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Digital innovation, institutional environment and air quality improvement

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The advancement of digital innovation has provided new perspectives for promoting green and sustainable development. This study examines data from 285 prefecture-level cities in China between 2015 and 2022 to systematically investigate the impact of digital innovation on air quality improvement, with a specific focus on the moderating role of institutional environment in the relationship between digital innovation and air quality enhancement. The findings reveal that the development of digital innovation has a significant positive effect on air quality improvement, a conclusion that remains robust after a series of robustness tests. Mechanism analysis indicates that digital innovation can improve air quality through channels such as optimizing industrial structure, increasing government expenditure on energy conservation and environmental protection, promoting green technology advancement, and facilitating the development of digital finance. Heterogeneity tests demonstrate that the air governance effect of digital innovation is more pronounced in central cities, large-scale cities, and cities with higher levels of education investment. Further analysis shows that the institutional environment can amplify the positive impact of digital innovation on air quality, particularly in regions with well-developed institutional environments, such as cities with sound market mechanisms, favorable financial innovation conditions, and high economic openness. Therefore, it is essential to strengthen the foundation of digital innovation and optimize the support of institutional environment to improve air quality.

KEYWORDS

digital innovation, institutional environment, air quality, industrial structure upgrading, governmental energy-saving and environmental protection financial expenditure, green technology advancement, digital financial development

1 Introduction

Against the severe backdrop of intensifying global climate change and tightening resource constraints, urban air quality, as the most direct reflection of public wellbeing, has become one of the core issues in global environmental governance. In 2015, the United Nations adopted the 2030 Agenda for Sustainable Development, explicitly proposing SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action), identifying air quality improvement and climate action as common goals for the international community. Recently, China has successively introduced a series of policies such as the *Air Pollution Prevention and Control Action Plan*, the *Three-Year Action Plan for Winning the Blue-Sky Defense War*, and the *Air Quality Continuous Improvement Action Plan*, gradually establishing a systematic and multi-phase air pollution governance system aimed at

achieving environmental quality improvement. In the face of the mounting global climate crisis and growing resource constraints, air quality, as the most tangible reflection of people's wellbeing, has undoubtedly become a central concern for global sustainable development. Despite the implementation of a series of policies aimed at improving atmospheric pollution, their effectiveness remains unstable, with frequent occurrences of severe pollution events, leaving the task of atmospheric pollution prevention and control still daunting. Current end-of-pipe treatment policies tend to focus on mitigating and handling the effects of pollutants that have already been produced, ensuring compliance with environmental quality standards. However, their limitations cannot be ignored, such as the fact that flue gas desulfurization and dust removal generate a large amount of waste residue, and centralized wastewater treatment results in substantial sludge, etc. If these wastes are not managed appropriately, they can still lead to secondary pollution. Coupled with the complexity and dynamism of air pollution transmission, the governance efforts often require substantial investment in human resources, material resources, and financial capital. This inevitably adds to the economic burden of enterprises, thereby dampening their enthusiasm for environmental protection, ultimately leading to suboptimal remediation outcomes. In order to improve air quality more effectively and address ecological environmental issues at their root, thereby realizing harmonious and sustainable growth that balances economic development with environmental protection, it is high time to open up a new track for governance.

At present, digital technology innovation represented by a new generation of artificial intelligence is driving the accelerated evolution of the global scientific and technological revolution and industrial change, and deeply reshaping the global governance system. Driving ecological civilization construction with digital innovation has emerged as a critical path and practical necessity for promoting green economic and social development. Through the deep integration of digitalization and greenification, we can achieve efficient utilization of energy resources, optimization and upgrading of industrial structures, and green transformation of consumption patterns, thereby promoting the sustainable development of the entire socio-economic system.

Therefore, how to seize the major opportunities presented by digital innovation to improve air quality, and delve into its underlying mechanisms and impact channels in depth with persistence, while infusing a strong and enduring source of momentum for green and sustainable economic and social development, has become a crucial and urgent theoretical and practical question of our time.

For an extended period, there have been ample discussions surrounding digital innovation. Yoo et al. (2010) defined digital innovation as the recombination of digital and physical components to produce new products. Barrett et al. (2015) argued that digital innovation is driven by digital technologies, marking a transition from a socio-technical structure predominantly characterized by non-digital tools. Abrell et al. (2016) similarly defined digital innovation as "the creation of new combinations of digital and physical components" in order to produce novel products and services. They emphasize that digital innovation is about the creation of new product forms and diversified services through the integration of various sources of digital data, with a focus on

innovation at both the product and service levels. Building on this foundation, Nambisan et al. (2017) further expanded the concept of digital innovation, which they define as the process of creating market products, business processes, or models through the use of digital technologies and the subsequent changes they bring. These changes encompass both innovations and conversions achieved by leveraging digital technologies and infrastructures to realize a series of outcomes such as products, platforms and services, as well as the emphasis on the externalities of digital innovation, which refer to the changes in socio-technical-social-technical environments brought about by the development of digital innovation.

Generally speaking, digital innovation stands as a unique form of innovation, relying on the integration of digital technologies and physical components to generate new digital objects. It encompasses not only advancements in information technology, such as innovations in digital technology products, but also transformations in the nature and structure of products and services, thereby giving rise to new goods, new services, or new business processes and organizational forms within industries driven by digital technology (OECD, 2016; Kollock et al., 2018; Antonopoulou and Begkos, 2020; Hund et al., 2021). In light thereof, digital innovation holds significant importance for the societal and economic functioning, with its impact gradually seeping into every facet of economic development. Existing literature has revealed that the development of digital technologies expands the boundaries of value creation (Huang Q. et al., 2023), contributing positively to corporate performance (Liu et al., 2023) and high-quality development, and has also positively discussed its impact on regional innovation and entrepreneurship development (Smith et al., 2017), urban resilience (Oikonomou et al., 2023), structural transformation (Acemoglu and Restrepo, 2018), and social welfare (Aceto et al., 2018).

In the current landscape, scholars are commencing an exploration of the issue of green development within the context of digital innovation. Notably, the development of the digital economy has a significant inhibitory effect on local environmental pollution (Shin and Choi, 2015). Additionally, the development of financial technology (Chiu and Lee, 2020) and digital finance (Elheddad et al., 2020) is recognized as an important force in promoting green development, as it directs social financial capital towards environmental protection by providing innovative financial products and services, such as green bonds and green loans. Moreover, scholars have taken digital trade development as a starting point to empirically test its positive role in pollution control (Zhang and Liu, 2022).

Furthermore, the literature on digital innovation promoting sustainable development spans numerous disciplines and fields, aiming to address environmental challenges. Traditionally, social science literature has largely regarded environmental governance as the responsibility of institutional governance and economic behavior (Huang X. et al., 2025; Zhu and Chen, 2025). However, with the advancement of digital technology, innovations such as digital twins, artificial intelligence, big data, and the Internet of Things (IoT) are reshaping the logic of urban spatial governance (Weil et al., 2023). These technologies not only enable the analysis of massive datasets and identification of complex patterns through the development of machine learning models and artificial neural networks—thereby facilitating evidence-based solutions in areas

such as resource allocation, infrastructure development, traffic optimization, pollution prevention and control, energy management, and biodiversity conservation (Demirci et al., 2019; Wang and Srinivasan, 2017)—but also signify a profound transformation in governance models. More specifically, digital technologies are driving the evolution of urban governance toward a “data-driven ecosystem” (Allam and Dhunny, 2019). For instance, digital twin technology enhances the interoperability of various urban functions—including economic operations, government administration, urban planning, healthcare, and public welfare—by analyzing urban data and simulating urban development trajectories. This improves the predictability of governance decisions and provides technology-driven solutions for creating efficient and sustainable urban environments (Ferré-Bigorra et al., 2022; Huang J. et al., 2025).

However, while the application of big data and artificial intelligence enhances governance efficiency, it also introduces new challenges such as algorithmic opacity, data privacy, cybersecurity, and the digital divide (Kitchin, 2016; Nishant et al., 2020). More notably, digital technologies themselves and their applications entail new economic and environmental risks. On one hand, training and operating large-scale AI models consume substantial energy, potentially leading to significant carbon emissions (Kunkel and Matthes, 2020); on the other hand, the proliferation of digital technologies exacerbates interregional “digital divides” and economic disparities. Under the inertia of “growth-first” thinking, some local governments may compromise long-term sustainability goals for short-term economic gains, resulting in insufficient enforcement of environmental regulations or continued support for high-pollution industries. Therefore, the improvement of air quality through digital innovation is not merely a process of technological application, nor is its impact on environmental governance realized in an isolated or vacuum-like context. Rather, it constitutes a governance restructuring process deeply embedded in specific socio-institutional and political-economic contexts.

Especially under China’s current active pursuit of dual objectives—economic growth and environmental sustainability—a unique pathway of “ecological modernization” has emerged. This implies that when examining the environmental benefits of digital innovation, its interaction with complex economic contexts must be carefully considered. In light of this, this study incorporates institutional environment factors into the analytical framework when exploring the relationship between digital innovation and air quality improvement, attempting to answer a core question: Does the air quality improvement effect of digital innovation vary significantly under different institutional environments? This exploration aims to provide a more comprehensive, dialectical, and contextualized analytical perspective for understanding the governance effectiveness of digital innovation.

In summary, although the existing literature offers important references for this study, there remains a notable lack of studies focused on the effects of digital innovation on environmental impacts, particularly its impact on air quality improvement. At the same time, there is also a scarcity of literature that explores the impact of digital innovation on air quality improvement from the perspective of the institutional

environment. In this regard, the potential innovations of this study reside primarily in the following:

Firstly, from the perspective of digital innovation, this study integrates digital innovation and urban air quality within a cohesive analytical framework, employing a more comprehensive air pollution indicator to systematically investigate the environmental impacts of digital innovation. Simultaneously, by introducing the moderating role of urban institutional environment, it transcends the dualistic analysis model of technological development and environmental governance, offering new insights for understanding the governance efficacy of digital innovation. Secondly, this study delves into the black box of how digital innovation affects air quality, thoroughly exploring the specific mechanisms through which digital innovation contributes to air quality improvement. Furthermore, it examines the heterogeneous effects of digital innovation on air quality improvement from various dimensions, such as urban functional positioning, scientific and educational levels, and city size, revealing the varying effects that digital innovation may produce in diverse urban contexts, which increases the practical interpretability and policy relevance of the research findings. Thirdly, technological advancements consistently reshape governance models and refine institutional environments, while a favorable institutional environment in turn creates greater space and possibilities for technological innovation. Therefore, incorporating the urban institutional environment into the analytical framework not only broadens the research scope of digital innovation and air quality, but also contributes to understanding the core question of “how institutional environment empowers digital innovation to unleash environmental benefits.” It provides new empirical evidence and theoretical support for constructing an institution-technology collaborative governance model to achieve green and sustainable development.

2 Theoretical analysis and research hypotheses

2.1 Theoretical and mechanism analysis of digital innovation development affecting regional air quality

Digital innovation, as the leading force behind technological revolution and industrial transformation, demonstrates immense potential in the field of ecological conservation due to its high innovativeness, strong penetration, and wide coverage. On one hand, digital innovation inherently possesses green and environmentally friendly attributes, reducing pollution generation at its source by optimizing resource allocation and enhancing energy efficiency. On the other hand, digital innovation provides new approaches and methodologies for environmental protection by being embedded in every stage of environmental governance. Specifically, in the monitoring and perception phase, digital innovation facilitates the shift from “passive response” to “real-time perception” in environmental data collection. Technologies such as IoT sensors and visualization form ecological monitoring and early warning mechanisms (Hampton et al., 2013), enabling real-time tracking of pollution emissions and providing high-

precision, round-the-clock data foundations for environmental governance, thereby curbing pollution in a timely manner. In the diagnosis and analysis phase, digital innovation drives the transformation of environmental problem resolution from “vague inference” to “precise traceability.” Technologies such as big data analytics and cloud computing enable in-depth mining and correlation analysis of massive monitoring datasets (Klievink et al., 2017), which not only allows for rapid identification of pollution sources but also facilitates model-based analysis of pollution causes. This enhances the accuracy of environmental quality assessments and provides a scientific foundation for shifting from addressing symptoms to tackling root causes. In the decision-making and optimization phase, digital innovation supports the evolution from “experience-based judgment” to “intelligent simulation” in environmental governance strategies. Artificial intelligence (AI) algorithms and digital twin technologies allow the construction of real-time dynamic prediction models for urban air quality, simulating and evaluating the costs and benefits of different governance measures (e.g., staggered production in key industries, traffic flow optimization) (Liu et al., 2021), significantly enhancing the scientific rigor and foresight of environmental governance decisions. In the implementation and supervision phase, digital innovation promotes the shift from “manual supervision” to an “intelligent closed-loop” approach in environmental governance. The immutability and traceability of blockchain technology ensure the authenticity of monitoring data, while smart contracts are applied to scenarios such as green subsidies and carbon emission quota trading, achieving automated and transparent policy execution (Saber et al., 2019). Simultaneously, AI technologies can be embedded into industrial production processes to enable intelligent green manufacturing with energy conservation and consumption reduction, thereby reducing pollution emissions. In summary, through deep integration with all stages of environmental governance, digital innovation breaks down barriers between the environmental governance sector and the technology supply sector. It promotes the modernization of environmental governance, not only improving the efficiency and precision of environmental protection but also providing core technological support for sustained air quality improvement.

In addition to its direct impacts, digital innovation can also contribute indirectly to the improvement of air quality by optimizing industrial structure, increasing government fiscal support, promoting green technological advancements, and developing digital finance. In the first place, digital innovation improves air quality by upgrading industrial structures. On one hand, digital innovation aids in the adoption of more advanced and environmentally-friendly production techniques and processes within traditional industries, leading to a significant reduction in pollutant emissions. For instance, in the manufacturing sector, through the introduction of smart manufacturing systems, Internet of Things technologies, and big data analytics, businesses are able to achieve refined management of their production processes, this, in turn, reduces resource consumption and waste emissions. Likewise, in the energy sector, digital innovation promotes the development and deployment of clean energy solutions, such as the intelligent management and coordination of renewable resources like wind and solar power, ultimately

resulting in decreased greenhouse gas emissions and a decline in pollutants. On the other hand, digital innovation offers powerful technical support and fertile ground for the emergence and growth of green industries. Simultaneously, the establishment of digital platforms opens up vast space for the development of green products and services, thereby expanding the green consumer market and ultimately igniting the innovative vitality of the green industry. Thus, digital innovation, through continuous optimization of industrial structure layout and configuration, facilitates a comprehensive upgrade in terms of technology levels, product value-added, and production efficiency across diverse industries. This process fosters the emergence of numerous new industries characterized by high resource utilization rates and low pollution and emissions, and ultimately paves the way for the establishment of a vibrant, innovative, and environmentally sustainable modern industrial system. This industrial system, harnessing its dynamic innovation mechanism and green development orientation (Chen et al., 2020), continuously makes strides in the direction of greater environmental friendliness and efficiency, thereby realizing a green value-added increase in its performance that effectively contributes to regional air quality improvement.

In the second place, government fiscal support for environmental protection plays a pivotal role in air quality improvement. This support is further bolstered by the burgeoning development of digital innovation, which exerts several positive impacts on local government expenditure on energy conservation and environmental protection. On the one hand, digital innovation has broadened fiscal space, thereby enabling local governments to allocate more financial resources to environmental initiatives. The surge in digital industries, such as e-commerce and cloud computing, has spurred the growth of a series of related industries, thereby generating significant economic value and boosting government tax revenue substantially. Moreover, the adoption of digital management tools has improved the government's administrative efficiency and resource allocation capabilities, optimized the structure of financial expenditure and ensured the judicious use of limited financial resources simultaneously. On the other hand, digital innovation has improved the digital regulatory capacity of government departments (Janowski, 2015; Katsonis and Botros, 2015), and the advancement in regulatory capacity allows them to make more scientific and rational decisions grounded in comprehensive monitoring and analysis of ecological environment by utilizing big data technologies. Consequently, governments are able to allocate and utilize environmental protection funds more accurately to maximize the benefits derived from their expenditures on environmental protection (Hampton et al., 2013). Due to the substantial positive externalities associated with non-economic expenditures, effective government spending on energy conservation and environmental protection not only directly tackles pollution emissions but also encourages and scales up clean production practices. And then this accelerates a green transformation of society, facilitates shifts in production methods and lifestyles, and ultimately contributes to significant reduction in pollution emissions, thereby effectively enhancing air quality.

In the third place, digital innovation improves air quality by driving green technological advances. Digital innovation has accelerated the process of green technological progress. The

spillover effect of digital innovation has provided a remarkable opportunity for heavily polluting enterprises to develop and apply green technologies, such as carbon emission monitoring technologies, energy-saving and emission reduction techniques, and other advanced technologies and practices. The implementation of these advanced means is capable of promoting the transition of production patterns towards low-carbon and intelligent operations, thereby contributing to a decrease in industry carbon intensity. In tandem, the technological impact of digital innovation has accelerated the development of green technologies within resource-intensive enterprises. These green technologies, including intelligent photovoltaic power plants and remote monitoring systems for wind farms, have not only boosted the efficiency of energy resource utilization but also markedly reduced pollution emissions. In addition, the platform effect of digital innovation speeds up the introduction of eco-friendly consumer goods into the market, such as green building materials and biodegradable materials, and other eco-friendly consumer goods. The widespread dissemination and sales of them cater to consumers' escalating demand for environmentally friendly options. This shift in market demand, in turn, ignites enterprises' enthusiasm for developing eco-friendly technologies, fostering a virtuous cycle of green technological innovation that ultimately enhances overall green technological levels. Green technology advancement exerts a significant inhibitory effect on air pollution (Braungardt et al., 2016). This is due to the fact that, as the level of green technology innovation improves, the efficiency of resource utilization is greatly enhanced. This improvement not only leads to a direct reduction in local pollution emissions but also has a positive spillover effect on neighboring areas, as noted by Zhang et al. (2022). Consequently, the overall air pollution control effectiveness for the entire region can be comprehensively improved.

Finally, digital innovation plays an important role in advancing the development of digital finance to combat environmental pollution. Digital innovation propels the transformation of traditional finance, gradually giving rise to new financial models, notably digital finance. Not only does digital finance, as a newly emerging sector, maintain the core strengths of traditional finance, but it also achieves the intelligent upgrade and wisdom-oriented transformation in financial services through leveraging technological innovations, breaking geographical and temporal constraints while significantly enhancing processing speed and responsiveness. As a consequence, it greatly enhances the accessibility and efficiency of financial services. Digital finance plays an active role in environmental pollution management. On the one hand, as a resource-efficient and environment-friendly financial service, digital finance significantly optimizes business processes and substantially reduces resource consumption. On the other hand, the rapid development of digital finance injects new vitality and momentum into financial activities that aim to support the green development of the real economy. It achieves this through several key avenues: firstly, by providing a variety of personalized green financial products such as green bonds, green credit, green funds, green insurance, and other green financial instruments (Ran and Zhang, 2023), it provides strong financial support for the development of environmental protection projects and the green industries in order to make concerted efforts to cut carbon emissions, reduce pollution, pursue green development, and

boost economic growth; secondly, it utilizes digital technology to precisely pinpoint green investment opportunities (Gomber et al., 2018), guides the flow of social capital towards projects that offer both environmental benefits and economic returns, thus realizing the optimal allocation of resources; thirdly, the extensive development of digital financial platforms has profoundly transformed residents' lifestyles, significantly heightened public awareness of environmental protection and ecological issues, actively encouraged the public to embrace green consumption habits, and effectively fostered a societal pattern of participating in environmental protection, thereby making a vital contribution to the improvement of air quality.

Based on the above theoretical analysis, the following hypotheses are proposed:

H1: Digital innovations are conducive to reducing pollution generation to improve air quality.

H2: Digital technology positively impacts air quality through optimizing industrial structure, increasing government energy conservation and environmental protection expenditures, advancing green technologies, and developing digital finance.

2.2 Analysis of the moderating effect of the institutional environment

Both neoclassical growth theory and new growth theory concur that technological progress is the primary impetus behind the sustained economic growth of a country or region. However, the pace and characteristics of technological progress are affected by the institutional structure that supports it, while these institutions also exert a significant constraint on how new technologies can be successfully integrated and absorbed into the economic system (Nelson, 2002). In the digital era, with the continuous upgrading and breakthrough of digital technological innovation, the increasing optimization of the mode of knowledge production, the optimization and reorganization of factors of production, and the continuous emergence of new phenomena, an effective and continuously evolving institutional arrangement can be crucial in provide dynamic support for the evolution of the digital innovation economic system (Jovanovic et al., 2021).

First of all, a highly marketized environment tends to pay more attention to the protection of intellectual property rights and to providing robust innovation policy support, and also usually has higher resource allocation efficiency, which can stimulate the digital innovation vitality of the market entities and accelerate the transformation and application of digital technological innovation results in the practice of improving air quality. Secondly, the level of financial innovation serves as a potent driving force for digital innovation. Regions with a higher level of financial innovation incline to possess more developed financial markets, richer financing channels, and more professional risk management tools, which provide more ample financial support and effective risk mitigation for digital innovation, thereby guaranteeing the sound and healthy development of digital innovation activities. The “symbiotic” effect of financial and digital innovations has invigorated the research and development of environmentally

friendly technologies, optimized the energy structure, decreased pollution and carbon emissions, and ultimately contributed to the improvement of air quality. Finally, the degree of economic openness reflects the depth of a city's integration into the global market, and variations in openness lead to differing external institutional environments across cities (Sun et al., 2024). As a key institutional factor, it effectively transforms global knowledge resources into local innovation advantages and, through competition incentives and standard leadership, significantly enhances the efficacy and speed of digital innovation in improving air quality. On the one hand, economic openness facilitates technology spillovers and knowledge diffusion, introducing internationally advanced green production technologies, clean manufacturing processes, and cutting-edge environmental governance concepts. On the other hand, the competition effect brought about by foreign investment compels domestic enterprises to accelerate the enhancement of their digital innovation capabilities and environmental performance, amplifying the “pollution halo effect” (Bu et al., 2019) and further strengthening the application depth of digital innovation in emission reduction. Furthermore, economic openness promotes the alignment of environmental information disclosure, compliance management, and regulatory standards with international norms, urging local governments to improve environmental regulations, data sharing mechanisms, and emission monitoring systems. Such “institutional convergence” reduces institutional friction in the application of digital technology innovations in environmental governance, ensures the emission reduction effects of digital innovation, and ultimately contributes to the continuous improvement of air quality.

Based on the above theoretical analysis, the following hypothesis is proposed:

H3: The institutional environment plays a positive moderating role in the implementation of digital innovation to improve air quality.

3 Research design

3.1 Data

Given that the Air Quality Index (AQI) has only achieved full coverage of air quality monitoring in each city in China since 2015, for the purpose of ensuring both continuity of observation time and the availability of the data, this paper selects the relevant data of 285 prefectural-level cities (except for Hong Kong, Macao, and Taiwan as well as the Tibet Autonomous Region) for the period spanning from 2015 to 2022 as the research sample for conducting empirical tests. The data covered in this paper come from several reliable channels, including: *Chinese Urban Statistical Yearbook*, *Chinese Urban Construction Statistical Yearbook*, *statistical yearbooks of provinces and cities*, *statistical yearbooks of prefectures and cities*, *statistical bulletins*, *government websites*, *Chinese Research Data Services Platform (CNRDS)*, *Peking University's Digital Inclusive Finance Index (2011–2022)*, Zhang et al., 2024, and the *National Urban Air Quality Real-Time Release Platform*. For a few missing data points, linear interpolation is used to fill in the blanks.

3.2 Methodology

In order to examine the impact of digital innovation level on air quality, this paper establishes the following panel date regression model:

$$Y_{it} = \alpha_0 + \alpha_1 di_{it} + \alpha_2 Controls_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (1)$$

in Formula 1, i and t denote city and year respectively, Y_{it} is the dependent variable, denoting the air quality index (AQI) of city i in year t , and di_{it} is the core explanatory variable, denoting the digital innovation index of city i in year t . $Controls_{it}$ stands for a vector set of control variables. μ_t denotes the year fixed effect, λ_i represents the area fixed effect, α_0 is the intercept term, and ε_{it} is the error term.

Moreover, to delve deeper into the underlying mechanism of digital innovation's impact on urban air quality, this study adopts Dell's (2010) approach to mechanism testing. Based on the baseline regression model (1), this study conducts an in-depth analysis of the effects of core explanatory variables on mechanism variables, while also considering the impact of these mechanism variables on the dependent variables, as previously illustrated in this article through theoretical analysis and literature reviews. Consequently, on this foundation, the following model is established to examine the mechanism pathway through which the level of digital innovation development influences urban air quality:

$$M_{it} = \beta_0 + \beta_1 di_{it} + \beta_2 Controls_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (2)$$

in Formula 2, M_{it} represents the mechanism variable, which encompasses industrial structure upgrading, government financial support for environmental protection, green technology advancement, and digital financial development respectively according to the analysis above, and the definitions of the rest of the variables are consistent with those specified in the aforementioned model (1).

3.3 Variables

3.3.1 Dependent variable

The dependent variable is air quality (AQI), measured by the annual average air quality index. The Air Quality Index (AQI) is a comprehensive indicator for evaluating the extent of air pollution, covering the concentrations of major air pollutants such as fine particulate matter (PM_{2.5}), respirable particulate matter (PM₁₀), sulfur dioxide (SO₂), nitrogen dioxide (NO₂), ozone (O₃), carbon monoxide (CO) and other pollutants, which provides a more comprehensive portrayal of the air pollution situation. A higher AQI value indicates higher concentration of air pollutants, which subsequently results in more severe pollution and poorer air quality. Since sulfur dioxide is one of the prominent atmospheric pollutants, this paper draws on previous research (Wang Y. et al., 2016) to use industrial sulfur dioxide emissions as a proxy for the dependent variable air quality for robustness testing.

3.3.2 Core explanatory variable

The core explanatory variable is the level of digital innovation (di). Patents, as an important manifestation of innovation results, serve as a common indicator for assessing the level of innovation.

TABLE 1 Results of baseline regression.

Variables	(1)	(2)	(3)
	y	y	y
di	−1.419***	−1.508***	−1.578***
	(−3.20)	(−3.46)	(−3.26)
phone			0.045
			(0.90)
hc			−0.004
			(−1.13)
urban			−0.079*
			(−1.84)
ed			0.489***
			(3.19)
road			−4.111
			(−1.22)
fdi			−0.037
			(−0.37)
Constant	67.268***	79.790***	82.152***
	(151.78)	(233.39)	(32.46)
Year FE	N	Y	Y
City FE	N	Y	Y
Observations	2,280	2,280	2,280
R-squared	0.004	0.757	0.760

*, **, *** represent significance levels at 10%, 5%, and 1%, respectively, with t-values in parentheses.

Therefore, in the core areas of digital economy such as digital technology, network communication and artificial intelligence, the growth in the number of patents and the improvement in the quality of patents also directly highlights the innovation vitality and technological advantages in these areas. Due to the timeliness of patent applications, this paper determines the number of digital economy patent applications for each city based on the *Statistical Classification of Digital Economy and Its Core Industries (2021)* and the *Reference Relationship Table between International Patent Classification and National Economic Industry Classification (2018)*, using this as a key indicator to evaluate their level of digital innovation. In addition, the authorized quantity of digital economy patents is employed as an alternative explanatory variable for robustness tests.

3.3.3 Control variables

In this paper, the following control variables that may affect air quality are included in the regression analysis: fixed-line telephone penetration rate (*phone*), measured by the number of fixed-line telephones per 100 people; human capital level (*hc*), measured by the number of students enrolled in general higher education per 10,000 people; foreign direct investment (*fdi*), measured by the proportion of actually utilized foreign direct investment to GDP;

urbanization rate (*urban*), measured by the proportion of urban population to resident population; level of economic development (*ed*), measured by GDP *per capita*; and level of transportation infrastructure (*road*), measured by the length of paved roads at the end of the year.

4 Empirical results and analysis

4.1 Baseline regression results

In order to test the relationship between digital innovation and air quality, model (1) is empirically tested and the results of the benchmark regression are reported in Table 1. The results in column (1) show that the estimated coefficient of the core explanatory variable digital innovation is significantly negative at the 1% statistical significance level without introducing control variables, providing preliminary indications that digital innovation has a positive impact on improving urban air quality. After controlling for area and year fixed effects, the regression results in columns (2) and (3) show that the effect of digital innovation on air quality is significantly negative regardless of whether control variables are added, further indicating that the increase in the level of digital

TABLE 2 Results of robustness tests.

Variables	Variable substitution		Variable lag		Winsorization	Adding variable
	(1)	(2)	(3)	(4)	(5)	(6)
	so2	y	y	y	y	y
di	−0.064*				−1.880**	−1.429***
	(−1.80)				(−2.35)	(−2.96)
authorize		−1.714***				
		(−2.90)				
L.di			−1.190***			
			(−2.58)			
L2.di				−1.023**		
				(−1.97)		
phone	0.008**	0.049	0.006	0.103	0.096*	0.029
	(2.06)	(0.97)	(0.10)	(1.58)	(1.77)	(0.59)
hc	−0.000	−0.003	−0.005	−0.007**	−0.005	−0.003
	(−0.86)	(−1.00)	(−1.56)	(−2.22)	(−1.61)	(−0.85)
urban	−0.001	−0.079*	−0.092**	−0.075*	−0.116**	−0.090**
	(−0.21)	(−1.84)	(−2.32)	(−1.89)	(−2.25)	(−2.09)
ed	0.005	0.480***	0.293**	0.172	0.476***	0.308*
	(0.44)	(3.13)	(2.02)	(1.14)	(2.92)	(1.95)
road	−0.621**	−3.818	−0.764	4.397	−8.642**	−4.146
	(−2.48)	(−1.11)	(−0.23)	(1.19)	(−2.09)	(−1.23)
fdi	0.001	−0.050	0.037	0.097	0.035	−0.052
	(0.09)	(−0.50)	(0.42)	(1.12)	(0.27)	(−0.51)
fs						−1.246***
						(−4.58)
Constant	10.476***	81.955***	79.790***	78.067***	83.603***	86.852***
	(56.05)	(32.40)	(33.31)	(31.75)	(28.55)	(31.94)
Year FE	Y	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y	Y
Observations	2,280	2,280	1,995	1,710	2,280	2,280
R-squared	0.773	0.759	0.785	0.797	0.773	0.762

*, **, *** represent significance levels at 10%, 5%, and 1%, respectively, with t-values in parentheses.

innovation can indeed improve urban air quality. Thus, the core hypothesis H1 of this paper is verified.

4.2 Robustness tests

4.2.1 Substituting variables

Firstly, replace the dependent variables. Industrial sulfur dioxide, as the most significant industrial pollutant and the major culprit of environmental pollution, is closely related to air quality. In

line with previous studies, this paper uses industrial sulfur dioxide emissions as an indicator to characterize air quality for regression analysis. The corresponding regression results are reported in column (1) of Table 2, indicating that the regression coefficients for digital innovations remain significant. Secondly, replace the explanatory variables. When the explanatory variable is replaced with the number of patents granted specifically in the digital economy, the results of the re-regression analysis are presented in column (2) of Table 2 in this column, the estimated coefficients of the new explanatory variable attain statistical significance at the 1%

TABLE 3 Results of endogeneity tests.

Variables	IV1		IV2		IV3	
	(1)	(2)	(3)	(4)	(5)	(6)
	di	y	di	y	di	y
di		−1.462***		−1.580**		−12.535***
		(−2.58)		(−1.96)		(−5.02)
IV1	0.814***					
	(83.62)					
IV2			0.647***			
			(38.81)			
IV3					0.033***	
					(9.92)	
phone	−0.002	0.003	−0.004*	0.096	−0.020***	−0.227***
	(−1.30)	(0.06)	(−1.95)	(1.46)	(−8.84)	(−2.74)
hc	−0.000**	−0.005	−0.000***	−0.008**	−0.001***	−0.010**
	(−2.49)	(−1.63)	(−2.66)	(−2.34)	(−3.91)	(−2.47)
urban	0.001	−0.091**	0.001	−0.074*	−0.005**	−0.130***
	(0.65)	(−2.30)	(0.48)	(−1.87)	(−2.46)	(−2.61)
ed	0.001	0.294**	0.005	0.180	0.056***	1.198***
	(0.29)	(2.03)	(1.07)	(1.19)	(8.20)	(5.14)
road	−0.091	−0.897	0.040	4.460	1.424***	18.035***
	(−1.29)	(−0.27)	(0.34)	(1.21)	(8.99)	(2.90)
fdi	0.003	0.041	0.002	0.101	0.006	0.007
	(1.37)	(0.46)	(0.88)	(1.16)	(1.32)	(0.06)
Constant	0.091*	79.924***	0.174**	78.342***	0.360***	86.211***
	(1.81)	(33.33)	(2.21)	(31.70)	(3.15)	(28.94)
Year FE	Y	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y	Y
Observations	1,995	1,995	1,710	1,710	2,280	2,280
R-squared		0.010		0.010		−0.240
Anderson canon. corr. LM statistic	1,605.383***		882.369***		107.937***	
Cragg–Donald Wald F statistic	6,992.342 [16.38]		1,506.455 [16.38]		98.442 [16.38]	

*, **, *** represent significance levels at 10%, 5%, and 1%, respectively, with t-values in parentheses.

statistical significance level. The core conclusion of this paper remains unaffected: the progression of digital innovations can markedly decrease the emission of air pollutants, thereby improving air quality.

4.2.2 Considering the lag in patent applications

Given the lagged nature of patents filings in the digital economy, the regression analysis separately uses one-period lagged and two-period lagged digital innovation as the core explanatory variables at this stage. The regression results reported in columns (3) and (4) of

Table 2 show that the estimated coefficients of the new core variables are still significantly negative at the 1% statistical significance level. As a result, the core conclusions of this paper remain robust.

4.2.3 Winsorization

Since extreme values may have an adverse impact on the estimation results, the variables were winsorized at the 1% and 99% percentiles, and the relevant regression results are reported in column (5) of Table 2, which shows that the estimated coefficients of the core explanatory variables remain significantly negative after

winsorization. And this suggests that the development of digital innovations contributes to the improvement of air quality.

4.2.4 Adding control variables

Considering that improvements in air quality may be influenced by the abundance of financial resources in a city, cities with more abundant financial resources typically possess stronger economic capacity and financing capabilities, enabling them to prioritize environmental governance and provide greater financial support, thereby achieving air quality improvements earlier. To control for this potential influencing factor, we introduce the financial scale variable (*fs*) into the baseline model (1). Drawing on the approaches of Li, J. (2024) and Tian and Feng. (2024), this variable is measured by the ratio of the total year-end deposits and loans of financial institutions to the regional gross domestic product. As shown in column (6) of Table 2, after controlling for this variable, the estimated coefficient of digital innovation remains statistically significant and negative, indicating that the conclusion that digital innovation contributes to improving urban air quality is robust. Hypothesis H1 is once again validated.

4.2.5 Endogeneity tests

The aforementioned empirical results indicate that the advancement of digital innovation can improve urban air quality, whereas the demand for improving urban air quality, coupled with policy guidance, may promote the development and application of pertinent green technologies, which in turn drive the progression of digital innovation. Hence, there may be a bidirectional causal relationship between the advancement of digital innovations and air quality improvement. In order to mitigate the impact of endogeneity issues on the regression results, this study draws on the approaches of Bellemare et al. (2017), Guo et al. (2023), and Huang W. et al. (2025), selecting the first lag of digital innovation (IV1), the second lag of digital innovation (IV2), and the interaction term between the number of post offices in 1984 and information technology service revenue (IV3) as instrumental variables for regression. The regression results are presented in Table 3. The first-stage regression results, shown in columns (1), (3), and (5), demonstrate that the instrumental variables have a significantly positive impact on the core explanatory variable. The Anderson canon. corr. LM statistics are significant at the 1% level, rejecting the null hypothesis of underidentification. Furthermore, the Cragg–Donald Wald F-statistics substantially exceed the critical value of 16.38 at the 10% level based on the Stock–Yogo test, rejecting the weak instrument hypothesis. This confirms the validity of the selected instrumental variables. The second-stage regression results, presented in columns (2), (4), and (6), show that the estimated coefficients of digital innovation remain significantly negative. These indicate that, after addressing endogeneity through instrumental variables, the development of digital innovation continues to significantly improve air quality, consistent with the baseline regression results, further confirming Hypothesis H1.

4.3 Mechanism analysis

The empirical research presented earlier in this paper has demonstrated that the development of digital innovations can

TABLE 4 Results of mechanism tests.

Variables	(1)	(2)	(3)	(4)
	ins	ge	gt	gf
di	4.422**	6.391***	2.290***	2.653***
	(2.57)	(6.01)	(117.56)	(6.70)
phone	0.451**	0.192*	−0.004**	−0.171***
	(2.52)	(1.74)	(−2.07)	(−4.15)
hc	0.045***	−0.009	−0.000	−0.000
	(3.84)	(−1.18)	(−0.96)	(−0.02)
urban	−0.009	−0.025	−0.000	0.081**
	(−0.06)	(−0.26)	(−0.08)	(2.31)
ed	−7.120***	1.032***	0.011*	1.006***
	(−13.10)	(3.07)	(1.84)	(8.04)
road	25.671**	10.951	1.110***	7.250***
	(2.14)	(1.48)	(8.16)	(2.62)
fdi	−0.114	−0.035	0.012***	0.343***
	(−0.32)	(−0.16)	(2.98)	(4.16)
Constant	123.173***	7.488	0.074	164.743***
	(13.72)	(1.35)	(0.73)	(79.68)
Year FE	Y	Y	Y	Y
City FE	Y	Y	Y	Y
Observations	2,280	2,280	2,280	2,280
R-squared	0.360	0.087	0.913	0.988

*, **, *** represent significance levels at 10%, 5%, and 1%, respectively, with t-values in parentheses.

indeed lead to significant improvements in air quality, yet the underlying mechanisms of action require further investigation. Therefore, in order to further explore the mechanism by which digital innovation affects air quality, at this juncture, on the basis of the baseline regression model (1), the moderator variables industrial structure upgrading (*ins*), governmental energy-saving and environmental protection financial expenditure (*ge*), green technology advancement (*gt*), and digital financial development (*df*) are incorporated into Model (2) as dependent variables to conduct regression tests, respectively, and the results are shown in Table 4.

In order to test whether digital innovation has the potential to improve urban air quality by optimizing and upgrading the industrial structure to reduce air pollutant emissions, this paper utilizes the ratio of value added of the tertiary industry and the secondary industry as a metric to measure the upgrading of the industrial structure (*ins*). The regression results presented in column (1) of Table 4 show that the estimated coefficient for the effect of digital innovation on industrial structure upgrading is significantly positive, which indicates that the progression of digital innovation can significantly optimize the industrial structure of a city. The theoretical analysis in the previous section comprehensively

elucidates that upgrading of urban industrial structure can effectively improve air quality, and this enhancement is primarily manifested in the technological transformation and upgrading of traditional industries, the emergence of green emerging industries, as well as the optimization and adjustment of the industrial structure, and all of these can contribute to reducing the emissions of air pollutants collectively and effectively, and thus improving the level of air quality.

In column (2), this study employs urban expenditure on energy conservation and environmental protection (ge) from the general public budget as the dependent variable for empirical testing. The results show that the estimated coefficient of digital innovation on energy conservation and environmental protection expenditure is significantly positive, indicating that an increase in the level of digital innovation significantly promotes government expenditure on energy conservation and environmental protection. This suggests that the development of digital innovation reinforces the government's sense of urgency and responsibility toward energy conservation and environmental protection. In fact, the advancement of digital innovation has greatly enhanced the intelligence and data analysis capabilities of environmental monitoring, enabling the government to identify and respond to environmental issues more rapidly, thereby formulating more scientific and rational policies and measures for energy conservation and environmental protection. On this basis, the government can allocate fiscal resources more accurately and efficiently, directing funds toward key areas such as environmental protection technology innovation, pollution treatment facility construction, clean energy development and utilization, and public green awareness initiatives, thereby promoting sustained improvement of air quality through expanding effective governance investment.

In column (3), where the number of green patent applications is used as a metric for assessing the level of regional green technological progress (gt), the estimated coefficient of digital innovation's impact on green technology progress is significantly positive, indicating that the level of digital innovation fully unleashes the regional green technology progress effect. Furthermore, green technological progress can effectively reduce the level of air pollution by improving the production process, enhancing the efficiency of energy utilization, and optimizing the efficiency of pollution control. Therefore, it can be proved that there is a green technological progress effect in its pursuit of digital innovation to improve air quality.

In Column (4), the development level of regional digital finance (gf) is measured using the digital financial inclusion index published by Peking University, and the regression results show that the estimated coefficient for digital innovation is significantly positive at the 1% statistical significance level, indicating that regions with a better level of development of digital innovation exhibit a greater degree of digital financial penetration. The dynamic development of digital finance has broadened and deepened the breadth of coverage and depth of support for financial services, thereby furnishing diversified financial backing for environmental governance. This trend not only enhances the efficiency of resource allocation but also guides the flow of capital to green industries, effectively reducing pollution emissions at the source. Consequently, it also boosts the transparency and credibility of green finance, which not only

provides manufacturing enterprises and resource-based enterprises with sufficient special funds for greening and low-carbon development in order to guide and support them to accelerate green technological transformation, build green supply chains, and develop a circular economy, among other initiatives, but also attracts investors' attention and encourages their participation in green and low-carbon development projects, thereby effectively curbing pollutant emissions and significantly improving air quality.

Based on the comprehensive analysis presented above, Hypothesis H2 is rigorously tested.

4.4 Heterogeneity analysis

4.4.1 Heterogeneity based on city functions

There are large differences in resource endowment, political and economic functional attributes, economic development levels, and industrial structures among different regions in China, and the level of digital innovation development differs considerably across cities. Taking into account the differences of urban functions, this paper categorizes the sample cities into central cities and peripheral cities to examine the differential impact of digital innovation level on air quality in different cities. Specifically, provincial capitals and municipalities are identified as central cities, and the remaining cities are peripheral cities for the purpose of grouped regressions. The results in columns (1) and (2) of Table 5 show that the estimated coefficient of digital innovation is significantly negative at the 1% level in the sample of central cities, while the coefficient is not significant in the sample of peripheral cities, suggesting that the level of digital innovation development can effectively contribute to air quality improvement in central cities. Compared to peripheral cities, central cities boast a solid economic foundation and sound top-level design, and are also better in the research and development and application of green technologies, and the establishment and implementation of environmental supervision mechanisms. Therefore, the environmental benefits brought by digital innovations in central cities are usually more significant, providing strong support for the continuous improvement of urban air quality.

4.4.2 Heterogeneity based on city size

City size may be an influential factor in determining the effectiveness of digital innovation in improving urban air quality. Therefore, according to the *Circular on Adjusting the Criteria for Classifying the Size of Cities*, cities with a resident population of more than 3 million are classified as large-scale cities, while the remainder are classified as small and medium-scale cities. The regression results are shown in columns (3) and (4) of Table 5. For large-scale cities, the regression coefficient of digital innovation is significantly negative, whereas for small- and medium-sized cities, the coefficient is not statistically significant. This suggests that the development of digital innovations can significantly improve air quality, and this effect that is more pronounced in large-scale cities. Generally speaking, large-scale cities typically have a stronger ability to integrate resources, and are able to comprehensively utilize a combination of policies, funds, technologies, and talents to build a green innovation system in which major digital innovations in the field of ecology and the

TABLE 5 Results of heterogeneity tests.

Variables	Central cities	Peripheral cities	Large-scale cities	Small and medium-scale cities	High education investment cities	Low education investment cities
	(1)	(2)	(3)	(4)	(5)	(6)
	y	y	y	y	y	y
di	−2.836***	0.631	−1.170**	−1.545	−1.167***	−0.369
	(−3.10)	(0.94)	(−2.18)	(−0.27)	(−2.75)	(−0.14)
phone	−0.048	0.074	0.016	0.032	0.361***	−0.154*
	(−0.25)	(1.41)	(0.24)	(0.40)	(5.09)	(−1.92)
hc	0.004	−0.008*	−0.002	−0.004	0.004	−0.006
	(0.65)	(−1.83)	(−0.35)	(−0.71)	(0.84)	(−0.91)
urban	−0.256	−0.070	−0.176*	−0.011	−0.212**	−0.061
	(−1.32)	(−1.59)	(−1.85)	(−0.26)	(−2.57)	(−1.13)
ed	−0.054	0.626***	0.468**	0.649***	0.463**	0.494
	(−0.11)	(3.87)	(2.09)	(3.04)	(2.43)	(1.57)
road	9.465**	−18.314***	1.479	−0.781	−0.965	−6.877
	(2.02)	(−2.75)	(0.39)	(−0.06)	(−0.29)	(−0.91)
fdi	0.244	−0.118	−0.171	0.022	0.246**	−0.367**
	(0.93)	(−1.08)	(−1.26)	(0.15)	(2.13)	(−2.14)
Constant	102.920***	80.724***	91.953***	69.914***	78.912***	88.747***
	(6.85)	(32.52)	(17.10)	(25.49)	(15.52)	(28.76)
Year FE	Y	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y	Y
Observations	240	2,040	1,377	903	1,140	1,140
R-squared	0.812	0.758	0.772	0.761	0.791	0.696

*, **, *** represent significance levels at 10%, 5%, and 1%, respectively, with t-values in parentheses.

environment continue to emerge, so as to curb environmental pollution in a more scientific and efficient way.

4.4.3 Heterogeneity based on education investment level

Due to variations in educational resources across cities, these differences may influence how digital innovation improves urban air quality. In order to explore this issue, this study uses *per capita* education expenditure to measure the level of education investment in each city and divides the research sample into high- and low-education-investment groups based on the median value. The regression results are shown in columns (5) and (6) of Table 5. As indicated, the estimated coefficient of digital innovation is significantly negative in cities with higher education investment, whereas it is statistically insignificant in cities with lower education investment. Two factors explain this discrepancy. On the one hand, cities with higher levels of investment in education typically possess a larger number of colleges and universities, scientific research institutes and professional talents, who can quickly master and apply the latest digital

technologies to establish a comprehensive air quality monitoring network and quickly optimize and adapt the application of environmental protection technologies. On the other hand, the increasing emphasis on environmental education can also continue to stimulate the public’s environmental awareness and capabilities, thereby enhancing their environmental perception, fostering environmental activism, raising ecological protection awareness, and increasing their concern about air quality.

5 The moderating role of the institutional environment

This paper focuses on the question of how digital innovation development can improve air quality, and the above empirical results confirm that digital innovation development can indeed effectively improve air quality, and there are significant heterogeneity characteristics. In this process, the institutional environment is further introduced, and its moderating influence on the development of digital

TABLE 6 Results of moderating effects.

Variables	mkt	fintech	open
	(1)	(2)	(3)
	y	y	y
di	−4.120***	−2.086***	−3.180***
	(−4.31)	(−3.85)	(−3.85)
mkt	0.047		
	(0.72)		
di*mkt	0.074***		
	(3.34)		
fintech		0.000	
		(0.01)	
di*fintech		0.002*	
		(1.82)	
open			−2.843**
			(−2.00)
di*open			2.742**
			(2.29)
phone	0.032	0.038	0.039
	(0.63)	(0.76)	(0.77)
hc	−0.005	−0.004	−0.003
	(−1.35)	(−1.16)	(−1.03)
urban	−0.077*	−0.079*	−0.080*
	(−1.79)	(−1.82)	(−1.86)
ed	0.522***	0.509***	0.473***
	(3.40)	(3.32)	(3.08)
road	−3.499	−3.661	−2.254
	(−1.02)	(−1.05)	(−0.65)
fdi	−0.026	−0.039	−0.027
	(−0.26)	(−0.39)	(−0.27)
Constant	81.752***	82.137***	82.660***
	(31.97)	(32.47)	(32.52)
Year FE	Y	Y	Y
City FE	Y	Y	Y
Observations	2,280	2,280	2,280
R-squared	0.761	0.760	0.761

*, **, *** represent significance levels at 10%, 5%, and 1%, respectively, with t-values in parentheses.

innovation to improve air quality is examined from three perspectives, namely, the competitive market environment (*mkt*), the financial innovation environment (*fintech*) and the openness of the economy

(*open*). Therefore, the following model is constructed by incorporating the interaction terms between the core explanatory and moderator variables into the baseline model (1):

$$Y_{it} = \alpha_0 + \alpha_1 di_{it} + \beta_1 m_{it} + \beta_2 di_{it} * m_{it} + \alpha_2 Controls_{it} + \lambda_i + \mu_t + \varepsilon_{it} \tag{3}$$

in [Formula 3](#), m_{it} is the moderating variable, and the remaining variables maintain their respective meanings as outlined in the aforementioned model.

5.1 Market environment

The market environment is measured using the Market Environment Index from *the Chinese Urban Business Environment Database*, with larger values indicating a more optimized market environment and fuller market competition. Column (1) of [Table 6](#) reports the moderating effect of the competitive market environment on the relationship between digital innovation and air quality. It can be seen that the coefficient of digital innovation is significantly negative at the 1% level, while the coefficient of the interaction term between digital innovation and market competition environment is significantly positive, indicating that a perfect market competition environment is conducive to amplifying the contribution of digital innovation to air quality improvement. This is because sound market mechanisms offer superior conditions for digital innovation activities, accelerating the transformation and application of innovative outcomes in the field of ecology and environment, fully releasing the inhibitory effect on pollution, and thus enhancing the efficiency of efforts aimed at improving air quality.

5.2 Financial innovation environment

The financial innovation environment is measured by the number of fintech companies in each region, with larger values representing higher levels of fintech development. Column (2) of [Table 6](#) reports the moderating effect of the financial innovation environment on the relationship between digital innovation and air quality. The results reveal that the estimated coefficients of digital innovation are significantly negative, whereas those for the interaction term are significantly positive, indicating that a developed financial innovation environment exhibits a significant positive incentive effect in the implementation of digital innovation to improve air quality, which strengthens the effect of digital innovation to improve air quality. This also implies that a favorable financial environment is an important guarantee for the effectiveness of digital innovation in the field of ecological and environmental protection. In simpler terms, regions with more mature financial innovation environments will witness a more pronounced impact from digital innovation on air quality improvement.

5.3 Economic openness level

Regional economic openness is measured by the ratio of the total import and export value to the regional gross domestic product

(Tang et al., 2014; Sun et al., 2024). According to the regression results in column (3) of Table 6, it can be seen that the estimated coefficient of digital innovation is significantly negative at the 1% significance level, whereas the estimated coefficient of the interaction term between digital innovation and economic openness is significantly positive. The analysis demonstrates that there is a significant and positive moderating effect of economic openness in the impact of digital innovations on air quality. In other words, as the city's economic openness increases, the improvement effect of digital innovations on air quality becomes more evident. This is because a city with a more open economy is more prone to attracting high-quality foreign investment, embracing advanced environmental protection concepts and green technologies, and cultivating a richer array of digital innovation resources, all of which facilitate the achievement of better outcomes in air pollution control.

Based on the comprehensive analysis presented above, Hypothesis H3 is robustly tested.

6 Conclusions, policy recommendations and future prospects

At present, the mutual integration of digitalization and green initiatives has emerged as a pivotal concern in global sustainable development efforts.

Actively exploring effective pathways through which digital innovation can optimize air quality provides new perspectives for continuously addressing air pollution problems and achieving a win-win situation of economic growth and environmentally friendly development. In this paper, the development of digital innovation and air quality are included in the same analytical framework, and data from 285 prefecture-level cities in China from 2015 to 2022 are utilized as a research sample for quantitative analysis, aiming to explore the actual impact of digital innovation on regional air quality improvement. The results of the study show that the development of digital innovation can significantly improve urban air quality. The baseline regression conclusions remain robust even after a series of robustness tests, including variable replacement, winsorization, addition of control variables, and instrumental variable methods. Mechanism tests indicate that digital innovation can improve air quality by optimizing industrial structure, increasing government expenditure on energy conservation and environmental protection, promoting green technological progress, and facilitating the development of digital finance. Regional heterogeneity results reveal that the effect of digital innovation on air quality improvement varies depending on urban functional positioning, city size, and education investment level, with more pronounced effects observed particularly in central cities, large-scale cities, and cities with higher education investment. Further analysis of moderating effects demonstrates that a sound institutional environment can significantly amplify the impact of digital innovation on improving air quality.

Based on these conclusions, the paper makes the following policy recommendations:

Firstly, actively promote digital innovation. The primary task is to continue to strengthen the breakthroughs of digital innovation technology and the forward-looking layouts of cutting-edge technology. This involves not only advancing the core competitiveness of digital technology by fostering innovation in key areas such as artificial intelligence, big data, and cloud computing, but also actively exploring and deploying emerging technologies with high potential for future development, such as quantum computing, blockchain, and the Internet of Things. Attention should then be paid to the ongoing construction of a unified, efficient and secure data factor market. This entails not only clarifying the ownership of data, promoting trust among market participants, and encouraging data sharing and utilization, but also ensuring the orderly flow and rational use of data elements to maximize the value of data. More importantly, it is also essential to strengthen the corresponding policy innovation support system and establish a robust data supervision mechanism, in order to guide capital, technologies and talents to gather in the digital innovation field, to build a digital innovation ecosystem. Consequently, a well-functioning environment conducive to the deep advancement of digital innovation will be established.

Second, leverage the enabling advantages of digital innovation to comprehensively enhance air quality governance capabilities. It is essential to fully exploit the positive role of digital innovation in promoting industrial structure upgrading, increasing environmental protection expenditure, accelerating green technology progress, and deepening digital finance development. Encourage enterprises to adopt digital technologies for green and intelligent transformation, reducing pollutant emissions from the source. Integrate digital technologies into the performance evaluation management system of government environmental fiscal expenditure, such as establishing an intelligent management platform for environmental governance fiscal spending to achieve dynamic optimization and precise allocation of environmental funds, thus maximizing emission reduction benefits. Establish a "Digital Green Innovation" special fund to guide enterprises in leveraging digital technologies for research and development and application in energy conservation, emission reduction, new energy development, and pollution control. Encourage financial institutions to utilize digital technologies to develop green financial products linked to carbon emissions and real-time air quality, and construct a digital evaluation system for corporate environmental credit, thereby leveraging more social capital towards environmental protection.

Thirdly, formulate and implement pollution control strategies according to local conditions. Fully recognizing and respecting the heterogeneous characteristics of different regions serves as the crucial foundation for integrating cross-regional cooperation mechanisms. Such integration is highly conducive to breaking down market segmentation, so as to enable the full play of the positive spillover effect of digital innovation and the demonstrative effect of pollution management, ultimately achieving synergistic regional governance. The implementation of targeted measures tailored to regional characteristics not only ensures close alignment of pollution control initiatives with the specific needs and challenges faced by each region, but also substantially bolsters the synergy, effectiveness, and sustainability of the overall governance system. As a result, a more comprehensive and

sustained reduction in pollution levels can be achieved, which is essential for fostering environmental protection endeavors and sustainable development efforts.

Finally, create a fair, open and robust institutional environment for digital innovation and green and sustainable development. On the one hand, it is necessary to refine the market mechanism, enhance the allocation efficiency of data, funds, talents and other resources, and create a market environment in which digital innovations continue to emerge in the field of ecology and environment. On the other hand, it is equally imperative to continue to promote the layout and implementation of digital innovation policies in the field of ecology and environment, and to harness the power of financial science and technology to guide the flow of capital to the research and development of key technologies and application fields of air pollution prevention and control. What's more, it is crucial to improve the green list system for foreign trade, bolster the introduction of advanced environmental protection technology and equipment, and unleash the full potential of green innovation among market participants, and accelerate the localized transformation of green innovation resources.

While our findings confirm the positive role of digital innovation in improving air quality, its practical effectiveness is deeply constrained by the real-world institutional environment and political-economic structures. The heterogeneity in the governance effects of digital innovation reveals that environmental governance is not merely a technical issue but also a matter of governance systems and resource allocation. Well-developed cities typically possess more robust institutional frameworks, stronger fiscal capacities, and stricter policy enforcement capabilities, enabling them to fully leverage digital tools for pollution control. Conversely, under the “growth-first” development paradigm, the absence of effective environmental regulations and incentive mechanisms may lead digital technologies to serve merely economic efficiency without delivering their environmental benefits. Therefore, future research should incorporate more nuanced measures of digital capacity and institutional dynamics to further unravel the black box of digital environmental governance, overcome structural barriers such as the “growth-first” inertia and regional digital divides, and fully unleash its environmental potential.

Data availability statement

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

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HR: Conceptualization, Data curation, Formal Analysis, Investigation, Resources, Software, Validation, Writing – original draft, Writing – review and editing. JH: Conceptualization, Methodology, Project administration, Resources, Supervision, Writing – review and editing. JR: Formal Analysis, Supervision, Validation, Writing – review and editing.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2025.1658767/full#supplementary-material>

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