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Bilateral impact of digital economy on air pollution: Emissions increase and reduction effects

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China's rapid industrialization and urbanization have led to ecological and environmental problems, particularly air pollution. Digitalization has become a key component in high-quality development to overcome the previous high-energy and high-pollution development model. However, a certain degree of "green blindness" exists in the digital development process, and the impact on air pollution is not always positive. Therefore, the impact of the digital economy on air pollution is worth exploring. In this study, the authors examines the emissions increase and reduction effect mechanisms of the digital economy on air pollution using panel data in 30 provinces in China from 2011 to 2020. The two-tier stochastic frontier model showed that the interaction between the emissions increase effect and emissions reduction effect of the digital economy reduced the actual air pollution emissions level below the frontier level by 0.15%, on average. Overall air pollution level is characterized prominently by emission reduction, owing to the asymmetric bilateral effect of the digital economy. Second, the time trend characteristics of the net effect of the digital economy on air pollution emissions showed a wave-like change; the average values of the net effect in the three major regions (i.e., the east, central, and west) were all negative. Third, along with the development of digital economy, human capital levels, and general economic levels, the emissions reduction effect of the digital economy on air pollution has strengthened, such that the net effect became positive to negative. However, significant heterogeneous characteristics were noted in the effects of the digital economy on air pollution under different levels of digital economy development, human capital, and economic development. This study provides practical paths for air pollution management, strengthening inter-regional environmental synergy management and high-quality economic development.

KEYWORDS

digital economy, air pollution, two-tier stochastic frontier model, emissions increase effect, emissions reduction effect, heterogeneity

1 Introduction

According to the World Health Organization, air pollution has caused 4.2 million premature deaths in 2019, and 89% of those premature deaths occurred in low- and middle-income countries, for example, South-East Asia and Western Pacific Regions (World Health Organization, 2022). Airborne particulate matter concentrations in many developing countries are 5–10 times higher than in developed countries (Ebenstein et al., 2017). China is the largest developing country, and the research on its air pollution is representative, which can be a reference for other developing countries. China's rapid industrialization and urbanization have led to ecological and environmental problems typified by air pollution. Air pollution seriously endangers human health, reduces the life expectancy of residents, causes unemployment, reduces *per capita* GDP, and impairs the quality of economic development as well as the environment (Huang et al., 2014; Chang et al., 2016; Ebenstein et al., 2017). High PM2.5 pollution raise overall health risk to the population and economic loss (Li and Zhang, 2019). Therefore, air pollution has become an important issue for governments and scholars around the world (Feng et al., 2019). The alarming nature of this problem has led China to adopt a series of environmental policies to address it. The 20th CPC National Congress once again proposed the thorough promotion of environmental pollution prevention and control while continuously attempting to preserve blue skies, clear waters, and clean lands.

Ecological and environmental problems can be attributed to issues with the development model and lifestyle (Guo et al., 2022). The data element has become the key to achieving high-quality development by breaking the existing previous high-energy consumption and high-pollution development model (Zhou et al., 2022). The Industry 4.0 strategy has greatly promoted the process of digitalization. Its main purpose is to achieve the intelligent manufacturing through the Cyber-Physical System (Lasi et al., 2014). The core of Industry 4.0 includes digitization, networking, automation and intelligence. Since the release of Industry 4.0, digital technologies such as big data, blockchain and cloud computing have continued to develop, providing support for humanity to enter the era of digital economy. Chinese government departments also attach importance to the development of digitalization. The digital economy is an important factor in optimizing and upgrading to the economic structure and achieving high-quality economic development in recent times in China. Therefore, exploring the possible effects of the digital economy on air pollution is of great theoretical value and practical significance and provides a new perspective for research on air pollution impact factors, air pollution management methods, and governance policies.

Emissions are an important factor influencing air pollution, but socioeconomic factors also play important roles (Wang et al., 2022c). Thus, many researchers have examined environmental pollution emissions and their influencing factors from different perspectives using various approaches (Weis et al., 2017; Hao et al., 2019; Hille et al., 2019; Lin and Xu, 2019; Zhang et al., 2019). These influencing factors include economic growth (Hao et al., 2019), industrial structure, technological innovation, environmental regulation (Zhang et al., 2019), direct foreign investment (Hille et al., 2019), international trade (Lin and Xu, 2019), energy structure, and urbanization (Weis et al., 2017). With the development of the digital economy, more scholars have started to focus on its impacts arising, such as the impact of the digital economy on general economic development (Jurayevich and Bulturbayevich, 2020), international trade (Ahmedov, 2020) and welfare (Grigorescu et al., 2021). However, along with the spread and development of information technology, digitalization exerts an increasing impact on environmental governance and green development.

The application of digital technologies is an effective means of addressing dynamic environmental issues (Feroz et al., 2021), such as air pollution and carbon emissions. In the context of rapid industrialization and urbanization, digitalization has a significant impact on the relationship between ecosystems and human wellbeing. Despite the increasing scale of the digital economy, relatively few studies exist on the relationship between the digital economy and environmental pollution. However, in the context of increasingly serious atmospheric pollution and the booming internet, the application of internet technology in the field of environmental protection is of great value for improving environmental quality and achieving sustainable economic development (Li et al., 2018). For example, big data contributes to many aspects of sustainable development, especially environment pollution management and preventive measures (Honarvar and Sami, 2019; Zhang et al., 2022). Studies that noted the positive role played by big data and internet technology in environmental sustainable development are increasing (Murshed, 2020; King et al., 2021; Chen, 2022), without enough consideration about the possible negative effects of the digital technology (Salahuddin and Alam, 2015; Usman et al., 2021). Few empirical studies have examined the impact of digital economy on air pollution comprehensively, both positive and negative.

Therefore, to exploring the actual effects of the digital economy on air pollution emissions in depth is necessary. This study constructs a two-tier stochastic frontier model using interprovincial panel data in China from 2011 to 2020 to measure the impact of the digital economy on air pollution. It examines whether the emissions increase or emissions reduction effects plays a dominant role to identify the net effect of the digital economy on air pollution.

The innovations of this study are as follows. First, this study provides a new research perspective. In the context of China's vigorous digital economy development, its inclusion in the framework of air pollution research has aided air pollution management. Although many results have been obtained on the economic effects of the digital economy, there is scant literature analyzing the environmental effects of the digital economy.

Second, this study proposes a probable mechanism of the impact of the digital economy on air pollution, explaining the emissions increase and emissions reduction effects of the digital economy on air pollution. This enriches theoretical research fields related to both the digital economy and air pollution. The study examines the environmental effects of the digital economy in an integrated manner and provides a theoretical basis for the empirical study of the effects of the digital economy on air pollution.

Third, on a practical level, the study provides a new solution to China's air pollution challenges by leveraging the digital economy as a path for achieving high-quality economic development and reducing negative environmental impacts.

Finally, a two-tier stochastic frontier model is applied for empirical validation. The authors further investigate the regional and temporal characteristics of the net effect of the digital economy on air pollution. The actual bilateral effects of the digital economy on air pollution emissions are explored based on three aspects under different levels of the digital economy, human capital, and economic development, which provides empirical evidence for China's different regions to propose the new pathway on air pollution management, and enriches the research on the relationship between digital economy and air pollution.

The remainder of this paper is organized as follows. Section 2 presents a literature review. Section 3 presents a mechanistic analysis. Section 4 presents an empirical two-tier frontier model and describes the data and variables used in this study. Section 5 presents the empirical results. Finally, Section 6 presents the conclusions from this study with policy implications and future perspectives.

2 Literature review

Previous studies can be divided into three categories: first, some studies conclude that digital economy suppresses air pollution. Research on the application of digital economy development in the field of environmental governance and green development is gradually increasing, especially regarding the relationship between digital economy development and carbon emissions (Balogun et al., 2020; Chen, 2022). The advancement of digitalization has had an impact on changes in energy and the environment. The development of the digital economy with information technology as its core has allowed for the supervision and management of an intelligent environment, which can help solve problems such as declining environmental carrying capacity and resource scarcity (Li et al., 2021). This shows that the development of the digital economy is an important solution for developing clean energy, improving air pollution, and promoting low-carbon development (Wang et al., 2022b). For example, previous studies have argued that digital technologies can help to reduce carbon emissions. The ability to identify the latest trends in the energy market through pricing and cross-subsidization due to the use of digital technologies allows the government to regulate the overall energy supply, which in turn aids in the efficient use of energy and reduces carbon emissions (Bhattacharya et al., 2015). The penetration of digital technologies contributes to the transfer of production factors from inefficient to efficient sectors, which increases the efficiency of resource allocation and ultimately improves energy efficiency and reduces air pollution emissions. Digitization breaks regional boundaries and time constraints, accelerates the flow of production factors, reduces energy consumption due to spatial and temporal factors in production and life, reduces energy consumption rates, and curbs carbon emissions. For example, some scholars have pointed out that the development of the digital economy is beneficial for reducing greenhouse gas emissions (Murshed, 2020; Wang et al., 2022a) and fossil fuel consumption (Lange et al., 2020). King et al. (2021) also pointed out that the development of the digital economy, especially the application of information and communications technology (ICT) devices, promotes the health of the local environment and can improve environmental problems, such as air pollution. Therefore, the relationship between the digital economy and air pollution is a topic of interest for both governments and scholars.

Second, a few studies conclude that the digital economy increases air pollution. Some scholars have argued that the development of the digital economy has a negative impact on air pollution emissions. Digital technologies are based on electricity. For example, the development and operation of cloud computing, blockchain, and data centers require increasingly energy-intensive infrastructures (Yang et al., 2022), which can generate more air pollution emissions. Further, the digital sector based on information services is highly power-intensive, accounting for 10% of global electricity generation (Salahuddin and Alam, 2015). Therefore, the use of large amounts of electricity increases coal consumption, which in turn increases air pollution emissions. Additionally, the use of digital technologies in transportation will further increase the scale of traffic trips, which in turn will lead to increased energy consumption, undoubtedly increasing air pollution emissions. For example, Shvakov and Petrova (2020) found that digitization does not lead to a reduction in CO_2 emissions through an empirical study of data from ten digitized countries. Digitization in ICT applications had a suppressive effect on CO_2 emissions only in relatively less-polluted Asian countries, whereas it did not lead to favorable environmental effects in countries with higher carbon emissions (Usman et al., 2021).

In the third category, the digital economy has been assumed to have non-linear effects on air pollution. Based on discussions of the positive and negative effects of the digital economy on air pollution emissions, some scholars have further proposed that there may be non-linear effects from the digital economy on air pollution emissions. However, few studies have been conducted on the non-linear relationship between the digital economy and air pollution; only a few scholars have explored the non-linear relationship between the digital economy and carbon emissions. For example, Han et al. (2016) found that the impact of digital transformation on energy use is U-shaped, suggesting that the relationship between the digital economy and pollution emissions may be non-linear. In different countries, the impact of the digital economy on carbon emissions is heterogeneous (Danish et al., 2019). Li and Wang (2022) demonstrated the non-linear impact of the digital economy on carbon emissions by constructing a theoretical model and further proposed an inverse U-shaped relationship between the digital economy and local and neighboring regional carbon emissions.

First, most studies have discussed the relationship between environmental regulation, technological innovation or industrial structure, and environmental pollution; few studies have focused on the impact of the digital economy on air pollution. The combined environmental effects of digital economy have not been discussed enough. Second, as human society steps into the digital age, the impact of digital technologies, such as big data, on green development has been explored. On this basis, some scholars began to concentrate on the research of the relationship between digital economy and environmental pollution. Very little indepth and systematic research has been conducted on the relationship between digital economy and air pollution. Nevertheless, the conducted studies did not identify or capture the bilateral effects of digital economy development on air pollution and did not estimate the emissions increase effect, emissions reduction effect, or the net effect, thus failing to comprehensively reveal the trend or direction of air pollution improvements or provide an effective reference for policy recommendations. Additionally, existing ideas on the mechanism by which the digital economy affects air pollution emissions needs to be further clarified. Finally, the regional heterogeneity of the digital economy's impact on air pollution emissions has to be addressed.

In conclusion, most studies have only explored the positive effect of digital economy on air pollution, without exploring the negative impact of digital economy on air pollution. This paper will focus on the construction of a comprehensive mechanism for digital economy on air pollution, study the net effect of digital economy on air pollution by the two-tier stochastic frontier model and propose the empirical evidence and suggestions for the government and industry managers when formulating air pollution control management policies.

3 Mechanism analysis

3.1 Emissions reduction effect

The development of the digital economy has influenced technology, fossil energy consumption, environmental regulation, and industrial structure from the supply side, as well as the green product consumption demand and dependence on traditional energy sources from the demand side, thus finally reducing air pollution emissions.

From the supply side, the digital economy improves the level of production technology and promotes the development of green technological innovation. Digital development relying on advanced technologies, such as ICT, 5G, blockchain, big data, and cloud computing, has improved the efficiency of using and allocating resources in innovation systems. Digitalization relying on internet technology effectively solves the problem of information asymmetry in innovation systems (Yang et al., 2022) and can reduce transaction and information search costs. The digital economy is reshaping the spatial pattern of the economy (Li and Wang, 2022). Specifically, the development of the digital economy overcomes the limitations of geographical conditions, information transmission, and time costs; breaks through spatial boundaries; promotes the flow of production factors such as capital and technology; accelerates the flow and concentration of innovation resources; accelerates knowledge spillover; promotes enterprise technology innovation by improving the level of innovation cooperation (Gómez et al., 2017); promotes green technology innovation; and reduces negative environmental impacts.

Second, the digital economy can help increase production efficiency, improve energy use efficiency, and reduce fossil fuel consumption, thus reducing air pollution emissions. Usman et al. (2021) also noted that the internet has achieved an increase in energy efficiency in India. Amin and Rahman (2019) suggested that the internet has facilitated waste management and pollution reduction.

Third, the development of the digital economy is conducive to the regulation and management of environmental pollution. The open, interactive, and real-time nature of the internet makes it possible for the public to participate in environmental governance. For example, Johansson et al. (2015) argued that the internet provides a channel for residents to participate in environmental protection activities and enhances public awareness regarding environmental protection and monitoring. Additionally, the application of digital technology in yields more intelligent and precise environmental regulation and governance, thus strongly promoting the regulation and governance of environmental pollution emissions, including the problem of air pollution emissions (Granell et al., 2016). Digital technologies accelerate the diffusion of environmental information, and instant access to environmental data such as PM2.5 is convenient for environmental regulation. Hampton et al. (2013) argued that using big data, cloud computing, and internet-based digital technologies can help integrate and analyze environmental data, such as air, which will increase the efficiency of environmental management and improve air pollution.

Fourth, the digital economy can reduce air pollution emissions by influencing the industrial structure. The digital industry is environmentally friendly, has less of a negative impact on the environment, and can drive the digital transformation of other industries. As a new model and new industry, the digital economy promotes industrial integration, but also gives birth to new green and high-tech industries while promoting foundational green production methods. The digital economy contributes to the adjustment and upgrading of the industrial structure, which provides a more rational industrial structure and promotes lower energy consumption and more efficient energy use, thus reducing air pollution emissions (Zhao et al., 2022). On the one hand, the greening level of digital industry is generally higher than that of the traditional manufacturing, which can better reduce environmental pollution, including air pollution. The digital industry is more environmentally conscious and also have the digital finance support to improve greening levels. For example, Zameer et al. (2020) pointed out that big data is a key resource for enterprises to obtain green competitive advantages and to solve environmental problems. On the other hand, the development of digital economy promotes technological innovation, promotes advanced industrial structure and upgrades industrial structure (Chen et al., 2022). The spillover effect and diffusion effect between the ICT industry and other industries have promoted the upgrading of industrial structure (Heo and Lee, 2019). This means that the development of the digital industry itself and its integration with traditional industries to improve the allocation of production factors, promote the greening of industries and reduce environmental pollution. From this perspective, this can effectively reduce the negative environmental impacts, typically including air pollution. For example, Wu et al. (2021) conducted an empirical study using the dynamic spatial Durbin model and suggested that the internet promotes the upgrading of the industrial structure and contributes to improving the regional green total factor energy efficiency and reductions in environmental pollution emissions. The close integration of digitalization and high-tech technologies can not only generate new industrial models, but also accelerate the low-carbon transformation of existing sectors, reflecting the beneficial impact of digitalization on the structure of internet-supported industries (Ren et al., 2021). The rapid development of the digital economy has accelerated the phasing out of old industries that consume a substantial energy, pollute the environment, and emit significant amounts of carbon; the production technology and management mode of remaining industries have been improved, promoting the upgrading of the industrial structure.

In contrast, from the demand side, the booming development of the digital economy and industrialization of the digital economy have made it possible to provide consumers with more green products, promote changes in the consumption structure, and guide consumer demand in the direction of green and low-carbon. Changes in the market demand in turn allow the digital economy to promote green production and lifestyle changes and further reduce air pollution emissions. Second, digital development can reduce air pollution emissions by reducing reliance on traditional energy sources, leading to the realignment of energy demand. Energy digitization on the one hand improves energy efficiency and on the other hand optimizes the structure of energy consumption, reduces the use of traditional energy sources, increases the proportion of renewable energy sources, gradually reduces the use of traditional fossil fuels, and reduces air pollution emissions (Pradhan et al., 2020). For example, Ishida (2015) argued that the internet has reduced dependence on energy in many industries. Martynenko and Vershinina (2018) emphasized that digitalization renders the manufacturing process more modern and environmentally friendly, which aids in reducing resource waste of resources and mitigates problems with environmental pollution emissions arising from the development of traditional manufacturing to some extent. Therefore, this paper proposes the following research hypotheses:

Hypothesis 1: Digital economy has a positive impact on air pollution, that is, digital economy has emissions reduction effect on air pollution.

3.2 Emissions increase effect

Many studies have shown that the digital economy can reduce environmental pollution. However, we cannot disregard the negative impact of the digital economy on environmental pollution. The development of the digital economy has improved the efficiency of environmental management, but the scale expansion owing to the development of the digital economy has caused energy rebound effects and exacerbated pollutant emissions (Li and Wang, 2022). Han et al. (2016) found that the impact of digital transformation on energy use first decreases and then increases. Danish et al. (2019) observed that the digital economy has a heterogeneous impact on carbon emissions. Digitalization does not necessarily lead to a reduction in CO_2 emissions (Shvakov and Petrova, 2020). Thus, the digital economy's impact on air pollution is not always positive.

The emissions increase effect of the digital economy on air pollution emissions is mainly reflected in the following factors. First, the digital economy development drives the expansion of the scale of economic activities and affects pollution emissions through the scale effect (Zhou et al., 2018). In addition to improving energy efficiency and environmental management efficiency, the application of the digital economy allows enterprises to purchase new production facilities, improve the level of production technology and expand the scale of production, thus causing the energy rebound effect (Li and Wang, 2022), which can increase the amount of energy and resource consumption and subsequently generate air pollution emissions.

Second, the application of digital technology itself also consumes electricity, such as in the development of the digital economy, which requires big data, cloud computing, and other technology support. The operation of these internet facilities requires a large amount of electricity (Salahuddin and Alam, 2015). Peng (2013) emphasized that digital infrastructure increases the electricity demand. Therefore, the development of the digital economy increases the pressure on the environment. Moreover, China's power industry is dominated by coal-fired power generation, which leads to increased air pollution.

Third, the application of digital technology in other industry sectors also partially accelerates the development of these industries, optimizes the supply of products and services, enhances consumer demand, partially increases energy consumption, and may increase air pollution emissions. For example, the use of digital technology in transportation facilities has increased operational efficiency while shortening travel times, such that people now travel more resulting in increased energy consumption and fossil fuel combustion, thereby increasing air pollutant emissions. Similarly, the application of digital technology in the logistics industry has led to shorter delivery times, more accurate delivery services, gradual development of the industry even in remote areas, and increased demand for industry expansion. This also increases energy consumption and, thus, air pollution emissions.

Digitalization has a certain "green blindness" and may have negative externalities on the environment (Yang et al., 2022), leading to increased air pollution emissions. For example, the widespread use of digital technologies in other industries, such as mining, has increased the scale of rare metal and mineral extraction, leading to the excessive consumption of resources and negative environmental issues, in turn leading to increased air pollution emissions. In view of this, the authors assert the following hypothesis:

Hypothesis 2: Digital economy has a negative impact on air pollution, that is, digital economy has emissions increase effect on air pollution.

Therefore, based on the analysis of the emissions reduction and emissions increase effects of the digital economy on air pollution, the authors found that the impact of the digital economy on air pollution contains both a reduction effect, i.e., the digital economy increases air pollution to a level greater than that of frontier air pollution, and an increase effect, i.e., the digital economy decreases air pollution to a lower level than that of frontier air pollution. Ultimately, the actual impact of the digital economy on air pollution is a combination of the two effects. Figure 1 illustrates the above mechanism.

4 Methodology

4.1 Two-tier stochastic frontier model

According to previous analyses, two opposite effects of the digital economy on air pollution emissions exist: emissions increase and emissions reduction effects. Therefore, this study used the idea of Kumbhakar and Parmeter (2009) to construct a two-tier stochastic frontier model (Liu et al., 2019):

$$\mathrm{InPm2.5}_{it} = i(x_{it}) + \omega_{it} - u_{it} + \varepsilon_{it} = i(x_{it}) + \xi_{it} = x_{it}\delta + \xi_{it} \quad (1)$$

where $\mathrm{InPm2.5}_{it}$ is air pollution; x_{it} is a set of control variables affecting air pollution, specifically the *per capita* GDP, *per capita* road area, population density, urbanization rate, industrial structure,

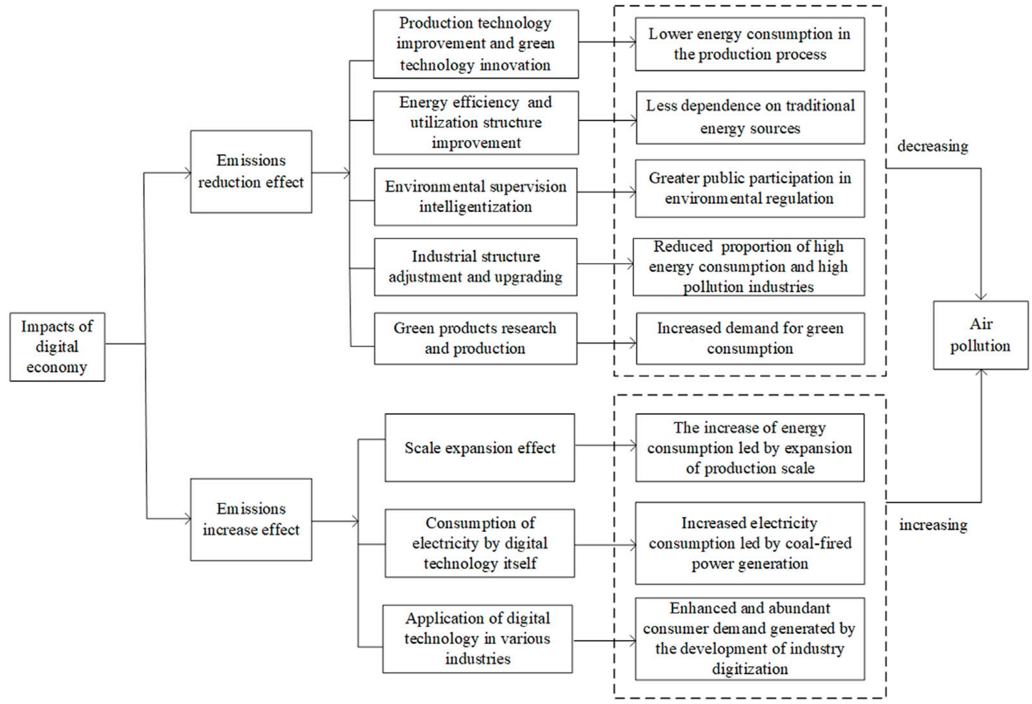

FIGURE 1
Mechanisms of bilateral effects of the digital economy on air pollution.

trade openness, government support, environmental regulation, average years of schooling, and energy consumption intensity; δ is the parameter vector to be estimated; $i(x_{it})$ is the frontier of air pollution; ξ_{it} is the composite error term; and $\xi_{it} = \omega_{it} - u_{it} + \varepsilon_{it}$, ε_{it} is the random error term, reflecting the deviation of air pollution from the frontier air pollution caused by unobservable factors. The conditional expectation of the composite residual term may not be equal to 0, which will lead to biased OLS estimation results. When the OLS estimation results are biased, the maximum likelihood estimation (MLE) method provides valid results. MLE, according to Eq. 1, ω_{it}, and u_{it} were decomposed to reflect the upward and downward bias effects in the optimal case, respectively. In Eq. 6, $\omega_{it} \geq 0$ denotes the emissions increase effect of the digital economy on air pollution; $u_{it} \leq 0$ denotes the emissions reduction effect of digital economy on air pollution; and $u_{it} \leq 0$, $\omega_{it} = 0$, or $\omega_{it} \geq 0$, $u_{it} = 0$ indicates that the model becomes a one-sided stochastic frontier model. In other words, the digital economy has only a unilateral effect on air pollution. When $\omega_{it} = u_{it} = 0$ the model becomes an OLS. If both are not zero, there is a bilateral effect of the digital economy on air pollution. As it may not be zero, this will lead to biased OLS model estimates.

According to Eq. 6, the actual air pollution is ultimately the result of a bilateral combination of both emissions increase and reduction effects of the digital economy. The emissions increase effect of the digital economy on air pollution increases air pollution to higher than the frontier air pollution amount, while the emissions reduction effect of the digital economy on air pollution decreases air pollution to lower than the frontier air pollution amount. The deviation in the actual air pollution can be measured by calculating the net effect of the joint influence of the two. Additionally, as the results obtained from the OLS estimations are biased, valid estimation results can be obtained using the MLE method. Therefore, the authors can use the following assumptions regarding the residual distribution. The random error term follows a normal distribution with a zero mean and zero variance. In other words, $\varepsilon_{it} \sim iddN(0, \sigma_\varepsilon^2)$; both ω_{it} and u_{it} follow an exponential distribution, i.e., $\omega_{it} \sim idd\,EXP(\sigma_\omega, \sigma_\omega^2)$, $u_{it} \sim iddNEXP(\sigma_u, \sigma_u^2)$, and the error terms satisfy the independence assumption condition between them and are not correlated with the inter-provincial characteristic variables. The probability density functions of ξ_{it} were derived based on the distribution assumed above (see Kumbhakar and Parmeter, 2009 for the full derivation):

$$f(\xi_{it}) = \frac{\exp(\alpha_{it})}{\sigma_u + \sigma_\omega}\Phi(\gamma_{it}) + \frac{\exp(\beta_{it})}{\sigma_u + \sigma_\omega}\int_{-\eta_{it}}^{\infty}\varphi(x)dx = \frac{\exp(\alpha_{it})}{\sigma_u + \sigma_\omega}\Phi(\gamma_{it}) + \frac{\exp(\beta_{it})}{\sigma_u + \sigma_\omega}\varphi(\eta_{it}) \quad (2)$$

where $\Phi(\cdot)$ and $\varphi(\cdot)$ are the standard normal cumulative distribution function (CDF) and standard normal distribution probability density function (PDF), respectively. The following settings were used for the other parameters:

$$\alpha_{it} = \frac{\sigma_v^2}{2\sigma_\omega^2} + \frac{\xi_i}{\sigma_\omega} \quad \beta_{it} = \frac{\sigma_v^2}{2\sigma_u^2} - \frac{\xi_i}{\sigma_u}$$
$$\gamma_{it} = -\frac{\xi_{it}}{\sigma_v} - \frac{\sigma_v}{\sigma_u} \quad \eta_{it} = \frac{\xi_{it}}{\sigma_v} - \frac{\sigma_v}{\sigma_\omega} \quad (3)$$

Based on the parameter estimation in Eq. 3, the expression of MLE was constructed as follows:

$$1n L(X;\pi) = -n\ln(\sigma_\omega + \sigma_u) + \sum_{i=1}^{n} 1n\left[e^{\alpha_{it}}\Phi(\gamma_{it}) + e^{\beta_{it}}\Phi(\eta_{it})\right] \quad (4)$$

Among them, $\pi = [\beta, \sigma_v, \sigma_\omega, \sigma_u]$. Likelihood function expressed by Eq. 4 was further maximized, resulting in a maximum likelihood estimate for all parameter values. Additionally, the authors estimated ω_{it} and u_{it}. Therefore, the conditional density functions for both were derived as follows (Kumbhakar and Parmeter, 2009):

$$f(\omega_{it}|\xi_{it}) = \frac{\left(\frac{1}{\sigma_u}+\frac{1}{\sigma_\omega}\right)\exp\left[-\left(\frac{1}{\sigma_u}+\frac{1}{\sigma_\omega}\right)\omega_{it}\right]\Phi\left(\frac{\omega_{it}}{\sigma_v}+\eta_{it}\right)}{\exp(\beta_{it}-\alpha_{it})\left[\Phi(\eta_{it})+\exp(\alpha_{it}-\beta_{it})\Phi(\gamma_{it})\right]} \text{ and} \quad (5)$$

$$f(u_{it}|\xi_{it}) = \frac{\left(\frac{1}{\sigma_u}+\frac{1}{\sigma_\omega}\right)\exp\left[-\left(\frac{1}{\sigma_u}+\frac{1}{\sigma_\omega}\right)u_{it}\right]\Phi\left(\frac{u_{it}}{\sigma_v}+\eta_{it}\right)}{\Phi(\eta_{it})+\exp(\alpha_{it}-\beta_{it})\Phi(\gamma_{it})}. \quad (6)$$

Based on Eqs 5, 6, the conditional expectations of ω_{it} and u_{it} could be estimated as follows (Kumbhakar and Parmeter, 2009):

$$E(\omega_{it}|\xi_{it}) = \frac{1}{\left(\frac{1}{\sigma_u}+\frac{1}{\sigma_\omega}\right)} + \frac{\sigma_v\left[\Phi(-\eta_{it})+\eta_{it}\Phi(\eta_{ii})\right]}{exp(\beta_{it}-\alpha_{it})\left[\Phi(\eta_{it})+exp(\alpha_{it}-\beta_{it})\Phi(\gamma_{it})\right]} \quad (7)$$

$$E(u_{it}|\xi_{it}) = \frac{1}{\left(\frac{1}{\sigma_u}+\frac{1}{\sigma_\omega}\right)} + \frac{\exp(\alpha_{it}-\beta_{it})\sigma_v\left[\Phi(-\gamma_{it})+\eta_{it}\Phi(\gamma_{ii})\right]}{\Phi(\eta_{it})+\exp(\alpha_{it}-\beta_{it})\Phi(\gamma_{it})} \quad (8)$$

Using Eqs 7, 8, the authors estimated the absolute extent of air pollution deviation from frontier air pollution, facing both emissions increase and emissions reduction effects.

To facilitate comparison, the absolute degree value of the deviation from the degree of air pollution influenced by the digital economy was further converted into a percentage above or below the frontier level using the following conversion formula (Cheng and Hong, 2022):

$$E(1-e^{-\omega_{it}}|\xi_{it}) = 1 - \frac{\frac{1}{\left(\frac{1}{\sigma_u}+\frac{1}{\sigma_\omega}\right)}\left[\Phi(\gamma_{it})+\exp(\beta_{it}-\alpha_{it})\exp\left(\frac{\sigma_v^2}{2}-\sigma_v\eta_{it}\right)\Phi(\eta_{it}-\sigma_v)\right]}{\left[1+\left(\frac{1}{\sigma_u}+\frac{1}{\sigma_\omega}\right)\right]exp(\beta_{it}-\alpha_{it})\left[\Phi(\eta_{it})+exp(\alpha_{it}-\beta_{it})\Phi(\gamma_{it})\right]} \quad (9)$$

$$E(1-e^{-u_{it}}|\xi_{it}) = 1 - \frac{\frac{1}{\left(\frac{1}{\sigma_u}+\frac{1}{\sigma_\omega}\right)}\left[\Phi(\eta_{it})+\exp(\alpha_{it}-\beta_{it})\exp\left(\frac{\sigma_v^2}{2}-\sigma_v\gamma_{it}\right)\Phi(\gamma_{it}-\sigma_v)\right]}{\left[1+\left(\frac{1}{\sigma_u}+\frac{1}{\sigma_\omega}\right)\right]\left[\Phi(\eta_{it})+\exp(\alpha_{it}-\beta_{it})\Phi(\gamma_{it})\right]} \quad (10)$$

Further, the net effect of the digital economy's impact on air pollution was derived based on Eqs 9, 10 as follows (Kumbhakar and Parmeter, 2009):

$$NE = E(1-e^{-\omega_{it}}|\xi_{it}) - E(1-e^{-u_{it}}|\xi_{it}) = E(e^{-u_{it}}-e^{-\omega_{it}}|\xi_{it}) \quad (11)$$

where NE represents the difference between the emissions increase effect and emissions reduction effect. If NE > 0, the emissions increase effect is stronger than the emissions reduction effect, i.e., the emissions increase effect plays a dominant role; if NE < 0, the emissions reduction effect is stronger than the emissions increase effect, i.e., the emissions reduction effect plays a dominant role.

4.2 Description of data and variables

With reference to the above theoretical and empirical model settings, as well as considering the data availability, the authors selected Chinese provincial panel data from 2011 to 2020 to analyze the impact of the digital economy on provincial air pollution. Tibet, Hong Kong, Macao, and Taiwan were excluded due to a lack of data. The data for the variables selected for this study were obtained from the China Statistical Yearbook, China Science and Technology Statistical Yearbook, ESP Global Database and National Bureau of Statistics. Specifically, the variables involved were set as follows.

4.2.1 Explained variable

4.2.1.1 Air pollution

Given that pollution data in China are difficult to obtain, the available data have disadvantages, such as short continuous spans, and are not suitable for long panel analysis. Therefore, in this study, based on Li and Zhang (2019), the authors used air pollution raster data jointly published by Columbia University and the U.S. Atmospheric Composition Group. By matching the PM2.5 raster data with the latitude and longitude of each province through the ArcGIS software, the average value of all raster data in each province was calculated to represent the PM2.5 concentration per cubic meter of air in that province. This core air pollution indicator was processed logarithmically and denoted as lnPm2.5. This indicator has two advantages. First, air pollution data extracted from satellite maps are more objective and cover a wider area than ground-based observation data, avoiding potential data manipulation and missing data problems. Second, particulate matter is the most important pollutant emitted in China; PM2.5 not only incorporates combusted fossil fuels and their pollutant emissions in the air as further chemical reactants but also easily penetrates indoor areas (Chang et al., 2016), aiding in analyzing interior or exterior enterprise production.

4.2.2 Explanatory variables

4.2.2.1 Digital economy development level

The authors used the approach reported by Zhao et al. (2020), and combined it with those by Liu et al. (2020) and Huang et al. (2019). Indicators, including the number of internet broadband access users per 100 people, proportion of employees in the computer services and software industry to the employees in urban units, total amount of telecom services *per capita*, and number of mobile phone users per 100 people, were selected to indicate the level of digital economy development. Digital financial inclusion is an important manifestation of digital economy development measured using the provincial digital inclusive finance index in China compiled by Guo et al. (2020). This measures the breadth of digital financial coverage, depth of use, and the degree of digitization in three main aspects. Based on these measurement indices, the entropy weight method was used to measure the level of regional digital economy development, denoted as sdig.

4.2.3 Controlled variables

1) The level of economic development, denoted as lnPGdp after taking the logarithm, was measured by the *per capita* GDP as reported by Kuang et al. (2022). 2) The natural logarithm of the *per capita* road area, denoted as lnTF, was selected to measure transportation infrastructure with reference to Sun et al. (2019). 3) Following Yi et al. (2020), the natural logarithm of the ratio of the total population to the total area of the administrative district at the

TABLE 1 Descriptive statistical analysis of the main variables.

Variables	Symbols	Sample size(obs)	Average value	Standard deviation	Min value	Max value
Air pollution	lnPm2.5	300	3.586	0.395	2.258	4.450
Digital economy	sdig	300	0.327	0.142	0.125	0.937
Per capita GDP	lnPGdp	300	10.841	0.436	9.706	12.013
Per capita road area	lnTF	300	2.710	0.360	1.396	3.288
Population density	LnPM	300	7.892	0.410	6.639	8.710
Urbanization rate	lnCity	300	4.046	0.199	3.555	4.495
Industrial structure	lnIND	300	3.739	1.261	0.457	7.294
Trade openness	lnOpen	300	1.722	2.277	−3.679	7.541
Government support	lnGOV	300	3.147	0.376	2.400	4.160
Environmental regulation	EG	300	0.049	0.090	0.016	0.767
Average years of education	Hum	300	9.229	0.911	7.514	12.718
Energy consumption intensity	EQ	300	0.825	0.485	0.207	2.327

end of the year was used to measure the population density and was denoted as LnPM. 4) The urbanization rate was measured by the ratio of the number of residents to the total number of urban residents and denoted as lnCity after taking the logarithm based on Gan et al. (2020). 5) Cheng and Hong, 2022) examined industrial structure, where the natural logarithm of the proportion of the value added from secondary industry in the regional GDP (lnIND) was used to characterize the level of urbanization. 6) Government support was expressed as the logarithm of the share of the general budget expenditure in the GDP. 7) The degree of trade openness was expressed by the logarithm of the ratio of total imports and exports to the GDP, referring to Li et al. (2019). As imports and exports for the year are denominated in US dollars, they were converted to RMB 10 000 using the annual average US-China exchange rate published in the China Statistical Yearbook; the logarithm of the GDP was calculated and denoted as lnOPEN. 8) Environmental regulation, based on Tian and Feng (2022), was measured by the proportion of environmental pollution control investment in the GDP and denoted as EG. 9) The logarithm of the average number of years of schooling was used to measure human capital according to Su and Yu (2020) and denoted as Hum. 10) The energy consumption intensity, using the total energy consumption as a share of the GDP, was symbolized by EQ. Additionally, variables involving price factors were deflated in this study using 2011 as the base period. Table 1 presents the results of the descriptive statistics for the main variables.

5 Empirical analysis, results, and discussion

5.1 Two-tier stochastic frontier estimation

5.1.1 Baseline regression model

Based on the MLE, the bilateral effects of the digital economy on air pollution were decomposed according to the econometric Eq. 1 model. Table 2 lists the estimation results. Among them, the second column shows the OLS estimation results of model (1) without considering the deviation effect; model (2) does not control the time-fixed effect and area-fixed effect; model (3) controls for area-fixed effects only; model (4) controls for both area-fixed effects and time-fixed effects; model (5) considers only the unilateral estimation results of the emissions reduction effect of the digital economy on air pollution, i.e., the model residual term u_{it}; model (6) shows the unilateral estimation results considering only the digital economy's increase effect on air pollution, i.e., the model residual term ω_{it}; and the estimation results of model (7) consider both the emissions increase effect and emissions reduction effect of the digital economy on air pollution, i.e., the model residual term ω_{it} and u_{it}. According to the model likelihood ratio test (LR), after adding the deviation effect, model (7) was more reasonable than the OLS estimation and remaining models. After a comprehensive comparison, the authors finally used model (7) as the basis for the subsequent analysis of the bilateral effect decomposition measure of the digital economy.

Based on the estimation results of model (7), the estimated coefficient of the emissions increase effect of the digital economy was significantly positive, indicating that it increases the amount of air pollution. The estimated coefficient of the emissions reduction effect of the digital economy was significantly negative, indicating that it significantly suppressed increases in air pollution. Accordingly, the hypothesis that the effects of the digital economy on air pollution exist simultaneously in the theoretical hypothesis of this study was initially verified based on the estimation results of model (7).

5.1.2 Variance decomposition: Measuring bilateral effects of digital economy on air pollution

To comprehensively analyze which of the two effects of the digital economy on air pollution is dominant, the authors must decompose the emissions reduction and emissions increase effects of the digital economy on air pollution based on model (7) in Table 2. Table 3 lists the decomposition results. The degree of the emissions increase and emissions reduction effects of the digital economy on air pollution were

TABLE 2 Basic estimation results of the two-tier stochastic frontier model for the digital economy.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	OLS	M0	M1	M2	M3	M4	M5
lnPGdp	0.139***	0.168***	0.035**	0.015	0.007	−0.002***	−0.005***
	(3.04)	(75.63)	(2.03)	(0.85)	(0.39)	(−8.32)	(−88.83)
lnTF	0.102*	0.101***	0.080	0.129**	0.134**	0.135***	0.101***
	(1.83)	(38.28)	(1.16)	(2.33)	(2.47)	(218.00)	(310.81)
LnPM	−0.030	−0.092***	−0.086**	0.019	−0.011	−0.026***	−0.012***
	(−0.67)	(−45.80)	(−2.42)	(0.64)	(−0.35)	(−68.11)	(−69.57)
lnCity	−1.064***	−1.258***	−0.962***	0.067	−0.216	−0.401***	−0.078***
	(−6.50)	(−128.77)	(−5.30)	(0.41)	(−1.16)	(−109.36)	(−90.98)
lnIND	0.205***	0.229***	0.048***	−0.000	0.005	0.007***	0.012***
	(7.86)	(316.23)	(3.09)	(−0.03)	(0.35)	(37.62)	(125.68)
lnOpen	−0.035*	−0.033***	−0.052***	−0.018**	−0.018**	−0.018***	−0.021***
	(−1.86)	(−39.58)	(−6.18)	(−2.30)	(−2.32)	(−272.23)	(−420.17)
lnGOV	−0.511***	−0.461***	−0.052	0.041	0.031	0.034***	−0.005***
	(−7.60)	(−123.94)	(−1.56)	(1.25)	(0.91)	(67.25)	(−29.20)
EG	0.088	0.029***	−0.267***	−0.180**	−0.181**	−0.180***	−0.313***
	(0.44)	(5.07)	(−4.05)	(−2.23)	(−2.28)	(−149.96)	(−958.97)
AEDU	0.365***	0.356***	−0.053**	−0.014	−0.007	0.012***	0.006***
	(10.58)	(159.97)	(−2.35)	(−0.81)	(−0.39)	(103.05)	(130.72)
EQ	0.039	0.126***	0.193***	0.073	0.089	0.138***	0.120***
	(0.70)	(47.62)	(2.85)	(1.18)	(1.52)	(234.70)	(543.29)
_cons	3.842***	4.591***	7.608***	3.470***	4.938***	5.466***	4.491***
	(4.05)	(121.73)	(9.19)	(4.19)	(5.27)	(351.20)	(906.09)
sigma_v							
_cons		−14.277	−2.680***	−2.901***	−3.184***	−17.975	−20.710
		(−0.04)	(−22.39)	(−17.49)	(−10.92)	(−0.06)	(−0.03)
sigma_u							
sdig					−2.464**		−1.319***
					(−2.48)		(−3.01)
_cons			−2.745***	−3.128***	−4.094***	−3.360***	−3.388***
			(−14.88)	(−16.81)	(−9.08)	(−41.28)	(−20.92)
sigma_w							
sdig						1.118**	0.329**
						(2.53)	(2.63)
_cons			−5.877	−4.876	−3.217***	−3.044***	−3.081***
			(−0.23)	(−0.64)	(−9.23)	(−19.02)	(−17.04)
pro fixed	No	No	Yes	Yes	Yes	Yes	Yes
Year fixed	No	No	No	Yes	Yes	Yes	Yes
N	300	300	300	300	300	300	300

Note: t statistics in parentheses. *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

TABLE 3 Variance decomposition: Emissions increase and emissions reduction effects of digital economy on air pollution.

	Variable meaning	Symbol	Coefficient
Digital economy	Random error term	sigma_v	0.0000
	Emissions increase effect	sigma_w	0.0512
	Emissions reduction effect	sigma_u	0.0530
Variance decomposition	Total random error term	Total sigma_sqs	0.0054
	Weight of the joint effect of emissions increase and emissions reduction effects	(sigu2 + sigw2)/Total	1.0000
	Weight of emissions increase effect	sigw2/(sigu2 + sigw2)	0.4829
	Weight of emissions reduction effect	sigu2/(sigu2 + sigw2)	0.5171
		sig_u–sig_w	0.0018

0.0512 and 0.0530, respectively, such that the degree of the net effect of the digital economy on air pollution was $E(\omega - u) = \sigma_{\omega}\text{-}\sigma_{u} = -0.0018$. The decomposition results show that the net effect of the digital economy on air pollution was manifested by the inhibition of the increase in air pollution. Generally, as the digital economy has both emissions increase and emissions reduction effects, the emissions reduction effect dominates, which eventually leads to actual air pollution lower than the frontier pollution level at the provincial level; in other words, the digital economy has a suppressive effect on air pollution.

Further, based on the decomposition model, the proportional size of the emissions increase and emissions reduction effects of the digital economy on air pollution were decomposed to more accurately compare the actual effects of the digital economy. Based on the results in Table 3, the emissions reduction effect of the digital economy accounted for 51.71%, whereas the emissions increase effect of the digital economy accounted for 48.29%. This result shows that the proportion of the air pollution emissions reduction effect of the digital economy was significantly larger than its air pollution emissions increase effect, indicating the domination of the reduction effect of the digital economy. This again shows the correctness of the above estimation result: the digital economy significantly suppresses air pollution aggravation through the reduction effect.

5.1.3 Degree of impact of the digital economy on the two effects of air pollution

After analyzing the effect of the digital economy on air pollution, the deviation in the regional air pollution compared to the optimal air pollution level was further calculated. The specific calculation was based on Eqs 7–11 in the model. These equations show the percentage of actual air pollution deviation from the air pollution frontier level and the final net effect weight after the digital economy influences air pollution. The authors compared the net effect size of the emissions increase effect and emissions reduction effect percentage. Thus, the real impact of the digital economy on air pollution was determined.

Based on the results in Table 4, the emissions increase effect of the digital economy resulted in air pollution higher than the frontier level by 4.87% while the emissions reduction effect of the digital economy resulted in air pollution lower than the frontier level by 5.02%. Finally, the combined effect of both caused air pollution to be lower than the frontier level by 0.15%. This suggests that the asymmetry of the bilateral effects of the digital economy is characterized by an overall emissions reduction effect on air pollution levels.

TABLE 4 Estimated net effect (%) of the digital economy on air pollution.

Variable	Mean	Variance	p25	p50	p75
Emissions increase effect	4.87	4.05	2.38	2.86	5.51
Emissions reduction effect	5.02	4.63	2.38	2.72	6.51
Net effect	−0.15	6.99	−3.85	0.00	3.02

Based on the above analysis, the distribution of the two effects of the digital economy on air pollution was further analyzed. Table 4 presents the differences in the two effects of the digital economy on air pollution at different percentile levels. Specifically, the emissions increase effect of the digital economy on air pollution increased from 2.38% to 5.51% at the p25, p50, and p75 quartiles, respectively, while the emissions reduction effect increased from 2.38% to 6.51%. The difference between the two effects is widening; at the national level, the emissions reduction effect consistently dominated during the sample period, suggesting that the digital economy improves air pollution, which is consistent with the above findings.

Figure 2 shows the frequency distribution of the emissions increase effect, emissions reduction effect, and net effect of the digital economy on air pollution. The emissions reduction effect of the digital economy on air pollution showed a right-trailing feature. The emissions reduction effect at approximately 40% indicates that air pollution in some provinces is more sensitive to the changes and hence, vulnerable to the level of digital economy development. The emissions increase effect of the digital economy to promote air pollution ended at approximately 25%, which is significantly lower than the emissions reduction effect, indicating that air pollution in some provinces is less affected by the emissions increase effect of the digital economy. The distribution of the net effect shows that most provinces are affected by the emissions reduction effect of the digital economy while only a few are affected by the emissions increase effect. These results show that the digital economy has a reducing effect on air pollution, which is consistent with the results of theoretical analysis.

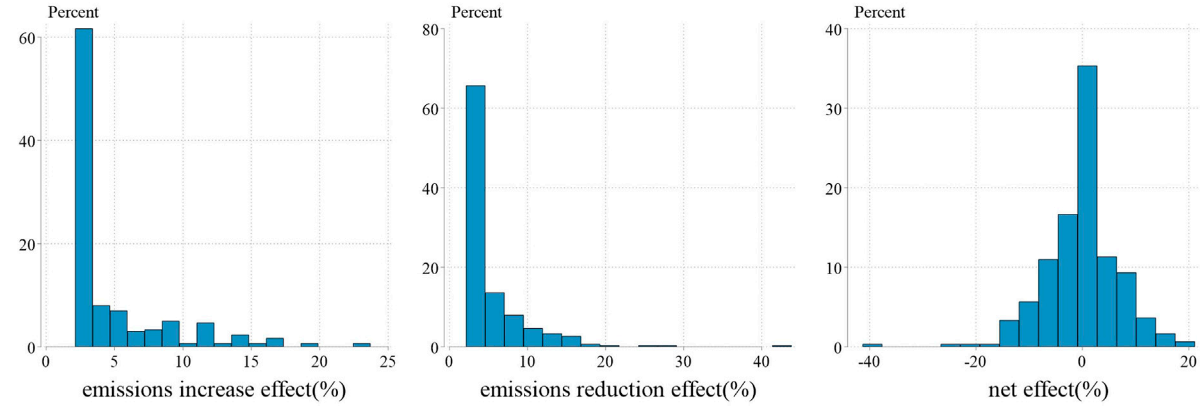

FIGURE 2
Distribution of the emissions increase effect, emissions reduction effect, and net effect of the digital economy.

5.2 Regional characteristics of air pollution affected by the digital economy

The distribution characteristics of the digital economy's net effect on air pollution in different provinces and regions were further examined (Table 5). In terms of the regional distribution, the net effect of the digital economy on air pollution was negative in all three regions with values of −1.22%, −0.28%, and −1.01%, indicating that the digital economy in all three regions had a suppressive effect on air pollution. Specifically, the net effect of the digital economy on air pollution was negative for the three major regions, ranking as East > West > Central. The eastern region has a higher level of digital economy development, better infrastructure, and stricter environmental regulations, which are conducive to air pollution control. Additionally, with the development of the digital economy, the regional industrial structure has been upgraded, which further strengthens the emissions reduction effect of digital economy. Second, the central and western regions have undertaken some of the high pollution, high emissions, and high energy-consuming industries from the eastern regions, leading to the intensification of environmental pollution in the region. The digital economy has been used at a large scale in production and urban operation and management, which accelerates the release of emissions reduction dividends. The distorted state of mismatch between the industrial structure and factor resources is notable; the development of the internet can yield a significant upgrading effect in the industrial structure, thus improving the level of air pollution. Particularly, the western region undertakes the transfer of industry and technology from the eastern cities to become the main position for energy savings and emissions reduction. The development of the digital economy can effectively promote the learning, digestion, and innovation of transferred technology in the western region to enhance the level of technological innovation, thus fully utilizing the advantage of technological innovation in the role of air pollution reduction.

5.3 Temporal characteristics of the digital economy affecting air pollution

To further identify the characteristics of the temporal trend changes in the digital economy's impact on air pollution, the differences in the impacts of digital economy on air pollution in different years were analyzed based on time variables, as shown in Figure 3. The emissions reduction effect of the digital economy dominated within the sample in most years, with effect sizes ranging from −1.39% to 1.21%. Overall, as time progressed, the emissions increase effect of the digital economy on air pollution alternately increased with the emissions reduction effect. The net effect of the digital economy changed in a wave-like manner under both effects combined. The net effect of the digital economy was positive in 2015, 2016, and 2018. This phenomenon shows that the two effects of the digital economy on air pollution co-existed and exhibited asymmetric changes, further validating the rationality of the theoretical analysis. This phenomenon can be explained by the fact that in the early stage of digital economy development, the effect of digital economy air pollution management emerged, air pollution partially improved, and the emissions reduction effect of the digital economy dominated during this period. Between 2014 and 2018, the digital economy further developed, but there was an "energy rebound" effect, a large amount of energy and materials, and infrastructure implementation, resulting in increased air pollution. During this period, the emissions increase effect of the digital economy was significantly stronger than its emissions reduction effect. After 2018, the net effect of the digital economy was significantly negative as the intelligence and precision of environmental regulation, governance, and services were being promoted to compensate for their existing deficiencies. In other words, the digital economy reduced air pollution as a net effect.

5.4 Analysis of differences between the impacts at different levels of digital economy development

Based on the previous analysis, digital economy is characterized by an overall inhibitory effect on air pollution levels. The distribution of bilateral effects under different levels of the digital economy development was analyzed by grouping digital economy development into high, medium, and low levels using the 25% and 75% quartiles as boundaries. Among them, digital economy with

TABLE 5 Characteristics of the annual distribution of the net effect of the digital economy on air pollution (%).

Province	Net effect mean	SD	p25	p50	p75
Shanghai	−3.68	15.44	−6.33	−0.48	6.41
Yunnan	3.26	6.43	−2.80	0.81	9.66
Inner Mongolia	−1.35	7.76	−6.10	0.00	5.08
Beijing	−7.61	10.47	−17.02	−2.76	0.66
Jilin	1.08	7.38	−4.55	0.00	4.51
Sichuan	−0.64	4.77	−3.73	−0.25	1.30
Tianjin	−1.22	4.43	−4.61	−1.62	1.90
Ningxia	0.14	6.08	−4.99	0.12	5.22
Anhui	−0.19	2.69	−1.15	0.20	1.70
Shandong	2.44	6.28	−0.13	0.19	8.77
Shanxi	−2.97	7.38	−9.25	0.00	0.87
Guangdong	−0.50	7.43	−5.89	0.00	1.12
Guangxi	0.90	6.45	−3.70	0.00	4.56
Xinjiang	4.85	10.01	−3.07	0.00	12.16
Jiangsu	−1.35	5.96	−3.08	0.00	1.61
Jiangxi	1.07	5.58	−2.25	−0.44	3.83
Hebei	0.55	3.92	−2.47	−0.08	2.76
Henan	−0.34	4.63	−1.24	0.00	2.52
Zhejiang	0.21	5.42	−3.68	−0.01	2.88
Hainan	−1.97	6.15	−7.10	−0.86	2.01
Hubei	−1.77	5.04	−5.59	−1.98	3.40
Hunan	0.05	5.97	−3.40	0.00	2.73
Gansu	1.93	6.03	−0.16	0.27	4.28
Fujian	−0.44	3.89	−3.22	−0.13	0.71
Guizhou	0.66	6.88	−1.48	−0.21	3.30
Liaoning	0.13	6.38	−4.69	0.22	3.41
Chongqing	0.65	7.12	−6.57	0.00	6.20
Shaanxi	−1.88	5.57	−7.32	0.00	1.81
Qinghai	2.60	8.22	−0.15	0.00	8.67
Heilongjiang	0.85	7.37	−3.26	0.00	7.09
Eastern Region	−1.22	7.67	−4.27	0.00	2.29
Central Region	−0.28	5.85	−4.10	0.00	2.97
Western Region	−1.01	6.93	−3.07	0.00	5.22

(Sdig) ≤ 0.223 represents the low-level group, 0.223 < (Sdig) ≤ 0.408 represents the medium-level group, and (Sdig) > 0.408 represents the high-level group; the results are listed in Table 6. As the development level of the digital economy increased, the mean value of the emissions increase effect of the digital economy on air pollution increased from 4.68% in the low-level group to 5.09% in the high-level group; the mean value of its emissions reduction effect from 4.12% in the low-level group to 6.29% in the high-level group. The combined effect of both allowed the mean value of the net effect to turn from positive to negative, indicating that although the emissions reduction effect of the digital economy on air pollution was always dominant on considering the complete sample, there was significant heterogeneity in the effect of the digital economy on air pollution at different levels of the digital economy. This may be because the integration of the digital economy and environmental governance not only changes the traditional environmental governance model but can also impact air pollution by improving the efficiency of environmental governance decision-making and regulation, as well as more efficient environmental governance models, such as network participation in governance. Considering the initial development of the digital economy, various factors are not well configured, and the effect of environmental governance is still unclear. As the level of the digital economy continues to improve, intelligent monitoring systems, energy-saving technologies, and environmental protection technologies will greatly improve the level of pollution generation and emissions monitoring, as well as the efficiency of resource utilization, which in turn can improve the level of environmental pollution prevention and control in enterprises and reduce air pollution. In summary, the impact of the digital economy on air pollution is a long-term cumulative process that requires dynamic consideration of its impact on air pollution.

5.5 Analysis of differences in impact of digital economy under different human capital levels

The development of the digital economy has placed a higher demand on human capital. When the human capital of a region is sufficiently large, its industrial structure and population structure will improve accordingly while the agglomeration effect of human capital can partially buffer negative effects such as air pollution due to the digital economy. To test this conjecture, the average number of years of education was chosen to characterize human capital (Han et al., 2019). Human capital was grouped according to 25% and 75% quartiles. When human capital (EDU) ≤ 8.725, it was classified as a low-skilled group; when 8.725 < human capital (EDU) ≤ 9.485, it was classified as a medium-skilled group; and when human capital (EDU) > 9.485, it was classified a high-skilled group. Table 7 lists the results. The emissions increase effect of the digital economy on air pollution increased from 5.43% in the low-level group to 4.57% in the high-level group. The emissions reduction effect increased from 3.87% in the low-level group to 6.26% in the high-level group. The net effect of the combined effect of both turned positive to negative. This result suggests that an increase in human capital skills can partially strengthen the emissions reduction effect of the digital economy on air pollution. The possible reason for this is that the level of human capital is closely related to the technological progress of the region while the impact of the digital economy on air pollution is mainly reflected in energy savings and consumption reduction through technological progress and improvements to industrial digitalization. When the level of human capital was low, the technology level was also correspondingly low. At this time, clean production technologies provided by technological innovation to

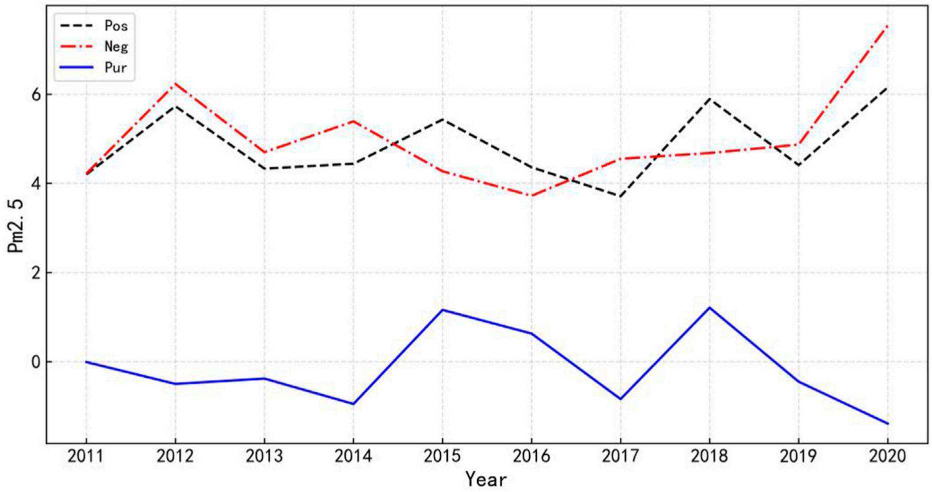

FIGURE 3
Characteristics of the annual distribution of the net effect of the digital economy on air pollution (%). Note: Pos indicates the emissions increase effect; Neg indicates the emissions reduction effect; and Pur indicates the net effect.

TABLE 6 Differences in the net effect (%) of air pollution at different levels of the digital economy.

Sdig	Effect decomposition	Average value	Standard deviation	p25	p50	p75
Low level group	Emissions increase effect	4.68	3.72	2.25	2.30	5.90
	Emissions reduction effect	4.12	3.43	2.23	2.28	5.15
	Net effect	0.55	5.91	−2.89	0.00	3.64
Medium level group	Emissions increase effect	4.85	4.23	2.40	2.57	5.23
	Emissions reduction effect	4.83	4.72	2.43	2.61	5.91
	Net effect	0.02	7.19	−3.46	0.00	2.76
High level group	Emissions increase effect	5.09	4.05	2.90	3.16	5.08
	Emissions reduction effect	6.29	5.25	2.84	3.18	8.33
	Net effect	−1.20	7.56	−5.48	−0.03	2.29

energy and production systems were being applied but could not actually improve air pollution prevention or management. Therefore, the emissions increase effect of the digital economy dominates at this stage. When human capital reached a high level, the technological innovation effect of the digital economy increased; its energy-saving and emissions reduction effects are also enhanced, effectively reducing the level of air pollution.

5.6 Analysis of differences in impact of digital economy at different economic development levels

The level of economic development in a region undoubtedly affects the local digital economy and air pollution. Accordingly, this study selected the *per capita* GDP to characterize the level of economic development and followed the grouping logic above to divide the level of economic development into three groups: high, medium, and low groups. Table 8 lists the results. The net effect of the digital economy on air pollution was 1.50% when economic development was in the low-level group ($PGdp \leq 3.717$), −0.22% when economic development was in the medium-level group ($3.717 < PGdp \leq 6.686$), and −3.40% when economic development was in the high-level group ($PGdp > 6.686$). The results showed that the digital economy's emissions reduction effect on air pollution increased as the level of economic development increased. When the level of economic development was sufficiently high, the digital economy development level was also relatively high; the scale of enterprises in these regions became larger. The size of enterprises is closely related to whether they can substantially invest in implementing intelligence and automation. With the

TABLE 7 Differences in the impact of the digital economy (%) on air pollution under different levels of human capital.

EDU	Effect decomposition	Average value	Standard deviation	p25	p50	p75
Low-skilled group	Emissions increase effect	5.43	4.80	2.28	2.57	7.71
	Emissions reduction effect	3.87	2.91	2.27	2.54	3.76
	Net effect	1.57	6.32	−1.36	0.00	5.28
Medium-skilled group	Emissions increase effect	4.73	3.83	2.37	2.73	5.58
	Emissions reduction effect	4.97	3.72	2.37	2.70	6.65
	Net effect	−0.24	6.30	−4.14	0.00	3.35
High-skilled group	Emissions increase effect	4.57	3.64	2.62	3.16	4.71
	Emissions reduction effect	6.26	6.88	2.63	2.98	7.42
	Net effect	−1.70	8.51	−4.69	0.00	2.13

Note: Years of education *per capita* = elementary school literacy * 6 + junior high school literacy * 9 + high school literacy * 12 + college and above literacy * 16.

TABLE 8 Differences in the impact of the digital economy (%) on air pollution at different levels of economic development.

PGdp	Effect decomposition	Average value	Standard deviation	p25	p50	p75
Low level group	Emissions increase effect	5.07	4.00	2.28	2.45	7.09
	Emissions reduction effect	3.57	2.58	2.24	2.34	3.76
	Net effect	1.50	5.45	−1.36	0.00	4.81
Medium level group	Emissions increase effect	4.85	4.39	2.38	2.68	5.18
	Emissions reduction effect	5.06	3.82	2.44	2.77	6.87
	Net effect	−0.22	6.75	−4.38	0.00	2.62
High level group	Emissions increase effect	4.70	3.38	2.69	3.24	4.78
	Emissions reduction effect	6.37	6.83	2.63	2.98	8.33
	Net effect	−1.67	8.44	−5.18	0.00	2.28

TABLE 9 Effect and variance decomposition of the impact of the digital economy on air pollution.

	Variable meaning	Symbols	Measurement coefficient
Digital economy	Random error term	sigma_v	0.0000
	Emissions increase effect	sigma_w	0.0380
	Emissions reduction effect	sigma_u	0.0701
Variance decomposition	Total random error term	Total sigma_sqs	0.0064
	Weight of the joint effect of emissions increase and emissions reduction effects	(sigu2 + sigw2)/Total	1.0000
	Weight of emissions increase effect	sigw2/(sigu2 + sigw2)	0.2274
	Weight of emissions reduction effect	sigu2/(sigu2 + sigw2)	0.7726
		sig_u − sig_w	0.0321

expansion of the enterprise scale, enterprises have sufficient capital to invest in production to improve productivity and intelligence, which will promote environmental protection and clean production, thus partially strengthening the effect of the digital economy on air pollution reduction.

5.7 Robustness test

To test the robustness of the results obtained, the authors used principal component analysis to recalculate the level of digital economy development based on Zhao et al. (2020) for robustness

TABLE 10 Degree of deviation in air pollution (%) due to the digital economy impact effect.

Variable	Average value	Standard deviation	p25	p50	p75
Emissions increase effect	3.49	3.70	1.79	1.95	2.92
Emissions reduction effect	6.35	6.63	1.83	2.65	9.07
Net effect	−2.86	8.59	−7.23	−0.80	1.53

testing. The emissions increase effect, emissions reduction effect, and net effect of the digital economy on air pollution were estimated again. The results are shown in Table 9. The results showed that the emissions increase effect of the digital economy on regional air pollution intensity was 0.0380 and the emissions reduction effect was 0.0701, consistent with previous results. This indicates that there is a bilateral effect from the digital economy on regional air pollution. In terms of the net effect, the emissions increase effect of the digital economy accounted for 22.74, and the emissions reduction effect accounted for 77.26%. This indicates that the robustness of the results can be further verified as the emissions reduction effect of the digital economy dominated the impact of the digital economy on air pollution, thus allowing the air pollution to deviate from its frontier level.

The emissions reduction effect, emissions increase effect, and net effect of the interaction between the digital economy on air pollution were further estimated. The results are listed in Table 10. The results show that as the development level of the digital economy increased, its emissions increase effect increased regional air pollution by 3.49%. In contrast, its emissions reduction effect reduced regional air pollution by 6.35%. The net effect yielded a regional air pollution level value relatively lower than the frontier level by 2.86%, which was roughly the same as that obtained during previous estimation.

6 Conclusion and policy recommendations

6.1 Conclusion

In this study, a two-tier stochastic frontier model was introduced to analyze the impact of the digital economy on air pollution using provincial Chinese panel data from 2011 to 2020. Based on existing studies, the authors analyzed the bilateral effects of the digital economy on air pollution through theoretical mechanism analysis and further empirically verified the effects using a two-tier stochastic frontier model. Specifically, this model was used to measure the net effect sizes of emissions increases, emissions reductions, and their mutual effects. On this basis, the impact of the digital economy on air pollution under different levels of the digital economy, human capital, and economic development was further discussed. The results of this study provided the following conclusions.

1. *Emissions increase effect and emissions reduction effect of digital economy on air pollution.* With the continuous development of China's digital economy, the emissions increase effect of the digital economy has allowed the air pollution to be higher than the frontier level by 4.87% while the emissions reduction effect of the digital economy has resulted in air pollution lower than the frontier level by 5.02%. The interaction of the two has eventually led to an actual air pollution emissions level that is 0.15% lower than the frontier level. Thus, the asymmetry of the bilateral effects of the digital economy at this stage caused an overall emissions reduction effect of the digital economy on the air pollution level. The digital economy development level was recalculated using principal component analysis and replaced with explanatory variables. The model results were consistent with those previous studies; therefore, the study findings remain robust. Therefore, when formulating policies to solve the air pollution problem, local government departments should consider the comprehensive impact of digital economy on air pollution. Otherwise, trying to reduce air pollution only by expanding the development scale of digital economy cannot fundamentally solve the air pollution problem.
2. *Spatial and temporal heterogeneity of bilateral effects of digital economy on air pollution.* The time-trend characteristics of the digital economy's net effect on air pollution emissions showed a wave-like change. The regional characteristics revealed that the average value of the net effect was negative. With the change in the time trend, the net effect of the digital economy on air pollution emissions increased alternately with the emissions reduction effect. The two effects co-existed and showed asymmetric changes, which resulted in a wave-like pattern for the net effect of the digital economy. The regional characteristics of the net effect of the digital economy on air pollution emissions showed that the mean values of the net effect in the three regions, i.e., east, central, and west, were negative: −1.22%, −0.28%, and −1.01%, respectively. The net effect of air pollution is dynamic, and although emissions reduction effect currently dominates, attention must be paid to reducing the negative environmental impact brought about by the development process of the digital economy; and the development gap of net effect of different regions cannot be ignored. The eastern or western region's digital economy has a greater emissions reduction effect, respectively on air pollution than the central region. By promoting the role of the digital economy in the green development of industries, green technological innovation and environmental regulation, the emission reduction of the digital economy is brought into play effect.
3. *Bilateral effects of the digital economy on air pollution under different constraints*. Along with the increase in the digital economy development level, human capital level, and economic development, the emissions reduction effect of the digital economy on air pollution was strengthened, thus achieving a positive to negative net effect. However, there were significant heterogeneous characteristics in the effects of the digital economy on air pollution under different

levels of digital economy development, human capital, and economic development. In particular, when the level of digital economy development from low to high, although both the emissions increase and emissions reduction effects of the digital economy on air pollution were strengthened, the emissions reduction effects was gradually stronger than the emissions increase effect, and the comprehensive impact on air pollution is changing from "increasing pollution" to "reducing pollution."

6.2 Policy recommendations

Based on the findings, the authors propose the following policy recommendations. The construction of a digital economy is important for enhancing the emissions reduction effect of the digital economy on air pollution.

First, it is necessary to comprehensively promote the digital economy such that it plays an effective role in enhancing the efficiency of energy use, improving the level of green technological innovation, giving birth to green industries, actively guiding enterprises to carry out digital transformation, and strengthening the construction of regional digitalization. Presently, China has implemented relevant regional policies for construction of digital economy, but he construction of the digital economy early zone needs to be strengthened. Particularly, the construction of the digital economy in areas with conditions of digitalization should be actively promoted to achieve the maximum effect of the digital economy word emissions reduction.

Second, under the constraints of different levels of digital economy development, human capital level, and economic development in different regions, a digital economy construction cooperation platform should be implemented, with the establishment of a mechanism for the cooperation and cultivation of innovative talents. This can aid in gathering innovative talent elements, receiving economic radiation from economically developed regions, and jointly building an integrated region for digital economy development. At this stage, the infrastructure and public services supporting the implementation of digital economy construction cooperation platforms and digital economy belts are relatively lagging, especially in the central and western regions. For the central and western regions, cooperation with the eastern region must be further strengthened to promote the construction of digital economy supporting facilities. The advanced technology spillover and management experience of digital economy construction must be more fully absorbed to improve the level of the digital economy in low-level provinces.

Moreover, from a pollution reduction perspective, in addition to focusing on the emissions reduction effect of the digital economy on air pollution, the government must also further improve regulations on air pollution, propose strict standards for emission generation and treatment of air contaminants, strengthen the supervision of enterprise air pollution emissions behavior, strengthen government supervision by increasing resources and environmental taxes, and accelerate the exit or transformation of polluting industries. Governments can encourage enterprises to carry out green innovation activities, accelerate the development of industrial green transformation to reduce air pollution emissions at the source, and promote green and low-carbon development to improve the efficiency of digital economy emissions reduction.

6.3 Deficiency and prospect of research

First, the authors note that the focus of this study is on provincial-level studies; thus, it could not fully capture the responses to firm characteristic heterogeneity. In the future, with the support of firm-level data, further extensions to this study could examine the bilateral effects of corporate digital development on environmental pollution at the firm level from a microscopic perspective.

Second, this study mainly explored bilateral effects of the digital economy on air pollution. The follow-up research can discuss more types of environmental pollution, such as carbon dioxide emissions, wastewater pollution, solid waste pollution, etc., and examine the bilateral effects of digital development on corresponding pollution based on the data availability to form a more comprehensive and complex research system.

Data availability statement

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

Author contributions

RW: Conceptualization, methodology, writing–original draft, writing–review and editing, project administration, supervision, funding acquisition. CD: Data curation, methodology, validation, investigation, writing–original draft, formal analysis, writing–review and editing.

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Conflict of interest

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

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