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Navigating the digital divide: unraveling the impact of ICT usage and supply on SO₂ emissions in China's Yangtze River Delta

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The relationship between information and communication technology (ICT) and environmental pollution is widely recognized and complex. To better understand the environmental impact of ICT, we divide it into two facets: the supply side and the usage side. This study investigates the impact of ICT usage and ICT supply on sulfur dioxide (SO₂) emissions using random effect and spatial Durbin model in China Yangtze River Delta from 2011 to 2019. The findings reveal an inverted U-shape relationship between ICT usage and SO₂ emission, while the supply of ICT has a significant negative impact on SO₂ emissions. Furthermore, the spillover effect of ICT usage shows insignificant outcomes, but the supply of ICT has a significant and negative impact on SO₂ emissions. Collectively, these findings provide fresh insights and empirical evidence into the effects of ICT usage and ICT supply on SO₂ emissions, bearing significant policy implications for promoting ICT to attain sustainable development goals.

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Introduction

Sulfur dioxide (SO₂) emissions have become a major environmental problem since the industrial revolution, attracting widespread attention due to their adverse effects on social well-being (Dou and Lee 2024; Lin et al. 2022). According to the United Nations Environment Programme (UNEP), SO₂ emissions represent one of the most pressing environmental health risks, a silent yet formidable killer responsible for claiming over 6.7 million lives annually. Similarly, the escalating SO₂ emissions in China have become a growing concern, as they account for approximately one-fourth of global emissions and over 90% of East Asia's emissions since the 1990s (Dou et al. 2023; Dou and Lee 2024). In 2018, data from the Bulletin on the State of China's Ecological Environment revealed that a mere 35.8 percent of the country's 338 cities above the prefecture level attained good air quality, while 64.2 percent of these cities exceeded air quality standards. Likewise, Statista Search Department (2021) reported total SO₂ emissions in China as 375.27 million tons, of which 45.47 million tons are related to the Yangtze River Delta (YRD), which makes 12.12% of total emissions from 2000 to 2020. However, China's active air pollutant reduction policies and implementation of advanced measures, facilitated by the digital economy with ICT usage (hereafter ICTU) and information communication technology supply (hereafter ICTS), have resulted in a decreasing trend, with emissions declining by approximately 88.22% from 2010 to 2020 (NBS, 2021).

On the other hand, ICT usage has remarkably surged from 9.5 trillion yuan in 2011 to 45.5 trillion yuan in 2021, constituting 39.8% of GDP. These upward trends position China as a significant driver of its own, as well as global economic growth. Likewise, ICT supply, which involves the production and distribution of ICT infrastructure and devices, can also impact SO₂ emissions. The expansion of ICT infrastructure may require energy-intensive manufacturing processes. The development and deployment of cleaner technologies and renewable energy sources in ICT production can mitigate environmental impacts (Usman et al. 2021). Moreover, ICT supply chains can benefit from enhanced efficiency and sustainability practices, which may indirectly contribute to reducing overall emissions (Kashif et al. 2024). Overall, the relationship between ICTU, ICTS, and SO₂ emissions is complex and depends on various factors such as the type of technology used, energy sources, worker skills, and disposal practices. Therefore, it is important to consider the environmental impacts of both factors and strive for sustainable practices in its use.

Moreover, being recognized as one of the most polluted regions, the YRD has attained limited attention regarding the influence of SO₂ emissions. YRD is the largest metropolitan area having 235 million people living there, a GDP of \$427 billion, and an area of 350,000 square kilometers (Abu et al. 2022; Wang et al. 2020). However, the uneven spread of resource endowments and development phases challenges the ecological shift in the YRD city cluster. Therefore, this research focused on the YRD region as a sample, given its substantial contribution to SO₂ emissions, and examined its relationship with ICTU and ICTS collectively to understand it comprehensively. In this regard, the present research centers on the following research questions: (i) Is there an inverse U-shaped relationship between ICTU and SO₂ emissions in YRD? (ii) Can ICTS effectively reduce SO₂ levels in YRD? (iii) Is there a spillover effect of ICTU and ICTS in YRD? To answer the research mentioned above questions, we utilized random-effect generalized least-squares (RE-GLS) regression. The spatial Durbin model (SDM) is applied to assess the impact of geographical spillover more precisely and comprehend the distinctions across cities better. In addition, to ensure the sensitivity and robustness of our main analysis, we used the dynamic panel

data model method. This methodological diversity enhances the reliability of our findings and contributes to a comprehensive understanding of the complex relationship between ICTU, ICTS, and SO₂ in the context of this influential region.

The following are the main contributions of this study. Firstly, current literature concentrates on the role of either ICTU or ICTS in mitigating emission levels individually, neglecting their combined effect on SO₂ emissions. Also, the literature mainly focused on using Particulate Matter 2.5 (PM_{2.5}), CO₂, and NO₂ concentrations to indicate environmental development, particularly by overlooking the examination of SO₂ emissions in the YRD. It is imperative to broaden the focus beyond usage patterns and delve into the sustainability of the entire ICT ecosystem, encompassing both demand and supply facets. This nuanced perspective can provide insights into crafting more comprehensive strategies for sustainable ICT development and deployment. Therefore, this study contributes novel insights to existing research by examining the impact of ICTU and ICTS on SO₂ emissions in 41 cities of the YRD region using secondary data sources from 2011 to 2019. Secondly, as regional integration advances, the economic and manufacturing growth within one region can catalyze a positive or negative spillover effect on the development of neighboring regions. It is particularly evident when considering the resource element of data, characterized by its low diffusion cost and rapid dissemination, allowing it to traverse geographical boundaries naturally. This type of mobility is less constrained by temporal and spatial factors, thereby leading to a noteworthy geographical spillover effect (Sun et al. 2022; Zhang et al. 2023). In addition, China has actively promoted regional integration and reinforced economic interconnections among regions. Consequently, the progress of ICTU and ICTS within one locality can trigger a distinctive spillover effect on adjacent areas, and this phenomenon gives rise to amplified and cascading impacts on emissions levels. Hence, this study analyzes the spatial spillover effect of ICTU and ICTS on SO₂ emission using the spatial Durbin model. It will deepen our understanding of this relationship and assist in promoting regional economic and environmental collaboration. The study also suggested policy recommendations for using indicators to reduce SO₂ in YRD.

Section 2 of the continuation segment reviews related literature and presents the research hypotheses. Section 3 outlines the methodologies and datasets used in the study. Section 4 discusses the empirical findings. Section 5 discusses the results, and Section 6 concludes with an examination of their potential policy implications.

Literature review and research hypothesis

The literature provides an expanding body of research, offering in-depth analyses of the variables under consideration across various scenarios. Various authors have assessed ICTU and ICTS relationship with emissions in numerous ways (Che and Wang 2022; Jiang et al. 2022; Luo et al. 2022). In this section, we highlight the different perspectives and debates surrounding this relationship, ultimately leading to the formulation of a testable hypothesis.

Effect of ICT usage on emissions. ICTU is an emergent paradigm that embodies the ICT in economy, production, and way of life (Yi et al. 2022). Carlsson (2004) explained that ICTU amalgamates a diverse array of generic technologies that facilitate a broad spectrum of economic and social activities conducted through the Internet, incorporating digital technologies that rely on physical infrastructure. The expansion of ICTU and, more notably, the surge in internet usage is anticipated to place growing

demands on energy consumption that are likely to result in increased emissions (Zhang et al. 2022).

Existing research underscores the pressing need to address air pollution as a significant environmental concern in China (Dou and Lee 2024; Khera et al. 2022), and it serves as a pivotal indicator for assessing regional environmental pollution (Pan et al. 2022). Wu et al. (2023) analyzed the influence of ICTU growth on SO₂ emission in 274 Chinese cities from 2011 to 2019 and found an inverted-N-shaped association between the variables. Their outcomes further reported a reduction in air pollution due to ICTU development, and this elasticity is more prevalent in central and western China. Hang et al. (2019) applied a process treatment perspective to industrial SO₂ emissions in 30 regions of China using data from 2005 to 2015. They found that the entire process leads to a reduction in SO₂ emissions. They further identified that the treatment emphasis differs among regions; however, Henan, Inner Mongolia, and Shandong were identified as the primary contributors to these emissions. Lou et al. (2021) analyzed the same relationship for China from 2005 to 2016 and revealed that the expansion of ICTU has played a pivotal role in enhancing the capacity to reduce SO₂ emissions in the local province and its neighboring regions. Similarly, Wan and Shi (2022) investigated the relationship between ICTU and the intensity of SO₂ pollutant emissions and also analyzed the moderating effect of environmental regulations in China. Their empirical results showed that the intensity of SO₂ pollution was negatively impacted by ICTU, with a more pronounced effect observed in medium-sized, resource-rich regions in eastern and southern China.

On the other hand, China's ICTU currently operates at a low technical level with incomplete hardware and software infrastructure, hampering efforts to improve energy efficiency in production. This situation is exacerbated by the drive for profit maximization, which often leads to resource-intensive optimization of communication technology, resulting in increased energy consumption and indirect energy depletion (Cao and Peng 2023). In this regard, Zhang et al. (2019) observed through panel data analysis spanning 2012 to 2019 that ICTU's development does not contribute to enhancing energy efficiency, consequently raising emission levels. Additionally, Li et al. (2020) noted that while ICTU drives technological advancement, it compels enterprises to invest in efficient production equipment initially. However, to meet rising production demands, enterprises resort to heightened resource extraction and energy consumption, inadvertently increasing harmful emissions. These findings suggest a dual impact of ICTU on emissions, indicating that the relationship between ICTU and environmental outcomes is complex and multifaceted. Therefore, further research is needed to complement ongoing initiatives and provide fresh insights to address climate change challenges while fostering low-emission sustainability. Based on the above discussion, we formulate the following hypothesis:

H1: ICT usage and SO₂ emissions have an inverted U-shaped relationship.

The effect of ICT supply on emissions. The ICT supply can have implications for SO₂ emissions. The distribution of emissions across different segments of the ICT sector, such as manufacturing processes and energy sources used in data centers and networks, plays a role in influencing pollutants like SO₂ (Kashif et al. 2024). The environmental footprint of ICT products is influenced by activities like device manufacturing, which can generate emissions concentrated in specific countries, and the operation of hyper-scale data centers serving global markets (Kashif et al. 2024). Strategies such as corporate climate

commitments, government policies, and the use of renewable energy sources are essential for lowering global ICT emissions and mitigating environmental impacts like SO₂ emissions. Furthermore, ICTS has been widely acknowledged as one of the most promising pathways to achieving sustainable development in the twenty-first century, prompting extensive scholarly efforts to comprehend its environmental implications (Asongu 2018; Ulucak 2020; Zhao et al. 2021; Zhu and Lu 2023). To thoroughly evaluate the environmental ramifications of ICTS, extensive research efforts have been made with the established Digital Economy Development Index (Ahmed 2017; Hao et al. 2023; Huang et al. 2023; Zhu and Lan 2023). However, this index fails to encompass all facets of ICT, as it does not fully disclose the true effects of ICTS on environmental degradation or establish causal identification (Zhu and Lu 2023). Additionally, previous research failed to arrive at a consistent result regarding ICTS and the environment because some researchers consider its industrial scale perspective, revealing that the expansion of the ICT industry has exacerbated environmental performance by driving up energy consumption. Conversely, alternative studies have shown that ICTS may actually enhance environmental sustainability by fostering green innovation and more efficient manufacturing processes (Bastida et al. 2019). These contrasting findings motivate us to investigate the environmental implications of ICT from new viewpoints. Based on the above discussion, we have formulated hypothesis 2 as follows:

H2: The ICT supply has a negative effect on SO₂ emissions.

The spillover effect of ICT usage and ICT supply. ICTU promotes energy utilization and emissions by investing in digital infrastructure in the early stages. After continuous evolution, emissions can be reduced by streamlining the manufacturing process and using digital technology (Lange et al. 2020). Likewise, some studies in the literature have recognized the spatial diffusion effects of ICTU, but limited empirical research has systematically investigated its spillover effects on reducing air pollution in China. Despite acknowledging the transformative role of ICTU in reshaping business models, energy consumption patterns, industrial structures, and environmental impacts, there remains a notable gap in understanding how spatial diffusion of ICTU contributes to mitigating SO₂ emissions across different regions. Consequently, there is a pressing need for comprehensive empirical studies that examine the spillover effects of ICTU development on environmental outcomes, particularly its role in reducing air pollution levels beyond the immediate vicinity of ICT hubs. Such research would provide valuable insights into the broader environmental implications of ICTU and inform targeted policy interventions to address air pollution challenges at a regional level (Xue et al. 2022).

Similarly, the existing literature also acknowledges the pivotal role of ICTS in driving economic growth in China; however, a significant gap exists in understanding its spatial spillover effects on emissions. While studies have focused on ICTS's contribution to regional integration and the concentration of production factors in high-emission cities, there is limited empirical research exploring how ICTS development influences SO₂ pollution levels beyond immediate urban centers (Zhao et al. 2023). Furthermore, the extent to which ICTS development contributes to reducing air pollution in China remains largely unexplored. Additionally, previous research has often overlooked spatial correlation and spillover effects in pollution analysis, leading to potential estimation inaccuracies and hindering a comprehensive understanding of the relationship between ICTS and emissions (Ahmed 2017). Therefore, there is a pressing need for empirical studies that delve into the spatial dynamics of ICTU and ICTS impacts

on emissions, examining how these effects interact with regional pollution levels and policy interventions to inform targeted environmental management strategies. Such research efforts would not only address the current research gap but also provide valuable insights for policymakers and stakeholders seeking to mitigate air pollution in China effectively. Hence, we formulated the following hypotheses:

H3: ICT usage has a negative spillover effect on SO₂ emissions.

H4: ICT supply has a negative spillover effect on SO₂ emissions.

Theoretical framework. In the theoretical framework, the relationship between ICTU, ICTS, and SO₂ emissions can be understood through several theoretical perspectives to provide a comprehensive understanding of the underlying mechanisms and dynamics involved. In the context of ICT usage and supply, the adoption of digital technologies may contribute to both an initial increase and a subsequent decrease in SO₂ emissions. Initially, the expansion of ICT infrastructure and digitization processes may lead to higher energy consumption and emissions, as highlighted by the rebound effect, where efficiency gains are offset by increased usage. However, as ICT technologies mature and become more widely adopted, they can facilitate the implementation of cleaner production methods, optimize resource allocation, and improve energy efficiency, ultimately leading to reduced SO₂ emissions. Researchers can develop a nuanced understanding of the complex relationships between ICT usage, ICT supply, and SO₂ emissions by incorporating this theoretical perspective. Link to Hypothesis 1–4, we graphically explains the theoretical framework in Fig. 1.

Variables, data, and statistical summary

Variables and data. This research obtained panel data for 41 cities of the YRD region between 2001 and 2019 and collected from various secondary sources. SO₂ emissions are used in this study by following Halkos and Paizanos (2013) and Wan and Shi (2022) as explained variables. SO₂ is a harmful gas released into the atmosphere due to industrial activities such as burning fossil fuels. SO₂ also contributes to environmental problems such as acid rain and respiratory diseases. The data on SO₂ emissions were taken from the China Statistical Yearbook on Environment and expressed as emissions of SO₂ tones per land area.

ICTU and ICTS are used as explanatory variables in this study. The level of digital economy in a city is employed as a proxy variable for ICTU, which is measured using the entropy method, incorporating several key indicators. These indicators include the digital financial inclusion index (sourced from Institute of Digital Finance, Peking University), the number of international internet users per 100 people (sourced from the China City Statistical Yearbook), the proportion of employees in information transmission, computer services, and software industries (sourced from the China City Statistical Yearbook), the per capita total volume

of telecommunications services (sourced from the China City Statistical Yearbook), and the number of mobile phone users per 100 people (sourced from the China City Statistical Yearbook). Meanwhile, ICTS is measured as the workforce employed in the ICT industry. The ICTU index, distinct from the ICTS, is a comprehensive indicator that takes into account the level of ICT technology development and application, as well as the supply of ICT workers in a city, thereby reflecting the level of digital economic development.

Control variables are gross domestic product (GDP), population density (POP), secondary industry (SDI), and investment (INS). We use the average annual growth rate of GDP referring to Shi et al. (2023), Markandya et al. (2006), and Zhao et al. (2021). It is considered an important indicator for assessing economic performance, monitoring trends, and comparing different periods and regions. POP is determined by the number of individuals residing in a given unit area, indicating population distribution and urbanization (Menz and Kühling 2011; Liu et al. 2019; Jiang et al. 2019). SDI is the workforce size that measures the industrial sector's contribution to employment and economic output and is adopted by Lou et al. (2021) and Yang et al. (2022). INS is taken by Bakhsh et al. (2022), and it is quantified by the number of fixed assets in billion RMB, reflecting the region's capital investment level. The data on GDP and POP were obtained from the China Economic Network database, while the SDI and INS data were attained from the China Statistical Yearbook. Table 1 presents variable types and names, and descriptions.

Analytical modeling and estimation method

Random-effect generalized least square (RE-GLS) model. In this paper, random-effect generalized least square (RE-GLS) regression is utilized, which is an effective technique for analyzing panel or hierarchical data where observations are grouped into clusters or units. It takes both within-group and between-group disparities in the data and incorporates random effects that capture the unidentified heterogeneity between units. These individual effects are supposed to be random and uncorrelated with the explanatory variables in the model, and the general specification is:

$$Y_{it} = \beta_i X_{it} + \vartheta_i + \varepsilon_{it} \quad (1)$$

where $\vartheta_i = \bar{\vartheta} + \epsilon_{it}$, if $E(\epsilon_i) = 0$, $cov(\epsilon_i \epsilon_j) = 0$, and $var(\epsilon_i) = \gamma_e^2$. Hence, changing the above equation leads to:

$$Y_{it} = \bar{\partial} + \beta_i X_{it} + \omega_{it} \quad (2)$$

where $w_{it} = u_{it} + \epsilon_{it}$. However, the main regression equation without spatial effect is as follows:

$$SO_{2it} = \alpha + \beta_1 ICTU_{it} + \beta_2 ICTS_{it} + \beta_3 ICTU_{it}^2 + \beta_4 Control_{it} + \epsilon_{it} \quad (3)$$

where SO_2 represents an explained variable, i denotes country, t means period, ICTU and ICTS are explanatory variables, and control symbolizes a series of control variables. α is the constant term, β are coefficients of explanatory and control variables, and ϵ_{it} is the stochastic error term.

Spatial Durbin model (SDM). The SDM, SEM, and spatial autoregressive (SAR) models are the frequently applied spatial models for dependent variables. LeSage and Pace (2009) developed the SDM, an extension of SAR, which includes spatial-lag factors for independent and dependent variables. The SDM has the benefit of addressing issues with spatial heterogeneity and missing elements that the SAR and SEM may have overlooked. Adopting a basic framework with one explanatory variable x , provide the

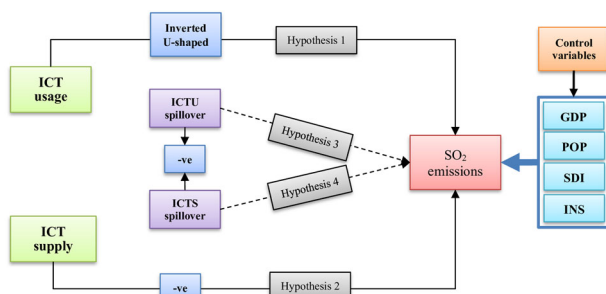


Fig. 1 Theoretical Framework.

Table 1 Research variables and description.

Variables types	Variables & Sign	Descriptions
Explained variable	Sulfur emission (SO ₂)	Emission of SO ₂ (tones)/land area
Explanatory variable	The Digital Economy Index (ICTU) The workforce employed in the ICT industry (ICTS)	Constructed by a set of individual variables. Number of workers in the ICT industry/the space of the region (10 thousand square kilometers)
Control variables	Gross domestic product (GDP) Population Density (POP) Secondary industry (SDI) Capital Investment Level (INS)	GDP - GDP of last year/ GDP of last year Number of people/the space of the region (kilometers, log form) Number of workers in secondary industry/ the number of workers Investment in fixed assets (billion Yuan, log form)

following description of panel SDM:

$$SO_{2it} = \delta_i + \rho \sum_{j=1}^N w_{ij}SO_{2jt} + \alpha + \beta x_{it} + \delta \sum_{j=1}^N w_{ij}x_{jt} + \alpha + \epsilon_{it}, \quad i \neq j \tag{4}$$

w_{ij} is the factor in the i th row and j th column of a spatial weight matrix W , $w_{ij}SO_{2it}$ is the effect of neighboring dependent variables SO_{2jt} on SO_{2it} , ρ represents spatial auto-correlation coefficients, δ , and β are explanatory variables coefficients, α denotes constant term, ϵ defines error term, δ specify the spatial specific effect. Nevertheless, to keep things simple, this analysis looks at the average direct impact of each SO₂ emission explanatory variable. Similarly, important elements in nearby regions have an impact on emissions in addition to the economy, policies, and other local issues. As a result, neglecting spatial correlations may result in erroneous estimates (Anselin and Griffith 1988). Therefore, the current study applied the spatial Durbin model to explore the impact of ICTU and ICTS on SO₂ emissions, considering spatial correlations. It can assess the impact of geographical spillover more precisely and comprehend the distinctions across cities better. Hence, we specified the model's equation as follows:

$$SO_{2it} = \rho_i + \beta_1 ICTU_{it} + \beta_2 ICTS_{it} + \beta_3 ICTU^2_{it} + \theta_1 WICTU_{it} + \theta_2 WICTS_{it} + \beta_6 Control_{it} + u_i + v_t + \epsilon_{it} \tag{5}$$

where W represents the spatial weight matrix, ρ is the auto-correlation coefficient, β , and θ is a spatial spillover effect from ICTU and ICTS, ϵ_{it} is the stochastic error term, u_i and v_t denotes city and year effects, respectively.

Dynamic panel data. In our study, we employed dynamic panel data analysis to investigate the relationships between various factors and outcomes of interest. Specifically, we used Stata's *xtdpdsys* and *xtabond* commands to analyze the data. These commands allowed us to account for the panel nature of our dataset, as well as the potential endogeneity of certain variables. In the *xtdpdsys* model, we specified one lag for all variables and used the lag struct option to account for the endogeneity of ICTU, ICTS, and ICTU2 (Windmeijer 2005). Additionally, we conducted Arellano-Bond tests for autocorrelation using two lags. The Arellano-Bond linear dynamic panel-data estimation model followed a similar structure, including the same set of variables and specifications for lags and endogeneity (Arellano and Bover 1995). By utilizing these dynamic panel data analysis techniques, we aimed to obtain more reliable and robust estimates of the relationships.

Table 2 Descriptive statistics.

Variable	Mean	Std. Dev.	Min	Max
SO ₂	5.426	6.409	0.001	37.871
ICTU	0.139	0.082	0.028	0.424
ICTS	2.569	7.358	0.051	65.870
SDI	0.525	0.198	0.183	2.870
INS	0.228	0.181	0.001	1.051
GDP	0.091	0.026	−0.063	0.160
POP	6.390	0.569	4.977	8.272

Empirical results

Descriptive statistics and correlation matrix. Descriptive statistics are crucial for understanding data, identifying outliers, and making initial observations. Table 2 exhibits descriptive statistic values of the variables. The mean SO₂ value during the sample period is 5.426, with a standard deviation (SD) of 6.409. Notably, Shanghai reported the lowest SO₂ values from 2013 to 2018, with a minimum of 0.001. These lower values place it among the least SO₂-producing cities in the YRD. Although most of the cities in YRD have reduced their overall emissions since the 2000s due to technological advancements, some others remain high compared to other cities. Despite the lowest value being reported for Shanghai, the maximum SO₂ value, 37.871, is also attributed to Shanghai in 2012, with other top-emitting cities including Suzhou, Zhenjiang, Ma'anshan, Tongling, Jiaxing, and Huainan.

Furthermore, the ICTU exhibits mean 0.139 and SD 0.082 values in the dataset. However, cities like Nantong, Yancheng, Ma'anshan, Chizhou, Anqing, Suqian, and Bengbu show relatively lower ICTU levels, with Luan having the lowest value of 0.028 in 2012. It could be due to a lack of necessary arrangements for widespread ICTU adoption or limited resources dedicated to these cities. Conversely, Nanjing reported the highest ICTU value of 0.424 in 2018, while Hangzhou and Shanghai also demonstrated higher ICTU levels. It is attributed to advanced infrastructure and robust economic development. These cities typically invest more in technology and have better access to high-speed Internet. Supportive government policies further encourage the adoption of ICTU across various sectors, fostering an environment conducive to technological innovation, productivity, and competitiveness.

The mean of ICTS is 2.569, with an SD of 7.358, indicating diverse levels of ICT supplies across different cities in the panel. Notably, cities such as Chuzhou and Xuancheng exhibit lower ICTS values, implying potential challenges in employing the workforce in the industry. The city of Chuzhou reported minimum values of 0.051 in 2018 in the YRD dataset. On the other hand, Nanjing and Shanghai consistently demonstrate high ICTS values, with the latter achieving a maximum value of 65.870 in 2019. This output suggests that urbanization in Shanghai is

Table 3 Correlation matrix.							
	SO ₂	ICTU	ICTS	SDI	INS	GDP	POP
SO ₂	1.000						
ICTU	0.103	1.000					
ICTS	−0.036	0.651	1.000				
SDI	0.300	0.076	−0.117	1.000			
INS	0.060	0.625	0.443	0.261	1.000		
GDP	0.148	−0.165	−0.120	−0.044	−0.085	1.000	
POP	0.287	0.363	0.491	0.311	0.461	−0.038	1.000

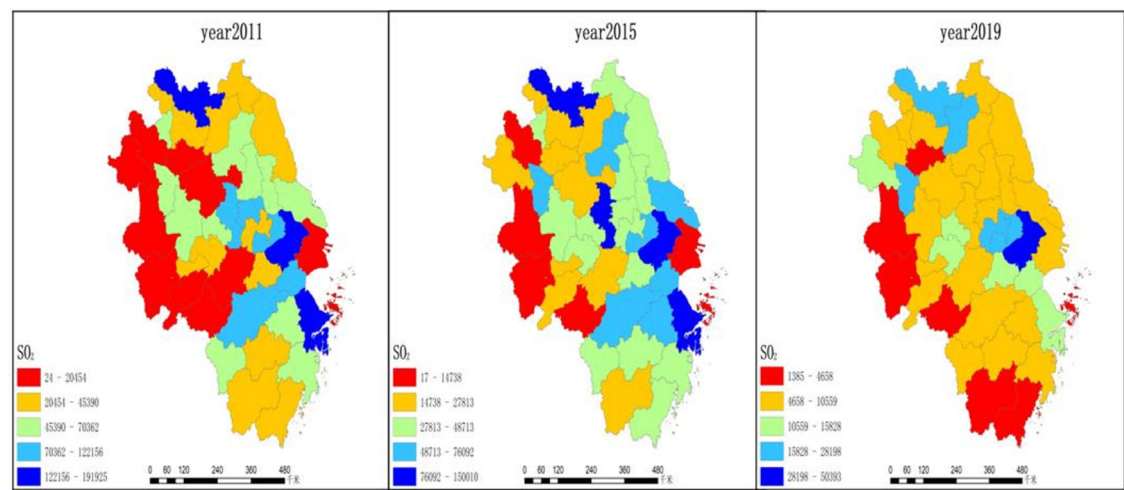


Fig. 2 Spatial distribution of SO₂.

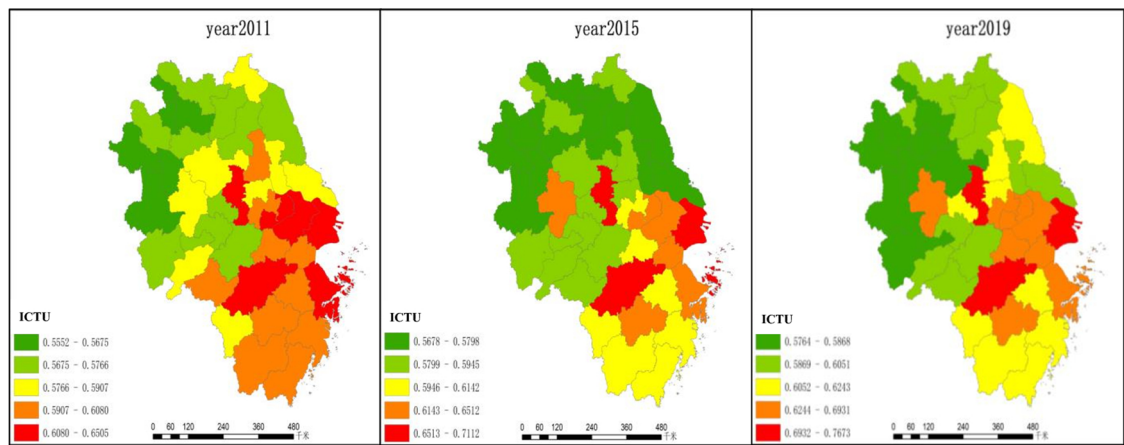


Fig. 3 Spatial distribution of ICT usage.

higher compared to other cities in China because it is among the most developed cities and serves as a major financial and economic hub. It attracts a large number of people from rural areas seeking better job opportunities, well-developed infrastructure, and a skilled workforce available to be employed in the ICT sector.

The SDI average is 0.525, with an SD of 0.198, while Luan reported the lowest value of 0.183 in 2016. Apart from Luan, Chizhou, Zhoushan, Lishui, and Bozhou cities also show lower values for SDI, which implies the shift towards automation and technological advancements, leading to a decrease in the need for manual labor. Also, rising labor costs and competition from other cities with lower labor costs may contribute to lower employment in these cities. However, SDI values for all cities exhibit a positive

trend, reaching a highest of 2.870 in 2017. The mean GDP is 0.091 with an SD of 0.026, reflecting the economic activity level of YRD cities, which constitute 20% of the Chinese economy in 2022. The cities of Huai'an, Tongling, Huainan, and Tongling reported negative values once, with the lowest of −0.063 in 2017 for Huai'an. Other than that, GDP revealed positive outcomes, which demonstrate strong infrastructure, technological advancements, a skilled workforce, stable political environments, and access to capital contribution to YRD cities. The mean INS is 0.228 with an SD of 0.181; Hefei reports a maximum value of 1.051, highlighting its significant investment portfolio. Tongling, Chizhou, and Huangshan have lower values for INS, but Quzhou exhibited a minimum value of 0.001 in 2018. The POP average value is 6.390, with an SD of 0.569. The minimum reported value

of POP is 4.977 for Lishui, and the highest is 8.272 for Shanghai. YRD is one of the most densely populated regions in China and includes one of the world's largest cities.

The correlation outcomes are presented in Table 3, indicating that multicollinearity issues are less likely to arise since none of the correlation coefficients are over 0.70.

Furthermore, Fig. 2 shows that around 2011, the haze problem in Zhejiang, Nanjing, Hefei, Maanshan, and Wuxi threatened the population's health. It was formerly one of the most pressing problems in China; however, SO₂ emissions have declined, suggesting that the country's air quality has improved from 2015 to 2019.

In addition, the initial phase of the sample period indicates that YRD cities are located in a highly developed region, including Shanghai, Hangzhou, Suzhou, Nanjing, Wenzhou, Wuhan, Chongqing, and Chengdu (Fig. 3). These cities represent the central hubs within major urban agglomerations, encompassing municipalities under the central government, provincial capitals, and selected highly developed urban centers. In 2015, the overall performance of ICTU had improved. Zhejiang Province has the highest percentage of rapid and advanced development. In 2019, the value of ICTU was highest on the whole, and the majority of cities in YRD appear to have a strong cluster pattern and are in the fast promotion and highly advanced areas.

Regression results. The current research explores the extent to which ICTU and ICTS impact SO₂ emissions in YRD. Table 4 provides the results of panel RE-GLS regression (columns 1–3) and SDM (columns 4–5). In column 1, SO₂ emission regresses with control variables, i.e., GDP, SDI, POP, and INS. Column 2 added ICTU and ICTS, and the outcomes of the inverted U-shape relationship were reported in column 3. The SDM results are mentioned in columns 4 and 5, in which the spatial spillover effect of ICTU and ICTS were examined.

Table 4 Regression Results.					
	RE (1)	RE (2)	RE (3)	SDM (4)	SDM (5)
ICTU		14.89** (6.99)	70.44*** (24.14)	14.71 (10.67)	86.07*** (31.51)
Wx.ICTU				4.83 (17.67)	−11.21 (19.74)
ICTS		−0.29*** (0.05)	−0.20*** (0.04)	−0.32*** (0.06)	−0.24*** (0.05)
Wx.ICTS				−0.45*** (0.17)	−0.40** (0.16)
ICTU ²			−137.55*** (51.48)		−161.58*** (56.96)
GDP	−1.86 (16.50)	2.06 (16.41)	8.49 (16.59)	4.37 (15.12)	11.01 (15.11)
SDI	5.07 (3.53)	4.50 (2.81)	4.43* (2.50)	4.63 (2.95)	4.77* (2.71)
POP	2.09* (1.16)	3.33** (1.48)	3.43** (1.54)	3.64** (1.76)	3.86** (1.73)
INS	0.21 (1.90)	−1.03 (2.44)	−1.25 (2.23)	−0.58 (2.27)	−1.06 (2.19)
_cons	−6.84 (7.43)	−16.42* (9.38)	−22.20** (10.27)	−17.49 (10.93)	−23.63** (10.91)
Spatial rho				−0.17 (0.12)	−0.17 (0.12)
R ²	0.42	0.44	0.47	0.47	0.50
χ ²	62.42	1115.16	3825.10		
p-value	0.00	0.00	0.00		
N	369	369	369	369	369

Note: Standard errors in parentheses *p < 0.15, **p < 0.1, ***p < 0.05.

The coefficient value of ICTU and its square term under both models reveal an inverted U-shape relationship with SO₂ emission. Based on this result, Hypothesis 1 is supported, which suggests that the impact of ICTU on SO₂ emission has an inverted U-shaped relationship. The outcome is supported by the earlier study of Cheng et al. (2023), who found a significant inverted U-shaped relationship between ICTU and SO₂ emissions in China.

Furthermore, the outcome shows that ICTS is negatively and significantly related to SO₂ emissions. The findings indicate that ICTS helps to reduce SO₂ emission at 0.01 significance levels, which confirms hypothesis 2. The results are endorsed by the prior study of Khan et al. (2022), who claimed that ICTS should be promoted to diminish emissions and enhance environmental conditions. At the same time, the outcomes contradicted the previous study by Weili et al. (2022), which stated that ICTS raised emission levels.

The spatial spillover effect of ICTU on SO₂ pollution was found to be insignificant, which does not provide sufficient proof to support H3. Meanwhile, the spillover effect of ICTS on SO₂ pollution has a significant negative impact at a 5% significance level. The finding endorsed Hypothesis 4.

Robustness results. To further support the study's findings, a dynamic panel model was employed to address the issue of endogeneity, with the outcomes reported in Table 5. Based on the findings, the signs and significance of almost all variables are coherent with the regression results presented in Table 4, showing the robustness of our research.

Discussion

Understanding the impact of ICTU and ICTS on SO₂ emissions is crucial as it provides a theoretical foundation for regional development, which is the central focus of this study. The main regression and robustness test findings affirm the reliability and stoutness of the conclusions drawn. Consequently, this section will delve into the SO₂ emission declining impacts of each explanatory factor on both the local cities and their surrounding regions based on empirical results. Firstly, ICTU found an inverted U-shaped relationship with SO₂ emissions, which suggests that at early stages of ICT adoption, emissions may increase, but after a certain point, further ICT usage can lead to a decrease in emissions. The reduction in

Table 5 Robustness results.		
	AR(1)	AR(2)
ICTU	52.561*** (17.968)	34.739* (21.460)
ICTS	−0.866*** (0.106)	−0.974*** (0.131)
ICTU ²	−156.547*** (36.710)	−138.324*** (42.879)
GDP	17.272*** (8.679)	11.927 (9.085)
SDI	1.274 (1.279)	0.879 (1.284)
POP	−2.016* (1.258)	−0.955 (1.970)
INS	0.367 (1.607)	−3.750** (1.946)
_cons	8.230 (7.910)	12.281 (12.615)
χ ²	573.41	524.01
p-value	0.00	0.00

Note: AR(1) is Arellano-Bond; AR(2) is Arellano-Bover/Blundell-Bond; Standard errors in parentheses *p < 0.15, **p < 0.1, ***p < 0.05.

SO₂ emissions observed in the YRD region with increased ICT usage aligns with EKC theory, suggesting that technological advancements enabled by ICT contribute to environmental improvement. Furthermore, the spatial distribution of ICTU within cities in the YRD region may also play a substantial part in reducing SO₂ emissions (Zhou et al. 2021). High-density urban areas with widespread ICT infrastructure and usage may experience greater benefits in terms of emission reductions due to the concentration of economic activities and technological innovation. For example, cities like Shanghai, Suzhou, and Hangzhou, which are hubs for ICT development and innovation, may contribute disproportionately to the overall reduction in SO₂ emissions in the region (Ruoyuan Lei et al. 2022).

Moreover, the spillover effect of ICTU shows an insignificant relationship with SO₂ emissions, which might be due to the continuous evolution of ICTU and its impact on various societal aspects and environments that may change over time. What may be insignificant now could change as technology advances and becomes more integrated into industries. Other factors can also contribute to insignificant spillover outcomes, including the complex and indirect nature of the relationship and the presence of other significant factors influencing SO₂ emissions. Further research and analysis are needed to offer a detailed understanding of this relationship. In addition, the negative and significant relationship between ICTS and SO₂ emissions signifies that ICTS can be pivotal in lowering emissions by enabling more effective monitoring and control, optimization of energy consumption, and resource management (Zhang et al. 2021). This finding supports sustainability goals by highlighting technology-driven strategies that can drive economic growth while reducing environmental harm. The evidence also highlights technology's potential for advancing environmental goals, guiding industries toward a greener and more sustainable future.

Additionally, the spillover effect of ICTS also has a significant negative impact on SO₂ emission, which reveals that ICTS can assist in reducing emission levels in neighboring cities. Due to the substantial spatial spillover effects of ICTS, the authorities must seize these opportunities to implement a cooperative regional plan for reducing emissions. In general, the accomplishments in reducing SO₂ emissions within a local province are intricately tied to neighboring provinces, whether geographically or economically. This dynamic often reflects a pattern of “rising and falling together.” In China, the overarching objective of reducing SO₂ emissions necessitates collaboration among all provinces to achieve a “win-win” outcome. Clearly, relying solely on the efforts of a single developed region is not a feasible approach. The outcomes of this research are aligned with the specified objective as ICTU and ICTS significantly lower emission levels in the YRD region, and they validate the stated hypotheses. Policymakers should consider these nuances when designing strategies to leverage ICT for environmental sustainability.

Conclusions and policy implications

The study has focused on the impact of ICTU and ICTS on SO₂ emission in the Yangtze River Delta using panel data from 2011–2019. This research utilized random-effect generalized least square and Spatial Durbin models for analysis. The outcomes show an inverted U-shape relationship between ICTU and SO₂ emissions, while ICTS is negatively related to SO₂ emissions. The spatial analysis reveals that the ICTS in one region can help to reduce SO₂ emissions in neighboring regions.

The results have significant policy repercussions as China gradually enters the mode of “made in China to Digitalize in China.” The reasonable and effective promotion of ICTU can provide a long-term and stable driving force for national economic growth. First, China should push for better cooperation between ICTU and environmental management to contribute to its improvement simultaneously. Promoting online shopping, fostering a culture of e-conferencing, and digitizing the economy can reduce energy consumption. Specifically, these measures would surge energy efficacy and reduce pollution. Secondly, the government should accelerate the development of ICTS and implement pollution control measures based on the actual circumstances. Enhancing information infrastructure, persistently reducing the digital divide, and advancing comprehensive industrial rearrangement and upgrading are imperative. Simultaneously, municipal administrations should proactively explore the potential of applying ICT to mitigate SO₂ emissions across various industries. This exploration can inform the development of well-founded policies to steer growth and foster the transition toward a low-emission economy.

Although the study has contributed to understanding how ICTU and ICTS contribute to SO₂, it also experienced some limitations. Firstly, the dataset used to analyze SO₂ levels in cities was relatively small, which may introduce a small sample bias and limit the generalizability of the findings. A more extensive and comprehensive dataset would provide a more accurate and robust result. Secondly, the data analysis in this research primarily focuses on the Yangtze River delta, which may overlook regional variations, challenges, and circumstances. Future research may incorporate regional division data to examine regional heterogeneity.

Data availability

The datasets are available from <https://doi.org/10.7910/DVN/AXADIS>.

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Umair Kashif, Writing—original draft and editing; Junguo Shi, Conceptualization, data analysis and visualization, Writing—original draft and editing, revised the manuscript, Funding acquisition, Project administration; Sihan Li, Spatial analysis, revised the manuscript; Qinqin Wu, Data collection, revised the manuscript; Qiuya Song, Data collection, Regression, revised the manuscript; Shanshan Dou, discussion, Writing—review & editing; Mengjie Wei, revised the manuscript; Snovia Naseem, conception and design, Writing—original draft and editing.

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The authors declare no competing interests.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

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