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Impact of the digital economy on low carbon sustainability evidence from the Yellow River Basin

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As the digital economy increasingly dominates a substantial portion of the national economy, comprehending its role in promoting sustainable development has become an imperative research question—particularly in the context of the Yellow River Basin, where there exists an urgent need to shift toward more sustainable modes of economic growth. Utilizing panel data spanning from 1999 to 2020 for 114 cities in the Yellow River Basin, this study develops a comprehensive evaluation framework for sustainable development, incorporating economic, social, and ecological dimensions. The empirical findings reveal that the digital economy acts as a catalyst for sustainable development. Importantly, these results withstand both endogeneity tests and robustness checks. Further heterogeneity analysis indicates that the positive impact of the digital economy on sustainable development is more pronounced in regions directly traversed by the Yellow River and in areas with higher sustainability levels. Moreover, the enactment and implementation of the 13th Five-Year National Information Plan have emphasized the role of the digital economy in enhancing sustainable development. Mechanism tests also illustrate those elevated levels of personal digital acceptance and government intervention contribution to amplify the digital economy's positive impact on sustainable development. In conclusion, policy recommendations are put forward, including optimizing industrial structure, strengthening data governance and environmental monitoring, promoting innovation-driven development, and fostering collaborative growth.

KEYWORDS

digital economy, sustainable, moderating effect, Yellow River Basin, government intervention

1 Introduction

Given the rapid advancement of information technology and the pervasive integration of digital processes, the digital economy has ascended as a primary engine of global economic growth in the 21st century (Ma and Zhu, 2022). Characterized by attributes such as efficiency, innovation, and broad societal benefits, the digital economy has radically disrupted traditional industrial frameworks and modes of economic expansion. Concurrently, it has facilitated the mainstream adoption of emergent information technologies such as artificial intelligence, blockchain, big data, and cloud computing, thus revitalizing the global economic landscape. This transformation is particularly salient against the backdrop of the COVID-19 pandemic, which has imposed constraints on traditional economic activities, further elevating the significance of the digital economy as a pivotal driver in the new economic era (Yin and Yu, 2022).

The Yellow River Basin, a region integral to China's economic and cultural landscape, possesses distinct resource advantages but also faces intricate challenges. These challenges encompass a fragile ecosystem, escalating resource conflicts, and the precarious equilibrium between developmental objectives and environmental preservation (Zhang et al., 2022a). Given China's Dual Carbon Policy initiative, the pursuit of sustainable development in the Yellow River Basin has garnered heightened attention from multiple governance levels and has become an urgent societal mandate (Zeng et al., 2023). The emergence of the digital economy offers innovative pathways for achieving low-carbon and sustainable growth in this region. In contrast to traditional economic systems, the digital economy minimizes reliance on and consumption of natural resources. Its decentralized and trans-regional nature alleviates limitations on the basin's sustainable development. Leveraging emergent digital technologies can facilitate efficient resource management and distribution, while the extensive deployment of environmental monitoring systems enhances governmental strategies for ecological governance (Zhao et al., 2023). Thus, the intrinsic strength of the nexus between the digital economy and sustainable development emphasizes its pivotal role in the low-carbon sustainability of the Yellow River Basin.

The current existing literature primarily revolves around the intersections between digital transformations and enterprise sustainability (Stefano et al., 2021; Gerard and Simon, 2022), governmental sustainability (Gema et al., 2021; Zhang et al., 2022b), and supply chain resilience (He and Bai, 2021; Sachin et al., 2022). Despite the extensive nature of existing research, there is a conspicuous scarcity of studies concentrating on the Yellow River Basin in China. Notably absent is an exploration of whether the digital economy in the 114 prefecture-level cities in the Yellow River Basin can propel sustainable development, the pathways for its realization, and the potential existence of heterogeneity issues in the influencing process. Examining these issues is of significant theoretical and practical importance for the reasoned development of China's digital economy and the achievement of sustainable long-term goals. Simultaneously, it can provide valuable insights and references for regions worldwide confronting similar conditions.

To address the aforementioned issues, this study employs panel data from the 114 prefecture-level cities in the Yellow River Basin spanning the years 1999–2020. The empirical analysis is conducted using Stata software. Firstly, it establishes a fixed-effects model to empirically analyze the relationship between the digital economy in prefecture-level cities in the Yellow River Basin and sustainable development. Secondly, it constructs an evaluation framework for sustainable development that considers economic, social, and ecological perspectives. This framework explores the different impacts of China's digital economy on sustainable development, distinguishing between periods before and after the issuance of the pivotal document "National Information Planning for the 13th Five-Year Plan." Simultaneously, the study conducts empirical analysis to address issues of heterogeneity during the influencing process. Lastly, examining from both individual and governmental perspectives, this study investigates whether there is a moderating effect of personal digital acceptance and government intervention in the baseline regression.

The research contribution of this paper is threefold: Firstly, it addresses the deficiency in empirical analysis of the relationship between the digital economy at the prefecture level in the Yellow River Basin and sustainability. It establishes a comprehensive evaluation framework for sustainable development, considering multiple dimensions. Secondly, the Yellow River Basin is categorized based on whether it is directly traversed, policy issuance timing, and levels of sustainability. This approach allows for the consideration of heterogeneity in baseline regression under different conditions. Simultaneously, a meticulous empirical and theoretical analysis of influencing mechanisms during the impact process is conducted, providing a more diversified reference for drawing research conclusions. Lastly, situated in the environmentally complex and infrastructure-limited context of the Yellow River Basin in China, this study holds relevance for sustainable development in other regions globally facing similar conditions. It offers valuable guidance on how regions can effectively develop and leverage the digital economy for sustainable development.

The structure of the remaining sections of this paper is organized as follows: Section 3 furnishes a theoretical analysis; Section 4 delineates the empirical models deployed for analysis, along with a discussion of the variables incorporated; Section 5 presents the results of the empirical regression, encompassing benchmark regression, endogeneity tests, robustness checks, and heterogeneity analyses; Section 6 delves into a mechanistic examination of the model, testing the mediating effects of individual digital adoption and governmental interventions within the benchmark regression; and finally, Section 7 consolidates the study's findings and proposes relevant policy recommendations.

2 Literature review

The integration of the digital economy with various industries and the increasing national strategic emphasis on sustainable development have brought significant attention to the relationship between the digital economy and sustainability across various sectors. Upon reviewing existing literature, the primary areas of discussion predominantly concentrate on three aspects: the impact of the digital economy on economic sustainability, its influence on social sustainability, and its effects on ecological sustainability. The following will provide a systematic summary and analysis of relevant literature on these topics.

When examining the impact of the digital economy on economic sustainability, existing literature primarily focuses on three key aspects: the in-depth application of digital technologies, the expansion of digital platforms, and the intelligent computation of production data. Firstly, concerning the in-depth application of digital technologies, Strandhagen et al. (2022) posit that incorporating digital technologies into the production process enables automation and intelligence, facilitating unmanned production lines. This not only reduces labor input and production time but also enhances production efficiency. Fu and Zhang (2022) contend that intelligent manufacturing systems can optimize production plans, reduce inventory costs, and diminish surplus capacity through real-time data analytics and predictive algorithms, thereby mitigating resource wastage and promoting sustainable economic growth. Additionally, Lee et al. (2023) posit that the digital economy has effectively alleviated geographical constraints on economic development. The creation of digital communication and collaboration platforms allows enterprises to source suppliers and partners globally, select optimal production locations, and ensure efficient resource allocation across the value chain, thereby reducing operational costs and stimulating sustainable economic growth. Furthermore, digital technologies enable personalized production and bespoke services, addressing issues related to overproduction and inventory surpluses while simultaneously catering to diverse consumer preferences and enhancing resource-use efficiency (Sjodin et al., 2020). Secondly, in the expansion of digital platforms, the widespread adoption of digital technologies and the proliferation of digital platforms have democratized market entry, fostering competition and innovation. This market diversification stimulates sustainable economic growth by engaging a broader array of innovators and entrepreneurs (Liu et al., 2022a). Through an empirical study on SMEs in Malaysia, Wong et al. (2020) deduced that the technological advancements mitigate information asymmetry and bolster market transparency, contributing to the economy's robust and sustainable growth. Ultimately, in the intelligent computation of production data, the advent of digital technology enables market participants to gain a more precise understanding of market supply and demand dynamics as well as price fluctuations. This precision enhances the market's ability to accurately mirror the supply-demand relationship, mitigating the risk of market failure and fostering market stability (Kong et al., 2022). Zhou et al. (2020) argue that decision-making frameworks fueled by big data, cloud computing, and artificial intelligence enable enterprises to adapt to market shifts more efficiently, tailor products and services that resonate with consumer demands, and enhance their competitive edge. The infusion of information technology in risk management and sustainability assessment induces enterprises to adopt a long-term perspective, thereby averting the deleterious impacts of short-termism on the environment and society (Urbinati et al., 2020).

Regarding the impact of the digital economy on social sustainability, prevailing literature predominantly highlights three crucial considerations: the promotion of employment and entrepreneurial opportunities (Ratten and Usmanij, 2021), the enhancement of policymaking and oversight capabilities, and the assurance of financial inclusion and social welfare (Lechman and Popowska, 2022). Firstly, regarding the promotion of employment and entrepreneurial opportunities, rapid technological advancements have catalyzed the emergence of new sectors such as e-commerce, intelligent manufacturing, and online education. These burgeoning fields have consequently created a diverse range of employment opportunities, fostering job diversification in roles spanning service, management, and beyond (Warner and Wäger, 2019). Concurrently, the establishment of digital communication platforms has lowered the barriers to entrepreneurship, invigorating economic activity and attenuating traditional employment scarcities (Fernandes et al., 2022). Novel work arrangements like remote working, freelancing, and the sharing economy enable individuals to customize their employment settings, enhancing job satisfaction, circumventing commute-related limitations, and elevating overall work efficiency (Lee and Lee, 2020). The advent of digital education and online training platforms cultivates and elevates the populace's awareness of lifelong learning, bolster the professional competitiveness of individuals, thereby enabling them to adapt more effectively to evolving labor market conditions (Anthonysamy et al., 2020). Secondly, in enhancing policymaking and oversight capabilities, the advent of data-driven governance enhances policy effectiveness by curtailing subjective biases and bolstering targeted approaches (Zhu and Chen, 2022). Additionally, the utilization of social media and online surveys equips policymakers with immediate public feedback, allowing for expedient policy adjustments and bolstering policy feasibility and rationality (Appel et al., 2020). As suggested by Ma and Wu (2020), digital platforms facilitate understanding of policy documents and government expenditures, thereby enhancing governmental transparency and fostering social sustainability. Thirdly, in ensuring financial inclusion and social welfare, digital financial instruments such as mobile payments, digital banking, and blockchain technologies transcend the geographical and sectoral limitations inherent in traditional finance (Ozili, 2018). This inclusivity extends financial services to previously marginalized demographics like rural inhabitants and low-income individuals (Mushtaq and Bruneau, 2019). The streamlining of online business processes significantly minimizes transactional delays, bolstering public engagement in economic activities and thus advancing financial inclusion (Chen et al., 2023). Furthermore, the digitalization of social welfare services, such as social security payments and e-healthcare, enhances service efficiency and convenience, contributing to elevated social welfare standards and the broader aim of social sustainability (Schou and Pors, 2019).

In examining the impact of the digital economy on ecological sustainability, existing literature places particular emphasis on three key dimensions: carbon footprint management (Zulfiqar et al., 2023), smart city construction (Rathore et al., 2018), and innovation in environmental monitoring (Xu et al., 2022). Firstly, concerning carbon footprint management, Yan et al. (2022) argue that real-time data collection through digital technologies such as big data and the Internet of Things (IoT) can establish an accurate carbon emissions database. This resource allows enterprises, governments, and individuals to comprehensively understand the magnitude and composition of their carbon footprints. Leveraging database-driven analytics, stakeholders can formulate targeted energy management strategies, optimize industrial processes, and consequently diminish carbon emissions, fostering energy conservation and emissions reduction (He et al., 2023). The development of renewable energy, clean technology, and other sectors is increasingly characterized by cost-effectiveness and heightened efficiency, facilitated by advances in digital technology (Townsend and Coroama, 2018). Simultaneously, traditional industries are undergoing a digital transformation, steering towards low-carbon operations in response to a myriad of carbon emission regulations (Cao et al., 2021). Secondly, in the domain of smart city construction, digital technologies are paramount in the evolution of smart cities. Their implementation elevates resource utilization rates and renders the management of pollutants like wastewater and exhaust gases more precise and controllable (Wang et al., 2022). Intelligent traffic systems optimize flow control, mitigating congestion and reducing energy wastage (Melkonyan et al., 2022). Furthermore, urban planning strategies bolstered by digital technology have successfully mitigated the ecological consequences of urban sprawl, fostering ecological sustainability

(White et al., 2021). Lastly, in the innovation of environmental monitoring, digital sensing and remote sensing technologies facilitate the real-time acquisition of essential environmental parameters. These data streams enable governmental agencies to gauge environmental shifts and pollution levels accurately, thereby informing more scientifically grounded policy decisions (Li, 2022). IoT and big data further augment regulatory oversight by allowing real-time monitoring of industrial emissions, facilitating prompt identification and remediation of excessive pollutant discharges (Wan et al., 2023). Moreover, digital tools offer a multi-faceted analytical framework for assessing ecosystem health, enabling predictive modeling of ecological trends (Li et al., 2020). This predictive power informs targeted ecological restoration strategies, enhancing the ecosystem's resilience and adaptability, thereby advancing its sustainable development (George et al., 2021).

Existing literature has extensively examined the individual impacts of the digital economy on economic sustainability, social sustainability, and ecological sustainability. However, there has been scarcity of studies that integrate these three aspects of sustainability for comprehensive examination. Dialectical materialism argues that an isolated and one-sided approach may struggle to grasp the essence of the issues. In line with this perspective, the present study considers the economic, social, and ecological dimensions, constructing a comprehensive evaluation framework for sustainable development. Through empirical analysis of the digital economy's impact on these indicators, the study aims to provide theoretical support for the development of the digital economy in the Yellow River Basin and the enhancement of its overall sustainability. This integrative approach is expected to offer a more holistic understanding of the intricate relationships between the digital economy and sustainable development in the specified region.

3 Research design

3.1 Model setting

3.1.1 Benchmark regression model

To empirically evaluate the association between the digital economy and sustainable development, this study focuses on 114 cities within the Yellow River Basin from 1999 to 2020. Utilizing a Fixed Effects Model, the paper employs Stata software to conduct a regression analysis on relevant data. The baseline regression model for this research is structured as follows (Ma et al., 2022):

$$s_{it} = \beta_0 + \beta_1 eco\text{-}dig_{it} + \sum \beta_k X_{k,it} + \mu_i + \varepsilon_{it} \tag{1}$$

In Equation 1, s_{it} denotes the level of sustainable development for city i in year t. The term β_0 serves as the intercept; $eco\text{-}dig_{it}$ is the core independent variable, representing the development level of the digital economy in city i at time t. β_1 is the coefficient for this variable; $X_{k,it}$ represents several control variables, reflecting the important economic and social characteristics of the Yellow River Basin, β_k are their respective coefficients; μ_i signifies the regional fixed effect; ε_{it} is the random error term.

3.1.2 Moderating effect model

To further elucidate the mechanisms through which the digital economy influences sustainable development, this study investigates the moderating roles of Personal Digital Acceptance (*tel*) and Government Intervention (*reve*) in the benchmark regression model, from both individual and governmental perspectives.

From the perspective of individual digital acceptance, firstly, regarding the impact of the digital economy on individual digital acceptance, as the integration of digital technologies into various facets of production and daily life follows a "technology acceptance curve." The advent of digital technology has drastically reduced the costs associated with information transfer and transactions. This enhanced efficiency enables individuals to acquire pertinent information promptly and accurately, thus lowering the entry barriers to the digital economy. As a result, individual acceptance of digital technology has been on steadily upward trajectory. Concurrently, the digital economy offers opportunities for personalized and customized services, further enhancing individual willingness to embrace this economic model (Wang et al., 2023a). Moreover, the proliferation of online social networking platforms has facilitated the exchange of opinions, bolstering individual acceptance rates under the influence of "herd behaviour" (Oh et al., 2022). The continual innovation within the digital economy also introduces more compelling digital products, better meeting diverse individual needs and bolstering digital economy acceptance (Grover et al., 2019). On the other hand, concerning the impact of individual digital acceptance on sustainable development. Elevated levels of personal acceptance of digital technologies have augmented access to information and knowledge about sustainable development. A comprehensive understanding of its principles, challenges, and solutions enables greater active participation in its advocacy and implementation (D'Amato and Korhonen, 2021). Digital platforms also play a crucial role in offering consumers comprehensive product information, influencing choices toward environmentally sustainable options. This, in turn, creates incentivizes manufacturers to adhere more closely to sustainability standards (Grunert et al., 2014). Additionally, improved individual technology acceptance facilitates sustainable investment and financial innovation. Through digital platforms, investors can obtain data on projects with significant environmental and social impact, thus directing capital flows into these sectors and bolstering financial support for sustainable development (Wang et al., 2023b).

From the vantage point of governmental intervention, firstly, concerning the impact of the digital economy on government intervention, Liu et al. (2022b) assert that the digital economy contributes to the scientific rigor of government policymaking. On one hand, the plethora of data generated by digital technologies illuminates trends in economic, societal, and environmental development. This enables governments to identify issues, establish objectives, and assess policy efficacy through data analytics, optimizing public service delivery and elevating societal wellbeing more precisely (Zhang et al., 2022c). Moreover, the digital economy not only presents novel fiscal and tax challenges but also offers innovative tools for governance. Technologies like digital currency and blockchain have notably heightened the efficiency of governmental oversight in financial markets and tax administration. Various digital regulatory mechanisms have refined the precision and intelligence of market intervention, effectively guiding market operations and mitigating financial and market risks (Oliveira et al., 2020). On the other hand, regarding the impact of government intervention on sustainable development. Hao et al. (2022) suggest that governmental intervention can act as a catalyst for sustainable development. Through various instruments like taxation, subsidies, and emissions caps, governments can compel enterprises to internalize environmental costs, encouraging a focus on environmental and social impacts. Concurrently, the establishment of environmental regulations and standards can modulate corporate production behaviours, fortifying environmental conservation measures and lessening environmental degradation (Xu et al., 2023). Furthermore, within the educational sphere, governmental initiatives can enhance public awareness and comprehension of environmental issues, fostering a shift toward sustainable consumption and lifestyles through public outreach and educational programs (Lin et al., 2021). Financial incentives such as scientific research funding and tax benefits, can also stimulate advancements in environmental protection technologies and sustainable innovation, thereby reducing resource consumption and environmental pollution (Khan et al., 2021).

Based on the preceding analysis, this study ultimately adopts the mobile phone penetration rate—defined as the ratio of the number of mobile phone users to the total population at the year's end—as a proxy variable for individual digital acceptance. Additionally, the fiscal health of a locality, expressed as the ratio of local general budget revenue to GDP, is selected as a proxy variable for governmental intervention. To investigate whether individual digital acceptance and governmental intervention exert a moderating influence on the promotion of sustainable development, this study constructs an interaction term between these moderating variables and the core explanatory variable. The aim is to explore whether there is a moderating effect by assessing the regression coefficient of the interaction ter. The formula for assessing this specific moderating effect is as follows (Liang and Li, 2023):

$$s_{it} = \gamma_0 + \gamma_1 eco\text{-}dig_{it} + \gamma_2 Med_{it} + \gamma_3 eco\text{-}dig_{it} \times Med_{it} + \sum \gamma_k X_{k,it} + \mu_i + \varepsilon_{it} \tag{2}$$

In Equation 2, Med_{it} denotes the moderating variables, specifically individual digital acceptance and governmental intervention. All remaining variables adhere to definitions established previously. The introduction of the interaction term $\gamma_3 \times Med_{it}$ in Eq. 2 highlights the need to manage the risk of multicollinearity between the core explanatory variable and the moderating variables. To address this, we center both the core explanatory and moderating variables prior to analyzing their moderating effects.

3.2 Variable description

3.2.1 Explained variable

Since the publication of the "China 21st Century Population, Environment, and Development White Paper" in 1994, which initially incorporated the concept of sustainable development into China's long-term economic and social planning, the enduring significance of sustainability in China's economic trajectory has been steadfast. Sustainable development encompasses economic, social, and ecological dimensions, which are interdependent and mutually reinforcing. This study undertakes a comprehensive review of extant academic literature and constructs an evaluative framework for sustainable development, focusing on its economic, social, and ecological facets.

First, with regard to economic sustainability, this study adopts metrics informed by the research of Cillo et al. (2019). Disposable income of urban residents is chosen as an indicator of income status, while the urban registered unemployment rate serves as a proxy for employment conditions. Additionally, the ratio of total retail sales of consumer goods to the year-end population size is utilized to gauge consumption levels (Azadi et al., 2015). To assess industrial development and infrastructure, key performance indicators include the proportion of the tertiary sector's total output value to GDP and total freight volume (Bui et al., 2021).

In the realm of social sustainability, we refer to the work of Li et al. (2021) and select the proportion of foreign direct investment in GDP as a proxy for openness of the economic environment. The ratio of fixed asset investment to GDP is employed to assess capital investment levels. Labor efficiency is quantified via the ratio of GDP to the year-end total population, while innovation output and input are measured respectively by the number of invention patents per 10,000 individuals and the ratio of science and technology expenditure to local government's general budgetary expenditure (Tan et al., 2016).

Concerning ecological sustainability, guided by the methodologies outlined by Yang et al. (Yang et al., 2020), this study opts for the ratio of annual total electricity consumption to GDP as a proxy for resource utilization. Urban greening is assessed through the greening coverage rate of built-up areas. Per capita greening is measured by the ratio of garden green space area to the year-end total population (Ameen et al., 2015). Finally, in relation to environmental remediation and pollution metrics, this paper references the work of Nizetic et al. (2019) and employs the ratio of total industrial wastewater discharge to annual water supply, as well as the ratio of industrial smoke (dust) emissions to GDP. For specific details regarding the variables, please refer to Table 1.

This study employs the entropy evaluation method to derive a comprehensive index for measuring sustainable development. Within this framework, metrics such as employment status, environmental remediation, resource consumption, and pollution discharge are considered as negative indicators, while all other parameters are deemed positive. To facilitate uniform comparison, each metric undergoes a dimensionless transformation through range normalization, which is followed by an additional normalization transformation through range normalization, flowed by an additional normalization process. The entropy evaluation method is then applied to calculate aggregate scores, enabling the assessment of sustainable development levels across different cities over varying time periods. A higher value of this comprehensive index correlates with an elevated level of sustainable development.

3.2.2 Core explanatory variable

Currently, the academic community employs two primary methodologies for assessing the level of digital economic development. The first approach involves constructing a comprehensive evaluation system for the digital economy, grounded in its formal definitions and inherent attributes (Luo and Zhou, 2022; Chen and Zhang, 2023). Alternatively, a singular metric can be utilized for this purpose, such as Li et al.'s usage of the digital financial inclusion index to depict the state of urban digital economic development (Li et al., 2022). Drawing upon the research of Wang et al. (2023a), this study measures digital economic development through the proportion of total industrial output value generated by computer, communication, and other electronic equipment manufacturing industries above a predetermined size, relative to the value-added in the broader manufacturing sector. This specific metric sheds light on the pivotal role the digital economy plays in resource allocation, production efficiency, and the harmonization of the industrial, value, and supply chains. Meanwhile, the manufacturing of computers, communication equipment, and other electronic devices plays a crucial role in the digitization process of industries. Its proportion in the total output value of the secondary industry effectively reflects the level of development in the digital economy.

3.2.3 Mediating variable

In evaluating personal digital acceptance, this study quantifies the mobile phone penetration rate as the ratio of the number of mobile phone users to the total population at year-end, utilizing it as a proxy for personal digital acceptance. Turning to governmental intervention, this research employs the ratio of local fiscal general budget revenue to GDP as an indicator to gauge the extent of such intervention.

3.2.4 Control variables

In terms of control variables, R&D capability serves as a pivotal catalyst for the advancement of the digital economy and its sustainable transformation, with technical personnel serving as crucial enablers for R&D functions. To capture research and development support, the study employs the ratio of employees in scientific research and comprehensive technological units to the total workforce as a metric to assess research and development support (*tech*). Concurrently, the ongoing expansion of higher education in China acts as a conduit for disseminating and actualizing sustainable development concepts, thereby elevating levels of sustainable innovation. This is quantified by the study through the indicator of the number of higher educational institutions per 10,000 individuals (*edu*). Moreover, significant income disparities between urban and rural sectors (*income*) can lead to resource allocation imbalances, impeding investment and human capital formation in rural areas, thereby negatively impacting rural sustainable development (Li et al., 2023). Therefore, an investigating of this urban-rural income gap is integral to this research. Lastly, financial support plays a crucial role in achieving long-term sustainable development by directing investments toward sustainable industries and ensuring a balance between economic growth and environmental concerns. To measure this aspect, the study uses the ratio of the deposit and loan balances in financial institutions to GDP ($fina$).

3.2.5 Data sources

This study utilizes panel data spanning from 1999 to 2020 for 114 cities in the Yellow River Basin. The primary sources of this data include the "China City Statistics Bulletin," the "China City Statistics Yearbook," records from various city statistical bulletins, and the EPS database. It is essential to highlight that statistical efforts commenced relatively late in certain remote areas, resulting in variations in data quality. To address minor gaps in the dataset over the sample period, this research employs linear interpolation for measurement and supplementation. The descriptive analysis of the variables used is presented in Table 2.

4 Results and analysis

4.1 Benchmark regression analysis

To explore the impact of the digital economy on sustainable development at the municipal level in the Yellow River Basin, this study conducted an analysis of the baseline regression model. In this regression, the Variance Inflation Factor (VIF) test indicated the absence of multicollinearity, suggesting that the selected variables do not display high correlations. The Hansen test demonstrated the overall effectiveness of the chosen control variables. Furthermore, based on the results of the Hausman test, fixed effects were ultimately selected for the regression analysis, indicating that this model is suitable for investigating the relationship between the digital economy and sustainable development while adequately controlling for potential confounding variables.

Table 3 delineates the specific regression outcomes. Notably, the digital economy serves as a significant catalyst for sustainable development, with its influence statistically significant at the 1% level. As indicated in column (1), a single-unit increase in the digital economy yields a 0.0563-unit upswing in sustainable development levels. This finding holds even when accounting for various control variables.

Digital technology contributes to sustainability through various avenues. First, it enhances efficiency, thereby reducing both energy consumption and resource waste, achieving a harmonious relationship between economic growth and environmental conservation. Second, the application of digital technology in environmental monitoring and data analytics enables a more nuanced approach to environmental management. This capability allows governments to formulate targeted environmental policies based on real-time data on pollution sources and resource usage. Finally, digital finance mechanisms, such as green bonds and sustainable investment funds, direct capital towards sectors dedicated to environmental preservation and social responsibility, thereby facilitating long-term, stable sustainable development.

In examining the control variables, we find several noteworthy outcomes deserve attention. The coefficient for R&D support is notably positive and statistically significant at the 10% level. This suggests that enhanced R&D capabilities not only contribute to sustainable development but also foster the growth of eco-friendly industries like renewable energy and clean technology, thereby reducing reliance on finite resources. Furthermore, the level of higher education exerts a considerably positive influence on sustainable development, evidenced by its statistical significance at the 1% level. Improved educational resources are linked with the advancement of innovation and technology, offering the intellectual and skills-based support necessary for sustainable

TABLE 1 Sustainable development evaluation system.

Level 1 indicator	Level 2 indicator	Description
economic sustainability	income status	income of urban residents
	employment conditions	urban registered unemployment rate
	consumption level	ratio of the total retail sales of consumer goods to the year-end population size
	industrial development	tertiary sector's total output value to GDP
	industrial infrastructure	total freight volume
social sustainability	economic environment	proportion of foreign direct investment in GDP
	capital investment levels	ratio of fixed asset investment to GDP
	labor efficiency	ratio of GDP to the year-end total population
	innovation output	number of invention patents per 10,000 individuals
	innovation input	ratio of science and technology expenditure to local government's general budgetary expenditure
ecological sustainability	resource utilization	ratio of annual total electricity consumption to GDP
	urban greening	greening coverage rate of built-up areas
	per capita greening	ratio of garden green space area to the year-end total population
	environmental remediation	ratio of total industrial wastewater discharge to annual water supply
	pollution metrics	ratio of industrial smoke (dust) emissions to GDP

TABLE 2 Descriptive statistical analysis of the used variables.

Variable	Abbr.	Obs.	Mean	Std. Dev	Min.	Max.
Sustainable development level	s	250,8	0.386	0.055	0.245	0.629
Development level of digital economy	eco-dig	250,8	0.107	0.123	0.000162	3.926
Personal digital acceptance	tel	250,8	0.593	0.477	0.00186	5.255
Government intervention	reve	250,8	0.0636	0.0348	0.00487	0.362
R&D support	tech	250,8	0.00334	0.0146	1.63e-05	0.409
Educational level	edu	250,8	0.0137	0.0188	0	0.122
Income gap between urban and rural areas	income	250,8	2.715	0.608	1.110	6.050
Financial support	fina	250,8	2.321	1.790	0.00017	21.63
Development level of digital economy*	eco-dig*	250,8	0.0501	0.0497	8.00e-05	1.138

Note: Eco-dig* represents the level of digital economic development after the transformation of the measurement method. For details, please refer to Section 4.2 Robustness Test.

development over the long term. Additionally, an improved level of education correlates with increased awareness of social responsibility, which is crucial for the widespread adoption and implementation of sustainable development principles. Conversely, a significant negative correlation exists between the urban-rural income gap and sustainable development. A pronounced income disparity often hampers the attainment of sustainability, potentially leading to rural labor migration to urban areas. This affects the effective utilization of rural resources and environmental sustainability adversely. Lastly, financial support also plays a pivotal role in facilitating sustainable development. This is likely because it offers the monetary backing needed for companies to transition to greener operations, influencing corporate behaviors in a way that minimizes environmental pollution and resource wastage.

4.2 Robustness test

4.2.1 Endogenous test

It is indicated by Table 4. To address the issue of endogeneity, we use instrumental variables that meet the dual criteria of orthogonality and correlation. Specifically, we use the first and second lags of the core explanatory variable as instrumental variables. The analysis commences with a Two-Stage Least Squares (2SLS) regression, scrutinizing both model (1) and model (2). Various tests affirm the validity of our approach: the Kleibergen-Paap rk LM test shows no identification problems, the Kleibergen-Paap Wald rk F test surpasses the minimum critical value—indicating that weak instruments are not a concern, and the Hansen J test rules out over-identification issues. Moreover, endogeneity tests indicate that the endogeneity of the core

TABLE 3 Benchmark regression results.

Variable	s				
	(1)	(2)	(3)	(4)	(5)
eco-dig	0.0563*** (5.07)	0.0563*** (5.07)	0.0469*** (4.51)	0.0290*** (3.01)	0.0294*** (3.09)
tech	—	0.1776* (1.94)	0.1660* (1.94)	0.1629** (2.06)	0.1517* (1.94)
edu	—	—	2.1926*** (18.58)	1.8251*** (16.52)	1.7457*** (15.94)
income	—	—	—	−0.0501*** (−20.32)	−0.0456*** (−18.28)
fina	—	—	—	—	0.0073*** (7.97)
c	0.3797*** (248.43)	0.3791*** (243.39)	0.3501*** (163.93)	0.4930*** (67.52)	0.4650*** (57.98)
R^2	0.0106	0.0122	0.1368	0.2640	0.2830
N	2,508	2,508	2,508	2,508	2,508

Note: *, **, *** denote significance levels of 10%, 5%, and 1%, respectively, and the numbers in parentheses below the coefficient estimates are the t-statistics of the coefficient estimates.

explanatory variable is not statistically significant. After controlling for time trends, missing data, and other confounding factors, the coefficients for the core explanatory variable in both models significantly increase without altering the level of significance. This suggests that the driving influence of the digital economy on sustainable development is more robust than initially estimated. For further robustness checks, we use Limited Information Maximum Likelihood Estimation (LIML) for empirical regression, with results shown in models (3) and (4). These findings are consistent with the 2SLS results, confirming that endogeneity does not significantly affect the study's benchmark regression outcomes. Therefore, our benchmark results stand as robust.

4.2.2 Transform and increase variables

To further validate the robustness of our regression results, we employed two different strategies: altering the core explanatory variable and incorporating additional control variable. Initially, we transformed the core explanatory variable to represent the digital economy as a proportion of GDP, rather than focusing solely on the secondary industry. This new variable, denoted as *eco-dig**, allows us to examine the impact of the digital economy on the national economy as a whole. Additionally, we introduced a control variable for the degree of economic servitization (*ser*). Economic servitizationis generally associate with various knowledge-intensive sectors such as culture, entertainment, and services. The achievements in the digital transformation of the third industry, such as digital services and platforms, also confirm the significant role of the service sector in the digital economy. At the same time, Given that a higher degree of servitization could facilitate sustainable consumption and lifestyle patterns, economies with a higher degree of service orientation often prioritize demands related to social equity and welfare, as well as promote environmental and social responsibility, it is an important variable to consider. For this purpose, the ratio of the added value of the tertiary industry to the added value of the secondary industry serves as our measure of economic servitization. The regression results, presented in Table 5, indicate that the core explanatory variable remains significantly positive at the 1% level, even after these adjustments. Although the size of the regression coefficient alters, it does not deviate significantly from our benchmark regression results, further affirming their robustness.

4.2.3 Exclude outliers

Given the specific challenges faced by some certain remote areas in the Yellow River Basin—such as limited resource endowments, less favorable geographic conditions, and lower education levels—the initial progress in digital infrastructure and the awareness of sustainability concepts trailed behind those in other regions. These challenges in conjunction with the influence of macro variables, resulted in significant data volatility during certain considerable data volatility in certain years. To mitigate the impact of outliers on our regression results, we applied a winsorizing and truncating technique to the data, removing the 1% tails on both ends. The processed regression outcomes, displayed in Table 6, affirm that the coefficient of the core explanatory variable remains significantly positive at the 1% level. Interestingly, the absolute value of this coefficient even increased after the bilateral truncation of data. This suggests that our main conclusion, asserting that the digital economy positive influence on sustainable development, holds true even after accounting for outliers. Thus, our benchmark regression results demonstrate strong robustness.

4.3 Heterogeneity test

4.3.1 Regional heterogeneity testing

The Yellow River is characterized by its high sediment concentration and significant water volume, particularly during the flood season. These natural conditions, along with differences in resource endowments, create distinct challenges and opportunities for cities located along the river's course compared to those that are not. To more precisely evaluate the inclusive potential of the digital economy in promoting shared development across diverse conditions, we have classified the 114 cities in the Yellow River Basin into two groups: those directly traversed by the Yellow River flows and those it does not. The regression results for these two subcategories are presented in Table 7.

TABLE 4 Endogenous test results.

Variable	2SLS		LIML	
	(1)	(2)	(3)	(4)
eco-dig	0.2053*** (9.84)	0.1207*** (7.28)	0.2052*** (9.83)	0.1207*** (7.28)
tech	—	0.1013*** (2.70)	—	0.1013*** (2.70)
edu	—	1.2727*** (7.67)	—	1.2727*** (7.67)
income	—	−0.0579*** (−20.56)	—	−0.0579*** (−20.56)
fina	—	0.0080*** (7.37)	—	0.0080*** (7.37)
Kleibergen-Paap rk LM	45.2150 (0.0000)	45.7830 (0.0000)	—	—
Kleibergen-Paap Wald rk F	842.0200 (19.9300)	834.3920 (19.9300)	—	—
Hansen J	2.9060 (0.0882)	1.9440 (0.1633)	—	—
Endogeneity test	7.0650 (0.0079)	1.6770 (0.1967)	—	—
R^2	0.0652	0.3593	0.0652	0.3593
N	2,280	2,280	2,280	2,280

Note: The Kleibergen-Paap rk LM, statistic corresponds to the *p*-value of the non-recognition test in parentheses, the Kleibergen-Paap Wald rk F statistic corresponds to the 10% critical value of the Stock-Yogo weak identification test in parentheses, the *p*-value of the overidentification test in parentheses of the Hansen J statistic, the *p*-value of the endogeneity test in parentheses corresponding to the endogenous test, and the remaining values in parentheses are t-statistics.

TABLE 5 Robustness test results.

Variable	Change the core explanatory variable	Adding control variable	Change the core explanatory variable and adding control variable
	(1)	(2)	(3)
eco-dig*	0.2275*** (6.91)	—	0.2460*** (7.71)
eco-dig	—	0.0400*** (3.68)	—
ser	—	0.0278*** (11.76)	0.0298*** (12.79)
c	0.3744*** (196.61)	0.3568*** (145.46)	0.3471*** (122.96)
R^2	0.0196	0.0647	0.0823
N	2,508	2,508	2,508

Note: *, **, *** denote significance levels of 10%, 5%, and 1%, respectively, and the numbers in parentheses below the coefficient estimates are the t-statistics of the coefficient estimates.

TABLE 6 Robustness test for excluding outliers.

Variable	Bilateral winsorization		Bilateral truncation	
	(1)	(2)	(3)	(4)
eco-dig	0.0533*** (4.87)	0.0267*** (2.86)	0.1835*** (9.22)	0.0994*** (5.66)
tech	—	0.1442* (1.88)	—	0.1312* (1.76)
edu	—	1.7401*** (16.17)	—	1.6843*** (15.80)
income	—	−0.0447*** (−18.22)	—	−0.0412*** (−16.60)
fina	—	0.0071*** (7.86)	—	0.0064*** (7.23)
c	0.3800*** (252.83)	0.4633*** (58.79)	0.3659*** (161.97)	0.4487*** (54.56)
R^2	0.0098	0.2832	0.0350	0.2779
N	2,508	2,508	2,458	2,458

Note: *, **, *** denote significance levels of 10%, 5%, and 1%, respectively, and the numbers in parentheses below the coefficient estimates are the t-statistics of the coefficient estimates.

TABLE 7 Regional heterogeneity test results.

Variable	Directly flow through area		Do not directly flow through area	
	(1)	(2)	(3)	(4)
eco-dig	0.1078*** (4.08)	0.0584** (2.39)	0.0447*** (3.69)	0.0203** (2.09)
tech	—	0.8625 (1.38)	—	0.1330* (1.84)
edu	—	1.3637*** (7.58)	—	1.9343*** (14.21)
income	—	−0.0423*** (−10.04)	—	−0.0461*** (−15.30)
fina	—	0.0017 (1.27)	—	0.0142*** (11.20)
c	0.3798*** (158.78)	0.4710*** (34.69)	0.3791*** (190.59)	0.4490*** (45.80)
R^2	0.0181	0.1979	0.0090	0.3724
N	946	946	1,562	1,562

Note: *, **, *** denote significance levels of 10%, 5%, and 1%, respectively, and the numbers in parentheses below the coefficient estimates are the t-statistics of the coefficient estimates.

From the regression analysis, we observe that the influence of the digital economy on sustainable development is significantly positive at the 1% level, irrespective of whether a city is directly traversed by the Yellow River or not. However, regional conditions do impact the magnitude of this influence. In cities through which the Yellow River directly flows, the promoting effect of the digital economy on sustainable development is even stronger than the benchmark regression suggests. Conversely, the impact is less significant in cities not directly intersected by the river.

For cities directly traversed by the Yellow River, several factors contribute to this heightened influence. Both strategically and culturally, these cities are often receive prioritized attention by government, resulting in heightened focus and investment in both digital infrastructure and sustainable development initiatives. Furthermore, the Yellow River's status as China's "Mother River" and its rich historical and cultural heritage have transformed it into a global tourist attraction. The consequent demand for maintaining an appealing urban image motivates these cities to invest further in sustainable development practices. Additionally, the river's unique topography provides opportunities for the water conservancy industry. As the digital economy increasingly intersects with various sectors, smart grid technologies and energy management systems have enabled more efficient utilization of renewable energy resources like hydropower, aligning with sustainable development objectives.

4.3.2 Policy heterogeneity testing

15 December 2016, marked a significant milestone for China's digital economy and its integration into the national strategic landscape. On this date, China's State Council enacted the "13th Five-Year" National Information Plan, explicitly outlining goals to advance regional digital economy cooperation, construct industrial parks, and establish high-level scientific research bases overseas. The plan also emphasized the importance of fostering international partnerships in the digital economy, information technology, and various other sectors. In light of this pivotal policy shift, this study aims to assess whether the enactment of the "13th Five-Year" National Information Plan has resulted in any noticeable changes in the impact of the digital economy on sustainable development. To perform this empirical analysis, the study period has been bifurcated into two phases: pre-policy enactment (1999–2015) and post-policy enactment (2016–2020). The findings of this analysis are detailed in Table 8.

Our analysis reveals a striking shift in the role of the digital economy in fostering sustainable development over different time periods. From 1999 to 2015, the regression coefficient for the impact of the digital economy on sustainable development was negative and statistically insignificant. However, from 2016 to 2020, following the post-implementation of the "13th Five-Year" National Information Plan, the coefficient became significantly positive at the 1% level. Moreover, the absolute value of this post-2016 coefficient exceeded that of the benchmark regression, highlighting the transformative impact of the plan.

This pivot suggests that 2016 served as a critical juncture. Prior to the rollout of the "13th Five-Year" National Information Plan, China's digital initiatives had not been explicitly emphasized in national policy documents. Efforts towards digital transformation were largely confined to enterprise-level informatization, resulting in disproportionate outcomes given the considerable resource investments. This led to an "information paradox," characterized by challenges such as the scarcity of specialized technical personnel, limitations in high-end, cutting-edge equipment, and a lack of scale effects. Post-2016, the landscape altered dramatically. The State Council's endorsement provided the digital economy with a newfound impetus, pushing it into the national spotlight. Leveraging its unique geographic and industrial advantages, the Yellow River Basin became a model for how the digital economy could seamlessly integrate with traditional industries. This not only elevated the digital economy from its ancillary role but also materialized its latent capability to drive sustainable development.

4.3.3 Heterogeneity test of sustainable development level

To probe the nuanced relationship between digital economy and sustainable development, this study acknowledges the varied levels of sustainability among cities in the Yellow River Basin. Recognizing that this heterogeneity could produce distinct impacts of the digital economy on sustainability, we use a stratified analysis approach. Specifically, we compute the arithmetic mean of sustainable development levels for each city over the study period. Cities with average scores at or above this mean are categorized as

TABLE 8 Policy heterogeneity test results.

Variable	Before 2016		2016 and beyond	
	(1)	(2)	(3)	(4)
eco-dig	−0.0047 (−0.30)	−0.0076 (−0.84)	0.1067*** (5.62)	0.0475** (2.55)
tech	—	0.1011 (1.44)	—	0.0041 (0.04)
edu	—	1.7502*** (16.21)	—	−0.1823 (−0.69)
income	—	−0.0106*** (−3.85)	—	−0.0562*** (−9.58)
fina	—	0.0035*** (3.54)	—	−0.0000 (−0.00)
c	0.3690*** (232.85)	0.3689*** (42.86)	0.4308*** (172.23)	0.5748*** (37.25)
R^2	0.0001	0.1503	0.0648	0.2260
N	1,938	1,938	570	570

Note: *, **, *** denote significance levels of 10%, 5%, and 1%, respectively, and the numbers in parentheses below the coefficient estimates are the t-statistics of the coefficient estimates.

TABLE 9 Heterogeneity test results of sustainable development level.

Variable	Areas with high levels of sustainability		Areas with low levels of sustainability	
	(1)	(2)	(3)	(4)
eco-dig	0.1827*** (6.19)	0.0904*** (3.54)	0.0243** (2.30)	0.0159** (2.00)
tech	—	0.9840* (1.89)	—	0.0960* (1.65)
edu	—	1.5701*** (10.94)	—	1.8895*** (10.45)
income	—	−0.0562*** (−9.69)	—	−0.0250*** (−14.24)
fina	—	0.0132*** (6.47)	—	0.0047*** (7.39)
c	0.3946*** (107.61)	0.4650*** (26.28)	0.3660*** (239.01)	0.4157*** (71.99)
R^2	0.0407	0.3196	0.0035	—
N	946	946	1,562	1,562

Note: *, **, *** denote significance levels of 10%, 5%, and 1%, respectively, and the numbers in parentheses below the coefficient estimates are the t-statistics of the coefficient estimates.

having "high levels of sustainable development," while those below are deemed to have "low levels of sustainable development." Empirical analyses are performed on these two subsets of cities, and the outcomes are documented in Table 9.

Table 9 shows a significant disparity in the effects of the digital economy on sustainable development between regions with high and low levels of sustainable development. In high-level regions, the coefficient for the digital economy's coefficient remains significantly positive at the 1% level, and its absolute value has even increased. Conversely, in low-level regions, both the significance and the absolute value of the coefficient have diminished.

This divergence can be attributed to a range of underlying factors. Low-level regions generally grapple with inadequate capital stock and marginal productivity, restricting the broad application of the digital economy. Their educational and training resources are often insufficient, impeding technological advancement and the growth of high value-added industries. Furthermore, the labor force in these areas is less adaptable to new technologies, increasing the risk of structural unemployment. Information asymmetry tends to be more pronounced, increasing the likelihood of market failure and inefficient resource allocation. Incomplete infrastructure and an underdeveloped institutional environment raise transaction and opportunity costs, further inhibiting the digital economy's contribution to sustainability. Additionally, the absence of effective environmental management not only undermines local ecosystems but also restricts the digital economy's ability to enhance environmental sustainability. Overall, the lack of a long-term sustainable development strategy in these low-level regions, often driven by short-term interests, limits the comprehensive impact of the digital economy on sustainable development.

4.4 Moderating effect test

The study further explores the moderating effects of personal digital acceptance and government intervention on the relationship between the digital economy and sustainable development. By considering both individual and governmental perspectives, we aim to provide a more nuanced understanding of how these variables interact. After centralizing the data, the study

TABLE 10 Mediation test results.

Variable	s			
	(1)	(2)	(3)	(4)
eco-dig	0.0347*** (6.13)	0.0315*** (5.66)	0.0923*** (9.11)	0.0672*** (7.29)
tel	0.0974*** (86.48)	0.0926*** (71.62)	—	—
eco-dig × tel	0.0896*** (12.52)	0.0864*** (12.32)	—	—
reve	—	—	1.1748*** (28.33)	0.8648*** (20.83)
eco-dig × reve	—	—	4.2482*** (14.62)	3.5234*** (13.30)
tech	—	−0.0542 (−1.24)	—	0.1761** (2.48)
edu	—	0.0394 (0.60)	—	1.4777*** (14.73)
income	—	−0.0091*** (−6.18)	—	−0.0347*** (−14.91)
fina	—	0.0038*** (7.29)	—	0.0026*** (2.94)
c	0.3242*** (331.23)	0.3431*** (71.75)	0.3032*** (102.76)	0.3925*** (48.95)
R^2	0.7660	0.7767	0.2741	0.4093
N	2,508	2,508	2,508	2,508

Note: *, **, *** denote significance levels of 10%, 5%, and 1%, respectively, and the numbers in parentheses below the coefficient estimates are the t-statistics of the coefficient estimates.

incorporates these moderating variables, along with the interaction terms between them and the core explanatory variable, into the benchmark regression model. The updated regression findings are presented in Table 10.

From the regression results presented in columns (1) and (2) of Table 10, it is evident that both the coefficients corresponding to the digital economy and its interaction terms pass the significant test at the 1% level. This suggests that personal digital acceptance serves as a moderating variable in the baseline regression, positively influencing sustainable development by enhancing the contributory role of the digital economy. Firstly, in social milieus characterized by high levels of digital acceptance, there are noticeable improvements in the velocity, accuracy, and overall information flow. This diminishes information asymmetry, facilitating more effective market supply-demand matching. Consequently, market efficiency is enhanced, and transaction costs are reduced, laying a critical foundation for advancement of sustainable economy. Secondly, elevated levels of personal digital acceptance can amplify network effects and positive externalities. Consumers are thus exposed to a broader range of goods and services, leading to increased consumer surplus and enhanced quality of life. Additionally, the proliferation of digital tools and online education platforms offers individuals in remote or poor areas access to better educational opportunities. This, in turn, fosters human capital development and narrows regional income disparities, thereby promoting long-term sustainability.

Further analysis of columns (3) and (4) in Table 10 reveals that the interaction coefficient between the digital economy and government intervention is statistically significant at the 1% level. This implies that government intervention also acts as a moderating variable in the baseline regression, positively influencing the digital economy's impact on sustainable development. Governmental actions can address market failures and externalities through the establishment of norms and standards, thereby reducing information asymmetry and enhancing market efficiency. The successive implementation of environmental standards and carbon trading mechanisms encourages enterprises to adopt eco-friendly practices, steering the digital economy toward a socially optimal outcome and furthering sustainable development objectives. Moreover, governmental intervention can alleviate digital divides through income redistribution and social welfare schemes. This helps alleviate income inequality exacerbated by the digital economy, thereby improving both the efficiency and inclusivity of the digital economy's role in fostering sustainable development. Finally, the continuity of long-term governmental planning and policy formulation provides a robust framework for the sustainable development agenda.

5 Conclusion and recommendations

5.1 Research conclusion

This study utilizes panel data from 114 prefecture-level cities in the Yellow River Basin spanning the years 1999–2020. A comprehensive evaluation framework for sustainable development is established, encompassing economic, social, and ecological dimensions. The study employs a fixed-effects model to empirically examine the impact of the digital economy on sustainable development. Subsequently, endogeneity and robustness tests are conducted on the regression results. Furthermore, the sample is categorized based on whether the Yellow River directly traverses the region, the period before and after the release of the "13th Five-Year Plan for National Information," and the levels of sustainability. Heterogeneity tests are performed to explore variations among different categories. Finally, at the individual and governmental levels, variables are selected as moderating factors to investigate the adjustment

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mechanisms in the baseline regression. This multi-faceted approach aims to provide a thorough analysis of the relationship between the digital economy and sustainable development in the Yellow River Basin.

The primary findings of this study are as follows: 1) Significant Impact of the Digital Economy on Sustainable Development: The digital economy significantly propels sustainable development. For every 1-unit increase in the digital economy, the sustainable development index rises by 0.0563 units. This conclusion remains robust after endogeneity and multiple robustness tests. 2) Regional Heterogeneity in the Impact of the Digital Economy: There exists regional heterogeneity in the influence of the digital economy on sustainable development. The impact is more pronounced in areas directly traversed by the Yellow River compared to those not directly traversed. The reasons for this difference may be related to regional policies and resource endowments. 3) Observation of Temporal Heterogeneity: Temporal heterogeneity is observed in the baseline regression. After the strategic policy "13th Five-Year Plan for National Information" related to the digital economy is implemented, a significant positive impact on sustainable development becomes evident. This indirectly validates the rationality of the baseline regression results. 4) Matthew Effect in the Impact of the Digital Economy on Sustainable Development: The impact of the digital economy on sustainable development exhibits a "Matthew effect." Constrained by factors like infrastructure, education levels, and information asymmetry, the promotional effect in areas with low sustainability is significantly weaker than in areas with high sustainability. 5) Role of Individual Digital Acceptance and Government Intervention as Moderating Variables: The degree of individual digital acceptance and government intervention serves as moderating variables in the baseline regression. Both moderating variables positively influence the impact of the digital economy on sustainable development.

This article addresses the deficiencies in the research of the relationship between the digital economy at the prefecture level in the Yellow River Basin and sustainability. This study holds relevance for sustainable development in other regions globally facing similar conditions. It offers valuable guidance on how regions can effectively develop and leverage the digital economy for sustainable development.

5.2 Policy recommendations

Based on the research conclusions of this study and drawing lessons from the experiences of developed regions in the integration of the digital economy and sustainable development, while considering the specific conditions of the Yellow River Basin and relevant policies, the following policy recommendations are proposed:

Firstly, enhancing the construction of digital infrastructure is essential. Different regions in the Yellow River Basin should leverage regional development policies and other preferential measures to strengthen the construction of communication infrastructure. This will ensure the integration and advancement of digital industrialization and industrial digitization. Encouraging traditional enterprises to actively undergo digital reforms is crucial, facilitating the transformation towards high-end manufacturing and service-oriented approaches. This transformation aims to minimize resource waste and consumption in the production process, promoting sustainable development. Strengthening collaboration between various levels of government, universities, and research institutions is also necessary. This collaboration effort should encourage the deep integration of industry, academia, and research, ensuring a continuous supply of talent and knowledge updates throughout the digitalization process. Simultaneously, it is imperative to disseminate and innovate existing digital production technologies, thereby enhancing digital production efficiency. Moreover, government departments should use means such as tax incentives and research and development subsidies to attract top digital talents and businesses, creating a regional "knowledge spillover effect" that establishes a solid foundation for the research, development, and application of digital economy. Establishing a sound market access mechanism is crucial to ensure the fairness and sustainability of industry development. This involves promoting the improvement of legal frameworks related to data ownership, data security, and intellectual property rights. By regulating market behaviour and protecting innovation, the legal framework contributes to the steady development of the digital economy at the superstructure level, consolidating the digital impetus for sustainable development.

Secondly, it is crucial to pay attention to regional disparities and tailor development strategies accordingly. In comparison to areas directly traversed by the Yellow River, regions without direct river flow generally face challenges such as insufficient strategic planning, weak awareness of sustainable development among the population, and inadequate driving force for urban sustainable development. In response, the government should formulate sustainable development policies for each city in the Yellow River Basin based on local conditions and timely considerations. Continuously infusing sustainable development concepts into basic education, the establishment of relevant reward and penalty mechanisms, and the rapid dissemination of advanced sustainable development ideas and technologies among regions should be prioritized. This process aims to optimize the sustainable development environment in areas without direct river flow. Furthermore, regions with higher levels of sustainability should play a leading and exemplary role, acting as catalysts for surrounding cities. Underdeveloped areas can learn from advanced experiences through forms such as learning exchanges, organized training, and cross-regional research. They can then optimize and improve based on their own development characteristics, raising their sustainable development standards and preventing the occurrence of a "siphon effect." Rational allocation of resources such as education and healthcare based on population distribution and needs is essential to narrow regional disparities. Simultaneously, the improvement of the social security system should be prioritized, ensuring that residents in all regions can enjoy basic social security services. Strengthening poverty alleviation efforts is crucial to safeguard the basic living standards of impoverished populations. Through the formulation and implementation of differentiated policies, a collaborative atmosphere involving the government, businesses, and various sectors of society can be established, narrowing the gap in sustainable development among different regions in the Yellow River Basin.

Thirdly, municipal government departments in each city of the Yellow River Basin should proactively advocate for environmental taxes and emissions trading mechanisms. Imposing taxes on pollution emissions and the use of non-renewable resources internalizes external costs through the "polluter pays" principle, effectively restraining the occurrence of the "tragedy of the commons" using market mechanisms. Simultaneously, it is imperative to gradually establish environmental and data regulations. This involves setting and enforcing clear environmental standards and conducting compliance audits to regulate the environmental performance of businesses. Economic fines or other penalties should be imposed on non-compliant enterprises to strengthen the credibility of standards. Mandating or encouraging companies to disclose information related to environmental and data governance helps reduce information asymmetry, promoting the effective operation of market mechanisms. Promoting the integration of Environmental, Social, and Governance (ESG) standards into investment decisions is essential. This elevates corporate attention to environmental responsibility and incentivizes companies to improve their environmental performance.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: http://www.stats.gov.cn/sj/http://www.tjcn.org/ https://www.epsnet.com.cn/index.html.

Author contributions

GW: Conceptualization, Data curation, Investigation, Resources, Software, Validation, Visualization, Writing–original draft. QY: Conceptualization, Funding acquisition, Methodology, Writing–review and editing. YJ: Conceptualization, Formal Analysis, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, 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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