3.10)	
_cons	0.000365** (3.16)	0.000313** (2.67)	0.000314** (2.71)	-0.00113* (-1.96)

Kleibergen-Paap rk LM	3.92078 ($p = 0.0477$)		9.60922 ($p = 0.0019$)	
Cragg-Donald Wald F	13660.3 (16.38)		26.1027 16.38	
N	1221	1221	1221	1221
R²	0.46	0.46	0.4617	0.2588
Adjusted R²	0.46	0.45	0.4586	0.25

Notes: t -statistics in parentheses; * denotes < 0.05 ; ** denotes < 0.01 ; *** denotes < 0.001 .

This study removed extreme variables for 1% shrinkage (Model (1)), incorporated control variables (Model (2)), and changed the regression method (Model (3)) to validate the impact of DTI on HQD. As shown in Table 7, the results of Model (1) revealed the consistency and robustness of the explanatory variables after shrinking the core variables. After the addition of control variables, the results of Model (2) demonstrated the consistency of DTI as a significant feature on HQD. The regressed results of Model (3) using OLS confirmed the robustness of the obtained results on the positive impact of DTI on HQD.

Table 7. Robustness Test Results

	Model (1) HQD1	Model (2) HQD1	Model (3) HQD1
DTI	0.0000876*** (5.20)	0.0000574** (3.24)	0.000302*** (23.11)
Openw	0.00722*** (7.20)	0.00696*** (6.92)	0.00531*** (5.26)
Urban	0.000187 (0.93)	0.0000933 (0.46)	0.000505*** (3.76)
Humanc	5.34e ⁻⁰⁸ (0.35)	0.000000121 (0.79)	0.000000100 (0.68)
Govtin	-0.00124*** (-5.53)	-0.000403 (-1.54)	-0.000234 (-1.13)
Intr	4.14e ⁻⁰⁹ (0.55)	4.31e ⁻⁰⁹ (0.57)	-6.17e ⁻⁰⁹ (-0.46)
gdp		0.000414*** (6.41)	
infrastructure		-0.000000617 (-1.08)	
_cons	0.000929*** (6.49)	-0.00328*** (-4.86)	-0.000564*** (-4.19)
N	1221	1221	1221
R²	0.4603	0.3998	0.4574

Notes: t -statistics in parentheses; * denotes < 0.05 ; ** denotes < 0.01 ; *** denotes < 0.001 .

5 Conclusions and Recommendations

Overall, this study presented demonstrated that digital technology innovation did exert substantial and positive impact on the high-quality economic development of 111 resource-based cities between 2012 and 2021. Besides that, this study empirically proved the varying impact of digital technology innovation at different development stages. The impact was found to be the most pronounced in declining resource-based cities, followed by growing, regenerating, and mature resource-based cities. Thirdly, this study empirically proved investment in S&T as a moderator in this relationship. All results were validated through multiple robustness tests.

Findings provided significant evidence-based guidance to resource-based cities globally, especially in China, in realizing sustainable development. This study proposed several evidence-based policy recommendations. Firstly, it is evident that these cities should be aware of their substantial reliance on natural resources and proactively shift their focus to embracing a more sustainable approach due to the finite availability of resources and the critical environmental issues. These cities should strategically leverage digital technology innovation to transform towards high-quality economic development. For instance, the government can allocate more resources and support to boost S&T and R&D in these cities. Increasing such investment can be particularly beneficial for cities with relatively weak resource endowments. Related policies should be strategically designed according to the local potentials and conditions and take into account the differentiated transformation paths in order to stimulate urban restructuring and industrial remodeling. Adequate resources should also be strategically allocated for these cities to construct optimal innovation environment. The integration of innovation bodies encourages businesses, universities, and research institutions to collaborate and transfer knowledge and innovation. The necessary support should also be provided for the construction of S&T parks, R&D platforms, and other carriers. Through these approaches, R&D activities for the development and application of digital technology innovation can be adequately supported. It should also be part of the national and market resources through multi-level and multi-disciplinary innovation exploration and in-depth integration of digital technology innovation with diverse needs of cities. In order to address the critical challenges of resource depletion and ecological degradation, all these efforts can be strategically emulated in other resource-based cities globally towards the realization of sustainable, low-carbon transformation paths in a timely manner.

Secondly, resource-based cities should embrace differentiated development strategies of digital technology innovation by taking into account their local conditions. For instance, the critical challenges of resource depletion and weak industrial base encountered by declining resource-based cities reflect untapped opportunities for digital technology innovation. These cities should prioritize digital transformation of traditional resource-based industries, developing new data-driven service industries and smart manufacturing industries, and exploring the innovative development model of resource-technology-service integration. These strategies ensure the development of new economic growth points, breaking away from the single dependence on natural resources.

Meanwhile, growing resource-based cities typically feature relatively weak digital technology innovation foundation, with their low technology penetration rate and flawed innovation system. This also reflects substantial potential for development. The allocated support should be optimized and leveraged to accelerate the construction of 5G, artificial intelligence and big data infrastructure for digital technology innovation. Successfully improving the innovation system can help revive these cities and their S&T innovation, which subsequently cultivate the digital industry chain and guide more social capital to be part of the digital transformation. These cities can strategically break away from “resource-driven” to “technology-driven”. As for regenerating resource-based cities, which already have certain foundation in place for industrial transformation and digital technology, these cities must strengthen their policy support and institutional supply to further release the potential of digital technology innovation. The development of a fair and transparent digital market environment, enhanced intellectual property protection, and expanded cross-border convergence applications, such as industrial Internet, smart cities, and green energy networks, should be prioritized. These measures provide a new impetus towards realizing sustainable development for these cities. Last but not least, apart from strengthening their efficiency of resource allocation, mature resource-based cities should drive in-depth integration of digital technology innovation with high-end manufacturing and modern service industries and enhance their industrial competitiveness despite their relatively perfect industrial system and digital technology ecosystem. Their inter-city digital innovation cooperation should be further strengthened as well. Besides that, these cities should consider establishing a cross-regional data element circulation mechanism and a new type of urban growth pole centred on digital innovation for the continuity and leadership of high-quality development.

Thirdly, industrial upgrading, which necessitates the advancement of S&T, helps cities to achieve high-quality economic development. The government should strengthen their policy guidance, increase investment in S&T R&D for industrial technological change, and guide resource-based cities towards a green and efficient development track. Priorities should be given to efforts of promoting green technology innovation and guiding innovation bodies to boost their R&D and application of green technology. Allocating special funds for green technology, the provision of R&D loans, and the reform of the resource tax system can enhance the effectiveness of policy support. Local governments should actively lead innovation, establish a favourable innovation-friendly institutional environment, boost their investment in S&T, and leverage collaboration for more efficient governance and market. Technological advancement itself will, in turn, promote the optimization of industrial structure. As businesses and cities with advanced digital technology innovation are more likely to attain competitive advantage and achieve breakthrough in this increasingly competitive market, it is pivotal that scientific research institutions accelerate the pace of innovation and transformation to cope with the industrial demand, strengthen the implementation of scientific and technological achievements, and promote scientific and technological advancement for the high-quality development of the regional economy.

6 Directions for Future Research

Addressing the limitation of this study of considering only digital technology patents despite the significance of other aspects (e.g., digital technology R&D investment, digital technology patent output, digital infrastructure construction, and digital applications), future research should considering gathering more comprehensive data for a more accurate representation of digital technology innovation quantitatively. Besides that, future research should consider exploring the firm level for more comprehensive insights on this phenomenon, as this study empirically explored resource-based cities at the city level only.

Acknowledgements

This study did not receive any funding

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