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Influence of digital economy on industrial wastewater discharge: evidence from 281 Chinese prefecture-level cities

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ABSTRACT

The development of digital economy affects environmental pollution emission and green sustainable development. However, the relationship between digital economy and industrial wastewater discharge has rarely been examined. This study establishes the urban digital economy evaluation index system, measures the digital economy indexes of 281 prefecture-level cities in China from 2011 to 2016, and examines the impact effect of digital economy development on industrial wastewater discharge using the system generalized method of moment method and the intermediary effects model. The empirical results indicate that the digital economy reduces the industrial wastewater discharge. As evidence shows, the digital economy significantly promotes the upgrading of industrial structure, which is an important factor affecting the industrial wastewater discharge. Additionally, the inhibiting effect of digital economy on industrial wastewater discharge is more significant in big cities. This study provides a scientific base and guidance for reducing environmental pollution emissions and promoting the development of digital economy.

Key words: digital economy, heterogeneity, industrial wastewater discharge, influencing mechanism, upgrading of industrial structure

HIGHLIGHTS

- The effect of digital economy on industrial wastewater discharge is explored.
- The digital economy reduces the discharge of industrial wastewater.
- The mediating role of upgrading the industrial structure is established.
- The inhibitory effect of digital economy on the discharge of industrial wastewater is significant in big cities.

INTRODUCTION

Since China began to reform and open up, its economy has experienced a rapid growth for nearly 40 years (Dong *et al.* 2019; Ma *et al.* 2020). At the same time, continuous haze weather has appeared in some cities in China, and the pollution of air, soil, and water has become more and more serious, which has seriously brought a series of environmental issues and endangered the health of residents (Pope *et al.* 2009; Ebenstein 2012; Chen *et al.* 2013; Lu *et al.* 2015). Therefore, clarifying the factors causing environmental pollution and taking measures to solve the environmental problems are not only one of the main topics of environmental economics, but also the main focus of the government in formulating environmental policies and improving the quality of economic development. There is no doubt that in-depth research on this issue has an important theoretical value and policy-guiding significance. With the continuous in-depth application of digital technologies such as Internet, big data, cloud computing, and artificial intelligence, the digital economy is becoming a new driving force for economic and social developments. In 2019, the added value of China's digital economy will reach 3.58 billion yuan, accounting for 36.2% of gross domestic product (GDP). The development of information technology and its innovative application in the field of environmental protection make the role of digital economy in environmental protection increasingly prominent.

Previous studies have shown that various social factors have different effects on industrial wastewater discharge (He *et al.* 2016; Tang *et al.* 2016; Wang & Zhao 2018; Bai *et al.* 2019). Many studies have found that environmental regulation (Jiang *et al.* 2019), FDI (Shahbaz *et al.* 2015; Liu *et al.* 2017), international trade, government enterprise collusion (Li *et al.* 2017; Dincer & Fredriksson 2018), finance and taxation system (He 2015; Kuai *et al.* 2019; Hao *et al.* 2020a), industrial structure (Chen & Zhao 2019;

Wang & Feng 2020), economic growth (Diao *et al.* 2009; Al-Mulali *et al.* 2015a; Halkos & Polemis 2018), technology innovation (Song *et al.* 2019; Liu *et al.* 2020), and urbanization (Duh *et al.* 2008; Hu *et al.* 2013; Han *et al.* 2014; Hao *et al.* 2020b) are all important factors affecting environmental pollution and industrial wastewater discharge. However, there are few studies on the impact of digital economy on industrial wastewater discharge, which provides an expandable space for this study.

The digital economy is a new economic form that takes digitization and informatization as the key production factors, continuously improves the digitization, networking and intelligence of economy and society, and speeds up economic development and governance model reconstruction. The development of digital economy has further promoted green technology innovation, product innovation, and business model innovation. By effectively integrating online and offline, the digital technology can build the whole industrial chain of production, transportation, consumption, and recycling, so as to improve the operation efficiency of resource utilization and reduce environmental pollution emissions. Based on the above analysis, what is the logical relationship between the digital economy and industrial wastewater discharge? In other words, can the development of digital economy significantly reduce industrial wastewater discharge? If the answer is yes, what are the transmission mechanisms? Systematic exploration of these problems has important policy implications for promoting the development of digital economy and solving the environmental pollution.

This study constructs the theoretical analysis framework of digital economy, industrial structure upgrading, and industrial wastewater discharge, establishes the urban digital economy evaluation index system, measures the digital economy indexes of 281 prefecture-level cities in China from 2011 to 2016, and empirically tests the impact effect of digital economy on industrial wastewater discharge and its underlying mechanism using a variety of econometric models. We make the following contributions to the existing literature. First, among all the factors affecting industrial wastewater discharge, there is a lack of understanding of the role of digital economy. Based on the data of prefecture-level cities, this study measures the digital economy index, evaluates the impact of digital economy on industrial wastewater discharge, and enriches the literature on the influencing factors of industrial wastewater discharge. Second, this study also investigates the impact mechanism of digital economy on industrial wastewater discharge, and uses a variety of regression analysis methods to explore the effect of industrial structure upgrading in the relationship between digital economy and industrial wastewater discharge, which reflects the mechanism and process of the impact of digital economy on industrial wastewater discharge. Third, this study is not satisfied with verifying the impact effect and mechanism, but also further investigates the heterogeneity of the impact of digital economy on industrial wastewater discharge, which provides deeper empirical evidence for the development of digital economy to reduce environmental pollution emission.

The remaining parts of the study unfold as the following: The next section presents the literature review and theoretical analysis. The next two sections elaborate the empirical methods and data and report the empirical results. The last section summarizes the research conclusions.

Literature review and theoretical analysis

Considering that there are few studies on digital economy and industrial wastewater discharge, this study mainly focuses on the literature on the impact of information technology on environmental pollution. However, the research conclusions on the relationship between digital economy and environmental pollution are inconsistent. There are two channels for digital economy to affect the industrial wastewater discharge. On one hand, it improves environmental quality through substitution effect and dematerialization effect. On the other hand, it exacerbates environmental degradation through compensation effect and rebound effect (Cheng *et al.* 2019).

Previous studies on the impact of information technology on pollution emissions have made some achievements. Some studies suggest that information technology exacerbates pollution emissions. Cheng *et al.* (2019) found that the coefficient of information technology on environmental pollution emission is significantly positive. Lee & Brahmasrene (2014) pointed out that information technology increases carbon dioxide emission. Some scholars put forward different views that information technology is conducive to improving environmental pollution. Gelenbe & Caseau (2015) argued that information and communication technologies can help reduce energy consumption in certain specific sectors. Asongu (2018) analyzed the impact of information technology on carbon dioxide emissions and proposed that information technology is conducive to reducing carbon dioxide emissions. Salahuddin *et al.* (2015) suggested that the potential of the Internet has reduced the carbon footprint in Australia. The third view is that the relationship between information technology and environmental pollution is uncertain. Al-Mulali *et al.* (2015b) proposed that Internet retail usually reduces pollution emission, but it is not established in developing countries. Higón *et al.* (2017) found an inverted U-shaped relationship between information technology and carbon dioxide emission. This study believes that the above literature may ignore the effect of the new generation of information technology on environmental pollution, which provides a basis for further research in this study. In addition, some studies have carried out research on industrial wastewater treatment methods and made some achievements (Buaisha *et al.* 2020; Mirra *et al.* 2020; Scharnberg *et al.* 2020).

To sum up, the research on the relationship between information technology and environmental pollution has not reached an agreed conclusion, but it provides a reference for the impact of digital economy and industrial wastewater discharge.

The digital economy can be understood as a new economic form integrating technological innovation, product innovation, market innovation, resource allocation innovation, and organizational innovation. By applying advanced information technology to the production activities of enterprises, the digital economy optimizes and upgrades the enterprise pollution control mode and technology in an all-round way, dynamically collects various resource information such as atmosphere, water, and energy closely related to enterprise pollution discharge activities in real-time, intelligently senses, and automatically controls environmental pollution, energy consumption, and ecological damage in the production process of enterprises.

The digital economy promotes the application of information technology and intelligent technology to traditional products of enterprises, improves the informatization and intelligence of production process, and realizes the upgrading of traditional products of enterprises in accordance with environmental purification and ecological optimization. The traditional production mode mainly relies on engineers to manually control and coordinate various subsystems, which cannot avoid the problems of slow response and control delay, resulting in energy waste. The use of emerging technologies such as industrial Internet and big data can turn the traditional manual and empirical into standardized and accurate control. At the same time, the improvement of data transmission and data processing capacity means faster response speed and shorter control interval, and finally improves quality, efficiency, and energy saving.

In conclusion, we believe that the digital economy is conducive to reducing industrial wastewater discharge. Among them, the reduction of industrial wastewater discharge is a positive effect of digital economy promoting the upgrading of industrial structure. The impact of the structure effect of digital economy on industrial wastewater discharge mainly lies in increasing the investment of emerging factors and the proportion of emerging industries. Different from industries that rely on traditional factors such as labor and capital, digital economy is mainly based on factors such as knowledge and technology. The digital economy speeds up the integration of information technology and traditional industries, optimizes the product structure and quality of traditional industries, improves energy efficiency, and finally promotes its transformation to low-energy consumption and low industrial wastewater discharge. The digital economy has promoted the development of high-tech industries and emerging industries with the characteristics of low-energy consumption and low pollution, accelerated the upgrading of industrial structure, and reduced industrial wastewater discharge.

The structural effect of the digital economy directly promotes the continuous optimization of industrial structure, resulting in the effect of pollution reduction. The structural optimization of the digital economy is reflected in the outward transfer of large and polluting industries, and the continuous upgrading of low-level, high energy consumption, and high pollution industries and their resource allocation methods.

Therefore, this study puts forward the following assumptions:

Hypothesis 1: The digital economy is conducive to reducing industrial wastewater discharge.

Hypothesis 2: The industrial structure upgrading is the intermediary mechanism of digital economy affecting industrial wastewater discharge.

EMPIRICAL METHODOLOGY, DATA, AND VARIABLES

Empirical method

The purpose of this study is to explore whether the digital economy can reduce the discharge of industrial wastewater, which needs to accurately identify the causal effect between them. The advantage of the system generalized method of moment (GMM) method is to reduce the problem of serial correlation and heterogeneity (Stephen 1981; Blundell & Bond 1998; Biresselioglu *et al.* 2016). Therefore, this study uses the system GMM method to analyze the impact of digital economy on industrial wastewater discharge. The regression test model is as follows:

$$pollution_{i,t} = \lambda_0 + \lambda_1 pollution_{i,t-1} + \lambda_2 digital_{i,t} + X_{it}T + \varepsilon_{it} \quad (1)$$

where i denotes city and t denotes year; $pollution_{i,t}$ is the industrial wastewater discharge; $digital_{i,t}$ is the independent variable measuring the digital economy; industrial wastewater discharge follows a first-order Markov process, lagged industrial wastewater discharge is included to control for serial correlation; X is the vector of control variable to capture other factors that affect the industrial wastewater discharge; ε_{it} is a random term. The estimation coefficient λ_2 measures the effect of digital economy on industrial wastewater discharge.

Our study further constructs the intermediary effects model to examine the influencing mechanism of industrial structure upgrading. That is, the digital economy promotes the upgrading of industrial structure, which will have an important detrimental effect on industrial wastewater discharge. Based on the study by Baron & Kenny (1986), our study constructs the estimated models as:

$$upgrading_{i,t} = \theta_0 + \theta_1 upgrading_{i,t-1} + \theta_2 digital_{i,t} + X_{it}T + \varepsilon_{it} \tag{2}$$

$$pollution_{i,t} = \omega_0 + \omega_1 pollution_{i,t-1} + \omega_2 upgrading_{i,t} + X_{it}T + \varepsilon_{it} \tag{3}$$

$$pollution_{i,t} = \eta_0 + \eta_1 pollution_{i,t-1} + \eta_2 digital_{i,t} + \eta_3 upgrading_{i,t} + X_{it}T + \varepsilon_{it} \tag{4}$$

where $upgrading_{i,t}$ measures industrial structure upgrading. This study examines the impact mechanism in three steps: first, this study constructs Equation (2) to examine the relationship between digital economy and industrial structure upgrading; second, the impact of industrial structure upgrading on industrial wastewater discharge is analyzed in Equation (3); finally, this study discusses the impact of digital economy and industrial structure upgrading on industrial wastewater discharge. θ_1 represents the time response coefficient; the estimation coefficient θ_2 measures the effect of digital economy on industrial structure upgrading; the estimation coefficient ω_2 shows the effect of industrial structure upgrading on industrial wastewater discharge. Equation (4) examines the role of industrial structure upgrading in digital economy affecting the industrial wastewater discharge.

VARIABLE SELECTION

Estimation of digital economy

The existing literature mostly constructs a multi-dimensional index system based on the provincial data to measure the digital economy, while there are few studies on measuring the digital economy based on the urban data. Therefore, considering the availability of data, this study builds an evaluation system to measure the digital economy in the city. The index system is shown in Table 1. Through the method of principal component analysis, this study standardized the data of the above seven indicators and then reduced the dimension to obtain the digital economy development index. In this study, the range standardization method was selected to deal with the evaluation index, and the calculation formula is as follows

$$X_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \tag{5}$$

The value of the first component accounted for 55.897% of the total variance, and the cumulative value of the first two components accounted for 85.149% of the total variance, showing that the value of the first two components can explain 85.149% of all indicators. As the total explanation of the principal components should reach 85% or more, the extraction

Table 1 | Digital economy index system

Primary indexes	Secondary indexes	Three-level indexes
Digital economy development index	Internet penetration rate	Number of Internet broadband access users among 100 people (X_1)
	Relevant employees	Proportion of employees in computer service and software industry in employees in Urban Units (X_2)
	Related outputs	Total telecom services per capita (X_3)
	Mobile phone penetration	Number of mobile phone users among 100 people (X_4)
	Digital inclusive finance	China's digital inclusive financial index involves coverage breadth, use depth, and digitization (X_5)

of the first two principal components can meet the requirements. Thus, the original five indicators could be transformed into two indicators by dimensionality reduction.

According to the principal component score coefficient matrix, the linear expressions of the two principal components were obtained as

$$Y_1 = 0.54X_1 + 0.53X_2 + 0.54X_3 - 0.14X_4 + 0.32X_5 \tag{6}$$

$$Y_2 = 0.08X_1 + 0.23X_2 + 0.24X_3 + 0.73X_4 - 0.59X_5 \tag{7}$$

Then, the variance contribution rate of the two principal components was divided by the sum of the variance contribution rates of the two principal components, respectively, to obtain their weights. The comprehensive evaluation function of the digital economy indexes of 281 prefecture-level cities in China was as follows:

$$digital = 0.656Y_1 + 0.344Y_2$$

Estimation of industrial wastewater discharge

Referring to the practice of Liu *et al.* (2018) and considering the availability of data, the logarithm of industrial wastewater discharge is used as the measurement index.

Estimation of industrial structure upgrading

Industrial structure is the link between social and economic activities and ecological environment. The change of industrial structure will have an impact on resource allocation, energy consumption, pollutant emission, and many other aspects. The upgrading of industrial structure has promoted the application and popularization of advanced technology, and led to the withdrawal of industries with serious pollution emissions, thus reducing pollution emissions. Our study uses the ratio of the added value of secondary and tertiary industries to GDP to estimate the upgrading of industrial structure.

Control variables

Control variables affecting the industrial wastewater discharge are also added in the model. The control variables include the economic development, population density, industrial development, fiscal expenditure, human capital, and financial development. We use the logarithm of per capita GDP to measure the economic development. At the same time, we also added the square of the logarithm of per capita GDP. Population growth increases pollution emissions (Chen *et al.* 2008). Population is measured by the logarithm of total population. Many studies have shown that industrial development is closely related to pollution emission (Chen & Zhao 2019). Industrial development is measured by the ratio of the added value of secondary industry to GDP. Fiscal expenditure is measured by the ratio of fiscal expenditure to GDP. Human capital is measured by the ratio of the number of college students to the population. Financial development is closely related to sustainable development (Yang & Zhang 2018; Zhou *et al.* 2019). Therefore, we add the financial development into the model. Financial development is captured by the ratio of various loan balances of financial institutions to GDP at the end of the year. Table 2 shows all variables and calculation methods.

Data description

The panel data of 281 prefecture-level cities in China are used for empirical test during the period of 2011–2016. The data of the variables were obtained from the China City Statistical Yearbook (2012–2017) and the China Regional Economic Statistics Yearbook (2012–2017). Table 3 presents the summary statistics of key variables that are used in this study during the period 2011–2016, which reveals the characteristics of data distribution. Table 3 further shows that all variables are positive mean and standard deviation values and have a significant peak of distribution. The data distribution also confirms regional disparities in digital economy, pollution emissions, and other control variables.

EMPIRICAL ANALYSIS

Benchmark regression analysis based on the system GMM method

Our study uses the statistical software *Stata 15* to analyze the dynamic model that contains the relationship between digital economy and industrial wastewater discharge. The empirical results are shown in Table 4. We report the empirical results

Table 2 | Main variables and calculation methods

Abbreviations	Variables	Calculations
water	Discharge of industrial wastewater	The logarithm of industrial wastewater discharge
digital	Digital economy	Estimation of digital economy based on the variable selection part
pgdp	Economic development	The logarithm of per capita GDP
Sq_pgdp	Economic development	The square of the logarithm of per capita GDP
population	Population density	The logarithm of total population
industrial	Industrial development	The ratio of the added value of secondary industry to GDP
expenditure	Fiscal expenditure	The ratio of fiscal expenditure to GDP
hum	Human capital	The ratio of the number of college students to the population
finance	Financial development	The ratio of various loan balances of financial institutions to GDP

Table 3 | Statistical descriptions of main variables

Abbreviations	Variables	Obs.	Mean	Std. dev.	Min.	Max.
water	Discharge of industrial wastewater	1,686	8.3390	1.0316	1.9459	11.6151
digital	Digital economy	1,686	−0.0795	1.1663	−1.3800	12.6400
pgdp	Economic development	1,686	10.5939	0.5746	8.7729	13.0556
Sq_pgdp	Economic development	1,686	112.5609	12.2669	76.9641	170.4510
population	Population density	1,686	5.8597	0.6730	2.9704	7.2435
industrial	Industrial development	1,686	0.4939	0.1014	0.1495	0.8934
expenditure	Fiscal expenditure	1,686	0.1918	0.1052	0.0153	1.5751
hum	Human capital	1,686	1.8177	2.5604	0.0182	35.0218
finance	Financial development	1,686	0.0023	0.0065	.00001	0.1337

based on the system GMM method, which can solve the endogeneity and excessive recognition of instrumental variables. The two tests are applied to ensure the accuracy of empirical results. First, our study examines the significance of the first-order autocorrelation AR(1) and second-order autocorrelation AR(2), which are shown in Table 4. AR(1) is significant, while AR(2) is not significant. These results indicate that the second-order sequence correlation is not significant. Second, over-recognition is analyzed by the Sargan test. The empirical results of the Sargan test indicate that there is no over-recognition of instrumental variable. In other words, instrumental variables with first-order lag are effective.

Our study displays the empirical results by adding one control variable at a time to improve the robustness of the regression estimation. According to Table 4, the core-dependent variable is the discharge of industrial wastewater, the regression coefficient of digital economy is significantly negative at the 1% level in column (1). Then, we add control variables one by one and eventually find that the regression coefficient of digital economy is −0.1088 at the 1% level in column (7). That is, the impact of digital economy on the discharge of industrial wastewater is significantly negative, which shows that digital economy reduces the discharge of industrial wastewater. Therefore, the digital economy reduces the discharge of industrial wastewater, which is consistent with the hypothesis 1 of this study. Our study also notes that there is a positive correlation between industrial development and industrial wastewater discharge. In other words, industrial development has increased the discharge of industrial wastewater.

DISCUSSION OF THE EMPIRICAL RESULTS

The application of technology, information, and other factors in the digital economy will improve the production structure and operation mode of polluting industries and enterprises, optimize the factor input structure of polluting enterprises, and then reduce pollutant emissions. A large number of new technologies have been applied to environmental protection

Table 4 | Regression of digital economy on the discharge of industrial wastewater

Discharge of industrial wastewater							
digital	– 0.1375*** (0.044)	−0.1228*** (0.041)	−0.1273*** (0.041)	−0.1124*** (0.033)	−0.1150*** (0.034)	−0.1117*** (0.034)	−0.1088** (0.043)
pgdp		−3.7297*** (0.847)	−3.9350*** (0.860)	−1.6391** (0.728)	−1.7974** (0.736)	−1.7368** (0.736)	−2.6550*** (0.845)
Sq_pgdp		0.1506*** (0.038)	0.1617*** (0.039)	0.0631* (0.033)	0.0697** (0.033)	0.0674** (0.033)	0.1090*** (0.038)
population			−0.1165 (0.336)	−0.0716 (0.284)	−0.1008 (0.270)	−0.1129 (0.270)	0.2015 (0.448)
industrial				2.2678*** (0.455)	2.1377*** (0.466)	2.1265*** (0.484)	2.7275*** (0.701)
expenditure					−0.2004 (0.132)	−0.1958 (0.131)	−0.3768** (0.158)
hum						−0.0233 (0.028)	0.0036 (0.043)
finance							−1.3819 (4.193)
$water_{t-1}$	0.7282*** (0.069)	0.4955*** (0.080)	0.5369*** (0.083)	0.3540*** (0.085)	0.3581*** (0.085)	0.3527*** (0.087)	0.3620*** (0.131)
constant	2.2144*** (0.585)	26.7544*** (4.967)	28.0266*** (5.385)	14.9507*** (4.672)	16.1183*** (4.690)	15.9012*** (4.680)	18.6927*** (5.680)
N	1,405	1,405	1,405	1,405	1,405	1,405	1,405
AR(2)	0.9895	0.3098	0.3173	0.3579	0.3526	0.3578	0.3310

Standard error of robustness is reported in parentheses.
*Significance at the 10% level.
**Significance at the 5% level.
***Significance at the 1% level.

and pollution control, which has greatly improved the existing environmental quality. Specifically, the digital economy realizes the government's strict and efficient environmental supervision and law enforcement from the technical level, and provides a good interactive platform for the public's real-time supervision and information feedback of environmental pollution. Environmental protection attention and real-time pollution supervision will force enterprises to reform the existing production technology, so as to reduce pollution emissions.

The digital economy reduces the cost of information, promotes inter regional economic exchanges and cooperation, and gathers talents, which is conducive to knowledge and technology spillover, reduces industrial wastewater discharge, and improves environmental efficiency. The digital economy accelerates technological innovation, significantly improves labor productivity, greatly reduces the environmental efficiency, and thus reduces industrial wastewater discharge.

To sum up, we believe that the digital economy is conducive to reducing pollution emissions.

ANALYSIS OF INFLUENCE MECHANISM

The benchmark regression results show that the digital economy is conducive to reducing pollution emissions. This study further analyzes the intermediary mechanism of the impact of digital economy on industrial wastewater discharge from the perspective of industrial structure upgrading. This study uses Equations (2)–(4) to explore the impact mechanism of industrial structure upgrading.

Table 5 reports the regression results of the impact mechanism of digital economy on industrial wastewater discharge. We find that there is a significant positive correlation between digital economy and industrial structure upgrading in column (1), which indicates that the digital economy promotes the upgrading of industrial structure. The regression coefficient of industrial structure upgrading is significantly negative in column (2), which reflects that the industrial structure upgrading reduces

Table 5 | Results of influencing the mechanism test

	Discharge of industrial wastewater		
digital	0.0021** (0.001)		−0.1003*** (0.033)
upgrading	/	−2.8199* (1.445)	−2.7421* (1.416)
pgdp	0.2422*** (0.052)	−0.7944 (0.883)	−0.8477 (0.889)
Sq_pgdp	– 0.0100*** (0.002)	0.0291 (0.039)	0.0308 (0.039)
population	– 0.0294*** (0.008)	−0.0489 (0.283)	−0.0348 (0.287)
industrial	– 0.7383*** (0.029)	−0.4176 (1.266)	−0.3749 (1.236)
expenditure	– 0.0028 (0.017)	−0.1503 (0.127)	−0.1545 (0.130)
hum	0.0070*** (0.002)	−0.0215 (0.029)	−0.0160 (0.029)
finance	– 0.0420 (0.052)	−2.2014 (2.872)	−2.7576 (2.827)
$upgrading_{t-1}$	0.2850*** (0.036)		
$water_{t-1}$		0.3669*** (0.088)	0.3581*** (0.086)
Constant	−0.6337** (0.272)	12.0709** (5.085)	12.3675** (5.165)
N	1,405	1,405	1,405
AR(2)	0.6243	0.3224	0.0426

Standard error of robustness is reported in parentheses.
*Significance at the 10% level.
**Significance at the 5% level.
***Significance at the 1% level.

the discharge of industrial wastewater. These verify that industrial structure upgrading has positive impact on industrial wastewater discharge. According to the column (3) of Table 5, the regression coefficient of digital economy is significantly negative at the 1% level, and the regression coefficient of industrial structure upgrading is significantly negative at the 10% level. That is, the digital economy reduces the discharge of industrial wastewater, while industrial structure upgrading also reduces it.

These results prove that industrial structure upgrading has a significant transmission effect on digital economy affecting the industrial wastewater discharge. Therefore, these conclusions fully illustrate the existence of the influencing mechanism of industrial structure upgrading in the relationship between digital economy and industrial wastewater discharge, which is basically in line with the hypothesis 2 of this study.

DISCUSSION OF THE INFLUENCE MECHANISM

The application of digital economy is inseparable from industrial development. The upgrading of industrial structure makes technology intensive and capital intensive prefers to use new technologies of digital economy to transform the production process and change the mode of production, which can better release the effect of digital economy to reduce pollution emissions. We analyze it from the following aspects.

The process of industrial structure upgrading reflects the flow of resource elements from low-efficiency departments to high-efficiency departments and realizes the redistribution of resources. The digital economy improves the upgrading of industrial structure by creating new supply, guiding new demand, optimizing factor allocation, and improving social productivity. The digital economy also optimizes the internal structure of the industry. The digital economy runs the new generation of information technology through all links of the industrial chain, promotes the deep integration of information technology and intelligent manufacturing, improves the efficiency of production and supply chain, and improves labor productivity. The digital economy also accelerates the penetration and integration of information and communication services and traditional services. Through the use of digital technologies such as blockchain and artificial intelligence in the service industry, it expands the market scale of the service industry, reduces the coordination transaction cost among enterprises, improves the transaction efficiency, and improves the labor productivity.

First, in the era of digital economy, data, together with land, labor, capital, and technology, has become a key factor of production. The input of data, information technology, and other factors has created new products, new formats and new models, realized the transformation and upgrading of production mode, provided better products and services, and improved the quality of new supply.

Second, the digital economy has stimulated new consumer demand. Through artificial intelligence, big data, Internet of Things, and other new generation information technologies, new demands such as online education and remote office have been spawned, and the consumer market of new products has been expanded, so as to create a new economic value.

Third, the digital economy has optimized the factor supply structure, reshaped the factor allocation with informatization, digitization and intelligence, accelerated the deep integration of data, labor, capital and other factors, and improved the efficiency of factor allocation.

Fourth, with the rapid development of digital general technology, digital economy has transformed the production and operation process of enterprises, improved the operation efficiency of enterprises, improved the production efficiency of the industry, and realized the interconnection of economic activities.

To sum up, digital economy has promoted the upgrading of industrial structure.

The optimization and upgrading of industrial structure can improve input–output efficiency and reduce the stress effect of economic development on resources and environment, which is conducive to green economic growth.

With the transformation of economic development mode and the optimization and upgrading of industrial structure, the proportion of industries with high energy consumption and high pollution has decreased, and the proportion of tertiary industry has increased. Compared with the primary industry and the secondary industry, the tertiary industry consumes less resources and emits less pollution. Therefore, the higher the proportion of the tertiary industry, the better the environmental quality and the less pollution emissions.

HETEROGENEITY ANALYSIS

Our study further discusses the heterogeneity effect of digital economy affecting the industrial wastewater discharge based on city size. According to the urban population, the whole sample is divided into two groups: big city and small city. Therefore, this study discusses the heterogeneity effect of digital economy affecting the industrial wastewater discharge in cities with different sizes. Table 6 presents the empirical results. We find that the coefficient of digital economy is significantly negative in big cities. That is, the effect of digital economy on reducing the industrial wastewater discharge is significant in big cities. The regression coefficient of digital economy is not significant in small cities. Therefore, the results of reducing industrial

Table 6 | Results of the heterogeneity test

	Discharge of industrial wastewater	
	Big city	**Small city**
digital	– 0.0887*** (0.031)	−0.1300 (0.312)
pgdp	– 1.4170*** (0.532)	−9.0344 (46.055)
Sq_pgdp	0.0561** (0.023)	0.3829 (1.990)
population	– 0.2544 (0.250)	0.8293 (3.172)
industrial	2.9435*** (0.419)	−4.0263 (4.087)
expenditure	– 0.1796* (0.104)	−9.1571 (9.999)
hum	– 0.0061 (0.025)	−0.0633 (1.132)
finance	1.1210 (2.865)	1.2044 (26.384)
$water_{t-1}$	0.2812*** (0.087)	0.5171 (0.847)
Constant	14.8261*** (3.601)	57.2700 (280.910)
N	1,350	1,405
AR(2)	0.2093	0.1813

Standard error of robustness is reported in parentheses.
*Significance at the 10% level.
**Significance at the 5% level.
***Significance at the 1% level.

wastewater discharge by digital economy are not significant in small cities. In conclusion, the effect of digital economy on reducing the industrial wastewater discharge is more significant in big cities.

ROBUSTNESS TEST

To enhance the validity of the research conclusion, our study explores some robustness tests. Our study introduces the alternative proxy for digital economy as an independent variable. More specifically, we use the ratio of Internet users to population to measure the digital economy (*A_digital*) and repeat the regression model as in Equation (1). Table 7 reports the estimated results of robustness test. Compared with benchmark regression, we find that the regression coefficients of digital economy are also significantly negative, which demonstrates that digital economy reduces the industrial wastewater discharge. That is, the above conclusion confirms that the effect of digital economy on industrial wastewater discharge is significantly negative, which is consistent with the expectation.

Second, this study considers the region dummy variable, the intersection of region dummy variable, and digital economy in the model. The results are shown in Table 8. We found that the regression coefficients of digital economy are also significantly negative, which demonstrates that digital economy reduces the industrial wastewater discharge. This robustness test is consistent with the expectation.

CONCLUSIONS AND IMPLICATIONS

This study discusses the effect of digital economy on reducing the industrial wastewater discharge and its mechanism. Our study establishes the urban digital economy evaluation index system, measures the digital economy indexes of 281 prefecture-level cities in China from 2011 to 2016, and empirically tests the impact effect of digital economy development on the industrial wastewater discharge using the GMM method. The empirical results indicate that digital economy reduces the industrial wastewater discharge. As evidence shows, digital economy significantly promotes the upgrading of industrial structure, which is an important factor affecting the industrial wastewater discharge. Additionally, the inhibiting effect of digital economy on industrial wastewater discharge is more significant in big cities. The conclusion promotes the understanding of the effects, mechanisms, and regional differences of reducing industrial wastewater discharge emissions and promoting green development by digital economy. The robustness tests confirm that the relationship between digital economy and industrial wastewater discharge is significant. The impact of digital economy on pollution emission provides a new reference for green sustainable development.

Table 7 | Robustness test for alternative measurement

	Discharge of industrial wastewater	
A_digital	– 0.2340*** (0.029)	– 0.0660*** (0.020)
pgdp		– 1.8477** (0.720)
Sq_pgdp		0.0760** (0.033)
population		– 0.1557 (0.275)
industrial		1.6846*** (0.543)
expenditure		– 0.1932 (0.128)
hum		– 0.0295 (0.029)
finance		– 2.6595 (2.921)
$water_{t-1}$	0.5325*** (0.075)	0.3619*** (0.089)
Constant	4.2740*** (0.651)	16.6339*** (4.576)
N	1,405	1,405
AR(2)	0.2455	0.2056

T-statistics are reported in parentheses.
**Significance at the 5% level.
***Significance at the 1% level.

Table 8 | Robustness test of modified samples

	Discharge of industrial wastewater		
digital	– 0.1167*** (0.035)	– 0.1148*** (0.034)	–0.2812*** (0.061)
pgdp	– 2.5071*** (0.884)	– 1.9239** (0.753)	–1.9109*** (0.734)
Sq_pgdp	0.1010** (0.039)	0.0761** (0.034)	0.0748** (0.033)
population	– 0.7350** (0.287)	– 0.3485 (0.301)	–0.1029 (0.284)
industrial	1.6800*** (0.530)	2.0963*** (0.508)	2.1246*** (0.498)
expenditure	– 0.2295*** (0.081)	– 0.2094 (0.128)	–0.1827 (0.133)
hum	– 0.0311 (0.029)	– 0.0332 (0.029)	–0.0233 (0.029)
finance	– 3.3793 (3.179)	– 2.6745 (2.899)	–2.6028 (2.853)
dummy1	–0.7979 (3.737)		
dummy2		2.7386* (1.509)	
dummy1**digital*			0.2633*** (0.071)
dummy2**digital*			–0.0018 (0.003)
$water_{t-1}$	0.2981*** (0.104)	0.3048*** (0.090)	0.3281*** (0.085)
Constant	24.7348*** (5.910)	17.7734*** (4.840)	17.0239*** (4.732)
N	1,405	1,405	1,405
AR(2)	0.2601	0.3339	0.5696

T-statistics are reported in parentheses.
*Significance at the 10% level.
**Significance at the 5% level.
***Significance at the 1% level.

The research conclusion of this study has important guiding significance for supporting the development of digital economy and reducing the industrial wastewater discharge. First, China's digital economy is generally on the rise year by year, but the problem of uneven development still exists. The development and wide application of digital technology have promoted the optimization of economic structure, social progress, and the improvement of resources and environment, but the improvement of economic efficiency is relatively lagging behind, and the problem of uncoordinated development has not been fundamentally solved. Therefore, the digital economy should be driven by innovation. The government should speed up institutional and management innovation, adapt to the development of digital economy, build an efficient management system, constantly improve the system and incentive policies, and optimize the digital development environment, which will help to promote the overall qualitative change of economy and society and realize the high-quality and coordinated the development of digital economy.

Second, the digital economy has become a new driving force to reduce pollution emissions. Therefore, we should increase investment in the Internet and promote the construction of Digital China, especially by accelerating the construction of 5G business, big data model, and artificial intelligence application, so as to further consolidate the dividend advantages of information technology for the high-quality development of green environment.

Third, the improvement of environmental quality is closely related to the industrial structure. We should continue to upgrade the industrial structure and continuously increase the proportion of the tertiary industry. In addition, industries with large emissions of environmental pollutants in the secondary industry should be treated with emphasis. We should vigorously develop high-tech industries and give play to the role of scientific and technological innovation, so as to improve resource utilization, reduce energy consumption, and reduce pollution emissions.

Fourth, the government's introduction of information technology in the process of implementing the new urbanization strategy is conducive to improving the efficiency of urban-scale development, giving play to the scale effect and agglomeration effect, and reducing urban pollution. On one hand, large-scale cities can vigorously develop and use information technology, apply information technology to all aspects of urban and enterprise production and life, improve resource allocation efficiency, improve urban residents' life satisfaction and enterprise production efficiency, so as to alleviate industrial wastewater discharge. On the other hand, small-sized and medium-sized cities should make full use of the dividends of digital economy development, give full play to their comparative advantages, improve urban governance and operation efficiency, and reduce pollution emissions.

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COMPETING INTERESTS

The authors declare no competing interests.

CONSENT TO PARTICIPATE

Not applicable.

CONSENT TO PUBLISH

Not applicable.

ETHICAL APPROVAL

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information. All data generated or analyzed during this study are included in this published article.

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