ISSN: 2029-4913 / eISSN: 2029-4921

VILNIUS TECH
Vilnius Gediminas Technical University

TECHNOLOGICAL and ECONOMIC DEVELOPMENT of ECONOMY

2026
Volume 32
Issue 3
Pages 840–863
https://doi.org/10.3846/tede.2026.25168

DIVIDEND DIFFERENTIATION, LATECOMER ADVANTAGE AND DIMINISHING RETURNS: THE HETEROGENOUS IMPACT OF DIGITAL TECHNOLOGY PROGRESS ON CHINA'S ECONOMIC MODERNIZATION

Xiaoyin HE[1], Hanchi CHEN[1✉], Han WANG[2]

[1] *School of Business, Zhengzhou University, Zhengzhou, China*
[2] *School of International Business and Economics, Henan University of Economics and Law, Zhengzhou, China*

Article History:
- received 26 December 2024
- accepted 25 September 2025
- first published online 4 March 2026

Abstract. Advances in digital technology are driving a new modernization of economic systems, but the impact is clearly heterogeneous. This study pioneers an economic modernization index evaluation system from the four dimensions of economic innovation, economic greening, economic openness and industrial modernization, and quantitatively analyzes heterogeneous impacts of digital technology progress on economic modernization by panel fixed effect model and threshold regression model, utilizing 11-year provincial panel data (2013–2023) across 30 China's provinces. The general findings discover that the progress of digital technology has significantly propelled the construction of China's economic modernization in general. However, in the sub-dimensions of economic modernization, the promoting effect of digital technology progress on economic innovation is stronger than its impact on economic modernization and greening, while the impact on economic openness is not significant and there is an obvious differentiation phenomenon. At the regional level, the promoting effect of digital technology progress on economic modernization is larger in China's western region relative to eastern China, and stronger in regions with lower level of economic modernization in comparison to regions with higher level, showing a latecomer advantage. Moreover, the enhancing effect of digital technology progress on economic modernization also has the nonlinear feature of "diminishing marginal effect". Such findings can offer government policy-designer insights in coordinating the use of digital technology dividend, narrowing the regional development gap, identifying the weak points of digital technology dividend, and accelerating the national economic modernization.

Keywords: digital technology, economic modernization, heterogeneity.

JEL Classification: O11, O33.

✉Corresponding author. E-mail: ***chc_1210@163.com***

1. Introduction

Modernization is a general process of human social progress, a worldwide objective phenomenon reflecting a shift in the stage of national development (Amin et al., 2022). Economic modernization is the material foundation for the modernization of the State and an important component of it (Belykh & Mau, 2020; Jafarli, 2023). The construction of economic modernization can stimulate the country's economic dynamics (Navickienė et al., 2023a) and fulfills key roles in maintaining economic stability and advancing sustainable economic development.

However, the modernization of socio-economic system is not an economic transformation that solidifies a single goal (Navickienė et al., 2023b; Skripnuk, 2020), but a dynamically deepening process in response to the evolution of the global technological revolution, with the changing economic needs. Digital technology has been recognized by academics as a fundamental driver of the next generation of industrial technology revolution (Fan et al., 2025; Growiec, 2023; Wang et al., 2020). Compared to traditional industrial technologies such as steam, electricity, etc., digital technologies possess greater transformative power (Growiec, 2023; Ross & Maynard, 2021), giving rise to entirely new techno-economic paradigms (Klingenberg et al., 2022; Ramirez, 2021).

More prominently, the current world economy is in a new time, and the role of innovative technology, green and low-carbon is becoming more fundamental to the sustainable development of the economic system (Chen et al., 2023b; Degirmenci et al., 2024; H. Lu et al., 2025; Thakur & Wilson, 2024; Zhang, 2021). The synergistic interplay between endogenous technological drivers and evolving exogenous economic imperatives is propelling the modernization trajectory of economic systems toward unprecedented manifestations. However, existing research in contemporary academia has not covered the key features of economic modernization in digital age, and in particular lacks a systematic quantitative metrics framework. This lack of research has left developing countries without a scientific basis in formulating policies for economic transformation, which can easily lead to a serious disconnect between their policymaking tendencies and the direction of economic modernization. Our study will help to address this issue.

Completely new technological developments can contribute to the modernization and transformation of national systems (Skripnuk, 2020). However, under the influence of factors, such as differences in technological adaptation, obvious heterogeneity may be observed in the facilitating effect of digital technology progress on the modernization of various dimensions of the economic system (Zhou et al., 2023). The long-term unbalanced release of digital technology dividend will not benefit the overall coordinated promotion of economic modernization but exacerbate the risk of internal structural imbalance. Therefore, this study will reveal the divergence phenomenon of digital technology dividend and provide enlightenment on how to guide the balanced release of digital dividend in modern economies.

In addition, differences in technology diffusion have important influences on development differences between regions (Pan & Yuan, 2024; Perilla Jiménez, 2024). So, in the process of modernizing a brand-new economy, will the dividend of digital technological progress lead to “the strongest being stronger” or “lagging behind to catch up”? This question is of great value to whether economies can take full use of digital technology progress dividend to level off the economic modernization gap. Finally, is there non-linearity on how digital technology progress affect economic modernization? If so, is it increasing or decreasing at the margin? The analysis of this question will help developing economies identify the tipping point of decline or jump of digital technology dividend, and provide a key basis for them to formulate response strategies. However, due to the lack of clarity in the system of economic modernization indicators, these questions have not been fully explored, and we will analyze them in turn to deepen the research and make more outstanding research contributions. Given China being a developing country with a huge economy, digital technology is widely penetrating into production, circulation, distribution and consumption economic activities (Y. Chen et al., 2023; H. Yu et al., 2024; Y. Yu et al., 2024), and is at a critical stage of the modernization of the economic system. Therefore, this study will focus on China, a typical modernization transition body, to explore heterogeneous impact of digital technology progress on economic modernization. Different to the existing literature, this study offers brand-new contributions in the following:

First, this study explains the definition and characteristics of economic modernization in the context of a new era from the four dimensions of "economic innovation, economic greening, economic openness and industrial modernization", and builds a mathematical and theoretical framework for measuring economic modernization, which improves the theory of economic modernization and serves as a reference for subsequent studies.

Secondly, this study decomposes economic modernization into dimensions, reveals the differentiation phenomenon about how digital technological progress affects economic innovativeness, greening and other dimensions, and carries out a cross-sectional comparative analysis of the impact effect, so as to provide a new revelation for avoiding falling into the trap of structural imbalance in the process of economic modernization.

Thirdly, grounded in the division of regions, regional heterogeneity phenomenon in promotion effect of digital technology progress on economic modernization is analyzed, providing brand-new empirical evidence as to whether lagging regions can take advantage of the dividends of digital technology progress to realize catching up in economic modernization.

Fourthly, panel threshold model is applied to uncover the nonlinear characteristics of how digital technological progress affects economic modernization, thereby providing empirical support for identifying the turning point of digital technology dividend. The research findings can test whether digital technology follows Metcalfe's law of increasing marginal or principle of diminishing marginal returns in the development process.

Finally, after explaining the heterogeneous impact of digital technology progress on economic modernization, this study provides several important implications.

The subsequent study is structured: Section 2 is about literature review, shortly describing the existing studies on economic modernization and digital technology; Section 3 provides the theoretical exposition and propositions of this paper; Section 4 focuses on introduction of empirical methods and data interpretation; Section 5 includes the regression analysis and other empirical research findings; Section 6 gives conclusions and advances relevant policy implications.

2. Literature review

The existing research on measurement of economic modernization predominantly revolves around the analysis of the technological revolution of traditional industries such as steam and electricity. At that time, the degree of industrialization and electrification of the economic system was the main indicator of economic modernization. As for the measurement of industrialization of economic system, most studies measure the value of industrial production output to GDP or the proportion of industrial employed population (Andal, 2022; Mignamissi & Nguekeng, 2022). Hong and Ngok (2022) paid more attention to the objective needs of economic development, integrating economic affluence and urbanization into the measurement for comprehensive quantification. Regarding the electrification of the economic system, Guo et al. (2022) incorporated the dimensions of social and environmental systems into the comprehensive quantification of national re-electrification.

Scholars have taken a preliminary look into the influencing factors of economic modernization. By extending Lewis's model, Sadik-Zada (2021) found that the capital intensity level in manufacturing sector was an important factor affecting economic modernization. Kovács and Bartók (2024), based on the perspective of financial banks, proposed that the deepening of the financial intermediary system plays an important role in promoting economic modernization. Jafarli (2023), taking Azerbaijan as the research object, believes that the choice of national economic system and development model is an important factor of economic modernization. However, there is no research on the influencing factors of economic modernization from the deep technical level. This study will also make up for this deficiency.

As the world enters the digital age, scholars have begun to explore the impact of digital technology on the modernization of different fields in a country. One group of scholars believes that there is an important relationship between digital technology and agricultural modernization. Their research shows that economic activities based on digital technology can improve the green development and sustainability of agriculture (Jiang et al., 2022; Liu & Li, 2025) and advance the modernization in both agriculture and rural areas (Ye, 2025). The other kind of scholars focus on how important digital technology affects enterprise development. This covers information systems such as accounting of enterprises (Chotia et al., 2025; Vărzaru, 2022), organizational structure (Michelotto & Joia, 2024; Philippart, 2022), and business process management (Cheng et al., 2025). In addition, impacts of digital technology on higher education and vocational education (Kamoyo et al., 2025; Oyetade et al., 2025) and other fields, have also been studied accordingly. However, in the existing research, no studies have focused on what effects and how digital technology progress brings through the lens of economic system modernization.

3. Theoretical background and hypotheses

3.1. Heterogeneous impacts under the sub-dimensions of economic modernization

Digital technological advances can have a dividend effect on the modernization of economic systems. However, this driving effect may be moderated by the degree of technological fitness. The innovation and transformation of the economic system relies on the promotion of new technologies. The progress of digital technology, characterized by technological innovations and breakthroughs, constitutes a pivotal impetus for innovation and transformation, sharing a strong compatibility with these processes (D. Lu et al., 2024). On industrial transformation, digital technology progress can give rise to new technology industries (Y. Wang et al., 2025), as well as upgrade and restructure traditional industries through technology spillover (Miao, 2022; Narula et al., 2024). In terms of green transformation, although digital technology can perform an important role in promoting industrial green transformation by improving energy efficiency (Chen et al., 2024). However, various economic activities derived from digital technological progress will increase carbon emissions (Y. Li et al., 2023; Zhang et al., 2022), so the effect of green transformation is relatively limited. In terms of trade openness, digital technology can reduce trade costs (Bellucci et al., 2025) and promote the realization of trade facilitation (Ismail, 2021). But at the same time, the instability of the international trade system environment (Jones, 2023), especially the existence of digital trade barriers (Y. Liu et al., 2024; X. Wang et al., 2025), will impede the open transformation effect of digital technology progress. Hypothesis 1 hence is given:

H1: *The promotion effect in digital technology progress on each sub-dimension of economic modernization is obviously differentiated, and the promotion effect on economic innovation and industrial modernization is stronger.*

3.2. Heterogeneous impact at the regional level

The progress of digital technology makes it possible for backward regions to catch up in the process of economic modernization. First, backward regions can benefit from digital technology and knowledge spillovers from developed regions (dos Santos & Mendes, 2023; Liu et al., 2022), through technology imitation, imitative innovation and other means, to realize the localization of digital technology production activities with lower cost input (Duan & Sun, 2024; Yang, 2023). Secondly, the late-developing regions can also learn some successful experiences from developed regions in technology application, and improve management skills and technological innovation level more quickly through technical knowledge learning (Galindo-Martín et al., 2019). Third, compared with traditional technologies, digital technologies have universal application scenarios, lower communication costs (Liu & Liu, 2023), and can better overcome geographical barriers (Zhang & Zhang, 2024) to help backward regions realize economic modernization. Finally, compared with developed regions, backward regions have worse digital transformation but greater space for digital technology diffusion, which also makes the marginal benefit of digital technology progress to backward regions stronger. Hypothesis 2 hence is given:

H2: *The influence of digital technology progress on economic modernization has regional heterogeneity, and the promotion effect on backward regions is stronger than that on developed regions.*

3.3. Heterogeneous impact under different levels of digital technology progress

The principle of diminishing marginal returns points out when other factors of production remain unchanged, the marginal returns brought by continuously increasing the input of a factor of production will gradually decrease (Zhu et al., 2022). Being a new type of productive factor, digital technology improves innovation performance through the release of positive external effects at the initial stage (Li et al., 2024), optimizing energy consumption along industrial chain (Wang et al., 2022a) and other aspects have significantly promoted the modernization of the economic system. Yet with the progress of digital technology, degree of digital transformation in various economic sectors is continuously improving (Su & Wang, 2025; X. Zhang et al., 2023), its incremental benefits to economic modernization will gradually decrease, and the phenomenon of diminishing marginal returns will appear. The diffusion depth and breadth of digital technology have typical S-shaped curve characteristics (Z.-Z. Wang et al., 2025). When digital technology enters the maturity stage, the technology penetration rate to the economic system is close to saturation, the space for further expansion and application is limited, and the diffusion speed slows down, presenting a relatively saturated condition of technology diffusion. In such case, the economic benefits of digital technology progress to economic modernization will gradually narrow. Based on this analysis, Hypothesis 3 hence is given:

H3: *The impact of digital technology progress on economic modernization has a nonlinear feature of diminishing marginal benefits.*

4. Methods and data

4.1. Data source

To ensure that the sample data chosen are as authoritative and complete as possible, we selected the provincial panel data, ranging from 2013 to 2023 and encompassing 30 China's provinces (excluding Tibet, Hong Kong, Macao and Taiwan), as the sample for research. Among them, the optimization and rationalization of industrial structure follow practices of Li et al. (2019) and Gan et al. (2011). The installed density of robots refers to practice of Lu and Zhu (2021), and the interaction term is constructed between the installed quantity of robots in various industries published by IFR in China and the percentage of employees in each industry across provinces to total national employment in China. We additionally utilize interpolation methods to impute missing values. Our data derive from China's Provincial Statistical Yearbooks, China National Statistical Yearbook, CSMAR, CNRDS and EPS global data statistics platform, etc.

4.2. Defining and selecting key variables

4.2.1. Dependent variable

The dependent variable of the study is economic modernization. As far as we know, there is no scholar in the existing research who has clearly constructed the indicator system of current economic modernization. By reviewing the measurement studies related to economic modernization, we found the following two obvious problems in the field. First, the existing measurement research still stops at the measurement of industrialization and electrification levels in the period of historical industrial revolution, and there is no systematic research such as quantitative measurement of the new modernization of the economic system based on the background of new era and the objective reality of digital technology change. Second, the existing studies greatly explore the transformation performance of the economic system, from the characteristics of green, low-carbon (Gao & Lu, 2025; S. Wang et al., 2024) and innovation-driven dimensions (Cheng et al., 2023), but have not yet formed a systematic integration framework from the perspective of economic modernization. There is a research gap on insufficient description of the path of economic modernization. Therefore, in order to solve the existing research deficiencies, we will analyze the typical characteristics of the new modernization of the economic system caused by digital technology, and construct the corresponding index system.

First, digital technology changes the existing innovation system. Digital technology breaks many limitations of traditional innovation mode in time and space (Lyu et al., 2023), enabling the emergence of open innovation (Eslami et al., 2023), distributed innovation, and entirely new innovation elements (H. Tang et al., 2023; Z. Zhang et al., 2023), which drive a comprehensive modernization of the innovation ecosystem (Tsou & Chen, 2023; Zhang, 2023). The innovation economy mainly promotes the innovation-driven growth of the economic system through the R&D investment and output trading of innovative technologies. Accordingly, we will measure the level of economic innovation in aspects of both innovation input and innovation output. In terms of input types, innovation input covers human and material input forms. On the one hand, innovation output covers the quantity of technology patent output, and on the other hand, it also includes technology market transactions, reflecting the degree of market recognition of innovation output technology.

Second, digital technology promotes low-carbon and green transformation. The application of digital technology in production chain can play a role in reorganizing the combination of factors and enhancing energy efficiency (Tan et al., 2024), thereby propelling industry transformation and upgrading (Chang et al., 2023; Dong et al., 2022; Wang et al., 2022b), enhancing carbon emission efficiency (Xia et al., 2025), and mitigating carbon emissions (Pu et al., 2025). These effects will contribute to the green modernization of the regional economic system. At the same time, green economy is mainly manifested in the realization of economic growth, while paying attention to production energy consumption, pollution emission and ecological treatment, taking into account economic development and environmental protection. Accordingly, we will measure it from three dimensions: production energy consumption, pollution emission and ecological governance. Energy production is defined as total energy consumed per unit of GDP; Pollution emission is assessed from three dimensions: waste gas, waste water and solid waste. Ecological governance is measured from two dimensions: ecological restoration and industrial governance.

Thirdly, digital technology transforms the whole process of international trade. Digital technologies provide digital solutions for the facilitation of international trade and improve the efficiency of cross-border and domestic trade flows (Liang & Tan, 2024; Takpara et al., 2024), expanding the scale of trade (Di et al., 2025). The open flow of capital and the prosperity of trade cooperation are the general manifestation of economic openness, and also the important support of modern economy. According to this, economic openness can be formally divided into trade openness and capital openness. Among them, trade openness is characterized by prosperity of import and export trade; Capital openness is subdivided into outbound investment and accepted foreign investment in terms of flow direction.

Finally, digital technology causes industrial system transformation. Driven by digital technology, high-tech industry, intelligent industry (Li & Zhou, 2024; Zhang et al., 2024) and other modern industrial economies have developed rapidly. In addition, digital technology will also transform the existing industrial system (Liu et al., 2024b; Wang & Li, 2024) and accelerate the modernization in industrial structure (Miao, 2022). The scale-increasing in modern industry and structure-optimizing in traditional industry constitute the modern industrial system. Accordingly, we measure the level of industrial modernization from the two dimensions of the scale and structure of modern industries. Among them, the scale of modern industry is represented by high-tech industry and intelligent industry from the level of technology content and industry type. The modernization of industry structure includes the coordination degree of industry structure and the advanced level of transformation.

Building on the above analysis of the modernization characteristics of the economic system caused by digital technology and the selection basis of relevant first-level and second-level indicators, we further select 17 closely related third-level indicators as measurement indicators and use the entropy method to measure them, so as to obtain the Economic Modernization Index (*ECM*). Table 1 shows the comprehensive index evaluation system of economic modernization constructed in this study.

Table 1. System for evaluating economic modernization indicators

Primary index	Secondary index	Three-level index	Variable selection	attributes
Economic innovation	Innovation economic input	Innovative material input	R&D expenditure by DLEs (Designated Large-scale Enterprises)	+
		Innovative human input	Full-time equivalent of R&D personnel in DLEs	+
	Innovative economic output	Technology patent output	Number of patent authorizations	+
		Technology Market Trading	Technology market turnover/GDP	+
Economic greening	Green economy energy consumption	Energy consumption per unit of GDP	Total energy consumption/GDP	-
	Green economy waste and pollution	Exhaust emissions per unit of GDP	Sulfur dioxide (SO_2) emissions/ GDP	-
		Wastewater discharge per unit GDP	Chemical aerobic (COD) emissions/GDP	-
		Solid waste generated per unit of GDP	General industrial solid waste production/GDP	-
	Ecological governance	Industrial Governance	Investment completed in industrial pollution control/ industrial added value	+
		Ecological restoration	Forest coverage rate	+
Economic openness	Openness of capital	Degree of foreign investment	Total foreign investment/GDP	+
		Degree of outward investment	Outward non-financial direct investment/GDP	+
	Openness to trade	Degree of import and export	Total import and export volume/ GDP	+
Industrial modern-ization	Expansion of scale	High technology industry	Main business income of high-tech industry	+
		Intelligent industry	Robot mounting density	+
	Optimization of structure	Rationalization of the industrial structure	The inverse of the Theil index	+
		High level of industrial structure	Output value of tertiary industry/ output value of secondary industry	+

4.2.2. Independent variables

The output of brand-new technology is the core embodiment of technological progress. In existing studies, the volume of patents of corresponding types is also mostly selected to quantify the progress of green technology and financial technology (Chen et al., 2021; Song et al., 2022; Wang & Sun, 2025; Zheng et al., 2023). Therefore, we use the number of authorized digital technology patents as level of digital technology progress (*DTA*). The specific data processing steps are as follows: First of all, according to China's Statistical Classification of DE&CIs (Digital Economy and Its Core Industries), the national economic industries are divided into three categories: large, medium and small, determining the specific scope of DE&CIs. The second step is to refer to the International Patent Classification Table (IPC) to determine the corresponding international patent classification number of each industry. Finally, we retrieve and summarize the digital technology-related patent applications in 30 China's provinces from 2013 to 2023 in the national Intellectual Property Patent database according to the classification number.

4.2.3. Control variables

For enhancing accuracy of regression analysis with digital technology progress as independent variable and controlling the possible other factors affecting economic modernization, this paper takes after the practice of Meng and Wu (2024), T. Tang et al. (2024) and Ma et al. (2023), and takes the following regional characteristic variables as control variables. (1) Fiscal Expenditure (*FIS*), denoted through ratio of regional fiscal spending to GDP; (2) Transportation Infrastructure (*TIN*), expressed as the logarithm of highway mileage; (3) Urbanization Level (*URB*), quantified by the ratio of a region's urban population to its general population; (4) Economic Scale (*ECD*), expressed by the logarithm of regional GDP; (5) Human capital level (*HUC*), indicated by the proportion of higher education population in a region; (6) Industrial scale (*IND*), expressed by the logarithm of industrial added value; (7) Fiscal sufficiency (*FSD*), quantified by percentage of a region's general budget revenue to budget expenditure; (8) Freight scale (*TIF*), expressed by the logarithm of the total regional freight volume; (9) Fixed assets investment (*FAI*), expressed by the ratio of fixed-asset investment to regional GDP.

4.3. Model construction

In view of the questions (H1 and H2) raised in this study, the heterogeneous impact of digital technology progress on economic modernization will be examined by the following econometric model:

$$ECM_{i,t} = a_0 + a_1 DTA_{i,t} + a_n X_{i,t} + \mu_i + \delta_t + \varepsilon_{i,t}. \tag{1}$$

In Eq. (1), $ECM_{i,t}$ represents the economic modernization level of the province i in the period t; $DTA_{i,t}$ represents the digital technology development level of the province i in the period t; $X_{i,t}$ represents a set of key control variables; μ_i represents the unobservable individual fixed effect of province i; δ_t is time fixed effect; $\varepsilon_{i,t}$ denote the random disturbance term. We first obtain the regression results of multiple groups by replacing the explained variable and setting conditional regression. On the base of the estimated signs and sizes of coefficients of the core explanatory variables in each group, a horizontal comparative analysis is conducted. At same time, we will also use the heterogeneity test between groups to verify the significance of the difference between the relevant regression results.

The threshold regression model provides a better methodological framework for checking the nonlinear interdependence between independent variables and dependent variables, and can identify the changes in the influence of independent variables on dependent variables among different thresholds (Lei et al., 2024). Therefore, to test whether there are significant differences in the impact of digital technology on economic modernization in different stages of progress (H3), we set the panel threshold model:

$$ECM_{i,t} = \varphi_0 + \varphi_1 DTA_{i,t} \times I(DTA_{i,t} \leq \theta) + \varphi_2 DTA_{i,t} \times I(DTA_{i,t} > \theta) + \varphi_c X_{i,t} + \mu_i + \delta_t + \varepsilon_{i,t}. \quad (2)$$

In Eq. (2), $DTA_{i,t}$ represents the threshold variable; θ represents the threshold value; I (·) is the exponential function, which takes the value 1 as the bracket condition is met, and 0 otherwise. Eq. (2) is only a single-threshold model that can be developed into the multi-threshold model through the specific testing of variables and the analysis of demands. According to whether the threshold variable DTA surpass the threshold, the samples are divided into two groups (regions) (Liao & Li, 2024).

5. Empirical outcomes analysis

5.1. Benchmark regression analysis

The outcomes of the benchmark regression of digital technological progress on economic modernization are listed in Table 2. Column (1) is the regression of the fixed effect of provinces and years without control variables, indicating that digital technology progress can promote economic modernization. In columns (2) to (4), in order to prevent regression errors caused by missing important variables, key control variables including FIS, ECD and HUC are gradually added. The results illustrate that the estimated coefficient of digital technology progress index is always significantly positive, further confirming digital technology progress has a positive function in promoting economic modernization. In existing studies, the influence of digital technology have been explored in many fields, such as agriculture and rural areas (Gong et al., 2024; Zhao et al., 2024) and educational training (Kayanja et al., 2025). However, no study has directly correlated digital technology progress with economic modernization, resulting in obvious omissions. Our findings make up for this deficiency. At the same time, the research findings also provide new empirical evidence for discussing the influencing factors of economic modernization from technical level.

5.2. robustness test and analysis

5.2.1. Replacing core explanatory variables

To ensure the robustness of the research outcomes, the number of digital technology patent applications is picked as a proxy for the digital technology progress index (*S.DTA*) for robustness test. The data in Column (1) show that digital technology progress still has a notably promotional effect on economic modernization, which aligns with the research conclusions above.

Table 2. Benchmark regression outcomes

Variables	(1)	(2)	(3)	(4)
	ECM	ECM	ECM	ECM
DTA	0.1509*** (0.0214)	0.1496*** (0.0156)	0.1407*** (0.0140)	0.1377*** (0.0144)
FIS		0.2295*** (0.0815)	0.1667 (0.1062)	0.1746 (0.1194)
TIN		0.0898 (0.0754)	0.0654 (0.0655)	0.0542 (0.0627)
URB		–0.2258 (0.2064)	–0.3021 (0.2321)	–0.2679 (0.2129)
ECD			0.1413** (0.0534)	0.1309* (0.0671)
HUC			–0.1376 (0.0895)	–0.1328 (0.0890)
IND			–0.0744*** (0.0257)	–0.0703** (0.0275)
FSD				–0.0147 (0.0507)
TIF				–0.0150 (0.0119)
FAI				0.0041 (0.0139)
Constant	0.0725*** (0.0028)	–0.9043 (0.7836)	–1.2635 (0.8898)	–0.9128 (0.9507)
Province_FE	Yes	Yes	Yes	Yes
Year_FE	Yes	Yes	Yes	Yes
R^2	0.6825	0.7195	0.7522	0.7538

Note: "*," "**," and "***" respectively denote significance at the 10%, 5%, and 1% levels. The standard errors appear in parentheses, and the same applies below.

5.2.2. Windup treatment

Considering that the sample may have extreme values, which may have an impact on the regression analysis, this paper winnowed the relevant indicators of the benchmark regression of the impact of digital technology progress on economic modernization by 5% and then regression again. The results in Column 2 interpret that the estimated coefficient of digital technology is still significantly positive after wind-down, the same as the benchmark regression outcomes.

5.2.3. Elimination of special samples

In the sample, megacities like Peking, Tianjin, Shanghai and Chongqing show marked differences from other provinces and cities in terms of policy support and political and economic positioning at the national level, so they are not comparable with other provinces to some extent. Therefore, the four municipalities are excluded and regressed again, and the outcomes are shown in Column (3) of Table 3. It demonstrates the estimated impact coefficient of digital technology progress remains significantly positive after elimination, and the research findings are robust.

5.3. Endogeneity test and analysis

5.3.1. Lag period regression of explanatory variables

Because of endogeneity problems caused by possible reverse causality and omitted variables, the one-period-lagged (*L.DTA*) and two-period-lagged (*L2.DTA*) of the core explanatory variables are used for regression. Data shown in Columns 4 and 5 again verify the robustness of the benchmark regression outcomes.

5.3.2. Analysis with instrumental variable approach

Selecting appropriate instrumental variables to participate in regression analysis is an important method to alleviate endogenous problems. Taking after the practice of Zhang et al. (2019), the spherical distance between each provincial capital and Hangzhou is picked as the instrumental variable of digital economy. Hangzhou is the starting point for the rapid development of digital technology in China, and the closer the provincial capital city is to Hangzhou, the more convenient and relevant the acquisition of digital technology in the province is. More importantly, the modernization of the economic system depends on the regional industrial foundation, technological innovation, structural optimization, etc., and there is no significant correlation with the spatial distance of Hangzhou's geographical location, which satisfies the exclusivity. However, since the research samples are balanced panel data, the cross-sectional data need to be adjusted. Therefore, we further take after the method of Nunn and Qian (2014) to deal with this kind of problem, and obtains the panel instrumental variable that meets the test requirements by introducing the time dynamic variable and constructing the interaction term with a certain cross-sectional variable in the historical period. Specifically, this study utilizes the spherical distance between each provincial capital and Hangzhou, as well as China's Internet broadband access ports quantity, to construct interaction terms respectively, which are represented as instrumental variables for digital technology progress. On the base of the data in Column (6) of Table 3, the estimated coefficient for digital technology progress remains significantly positive, which is similar to the benchmark regression conclusion. The p value of the Kleibergen-Paaprk LM statistic and the Kleibergen-Paaprk Wald F statistic pass the relevant instrumental variable test, and the research conclusion is robust.

5.4. Heterogeneity test

5.4.1. Heterogeneity analysis on the base of the sub-dimension of economic modernization

To verify Hypothesis 1, the four sub-dimensions of economic modernization, namely economic innovation (*I_ECM*), greening (*G_ECM*), openness (*O_ECM*) and industrial modernization (*D_ECM*), are respectively taken as the explained variables, and the scores of each dimension in the above research design are represented and participated in the regression. On the base of the data presented in Table 4, the promotion effect of digital technology progress on economic innovation is stronger than its impact on industrial modernization and economic greening, and the impact on economic openness is not significant, and the differences among groups meet the significance test (at the 10% level). And in terms of transformation technology demand, compared with industrial modernization, the dividend of digital technol-

Table 4. Outcomes of heterogeneity test grounded in the sub-dimensions of economic modernization

Variables	(1)	(2)	(3)	(4)
	I_ECM	G_ECM	O_ECM	D_ECM
DTA	0.0856*** (0.0062)	0.0027** (0.0012)	–0.0061 (0.0046)	0.0648*** (0.0118)
Constant	0.2124 (0.1987)	–0.0241 (0.0765)	–0.7614 (0.4928)	0.2604* (0.1511)
Controls	Yes	Yes	Yes	Yes
Province_FE	Yes	Yes	Yes	Yes
Year_FE	Yes	Yes	Yes	Yes
R^2	0.9044	0.4639	0.2990	0.8538
Test for differences in coefficients between groups	(1) and (2) 0.000, (1) and (3) 0.000, (1) and (4) 0.091; (2) and (3) 0.073, and (4) 0.000; (3) and (4) 0.000			

ogy progress has the highest degree of consistency with economic innovation. Because the progress of digital technology itself will produce additional carbon emissions, the promotion effect on the greening of the economy is relatively low. In addition, due to the existence of international trade barriers and policy instability, digital technology progress fails to show significant promotion effect on economic openness. In previous literatures, scholars solely examined the impact of digital technology progress on economic innovation and transformation (Chen et al., 2023a; Ge et al., 2025), green transformation (Liu et al., 2024a; Ma & Lin, 2025) and industrial transformation and upgrading (Liu et al., 2024b) from a single perspective, but there is no comprehensive analysis and horizontal comparison. The findings of this paper make up for this deficiency. This research finding also offers significant implications. The government should, through the formulation of relevant policies, enhance the positive promoting effect of digital technology on the green and open development of the economy, achieve coordinated driving of the economic modernization system, and avoid falling into structural imbalance. In addition, the research findings also deepen the existing economic theory of digital technology from the perspective of dividend differentiation.

5.4.2. Heterogeneity analysis on the base of the regional level

Across China's eastern, central, and western regions, there are obvious development gaps between regions (Shi et al., 2022). Compared with the eastern region, the western region remains in the initial stage of industrialization (Hu et al., 2020). Then, will the progress of digital technology help the backward western region to catch up in economic modernization, or help the strong eastern region to become stronger? In order to verify Hypothesis 2, 30 provinces in China are first classified into eastern, central and western areas, and heterogeneity test is conducted after the research objects are determined. The data in columns (1) and (3) of the Table 5, illustrate the promotion effect of digital technology progress on economic modernization is stronger in China's western region in comparison to the eastern region, and this difference is significant after testing. Considering that the heterogeneity test of regional division may not be rigorous enough to verify Hypothesis 2. Drawing on the median of the economic modernization levels across regions, we further divide the existing samples into two groups (high-level group and low-level group), before re-conducting heterogeneity test. According to the comparison of data in columns (4) and (5) of Table 5, the promotion effect of digital technology progress on the group with low level of economic modernization is stronger, and the difference is significant. Hypothesis 2 is proved. Most existing relevant studies show that digital economy in the eastern region keeps deeper promotion effect on economic growth (Shang et al., 2025), innovation and development (Bai et al., 2024) and urbanization construction (Chen et al., 2025), than that of the western region. This study takes digital technology progress as the research object, and finds the opposite. This may be because digital economy focuses on post and telecommunications services, telecommunications services and other industrial economic activities derived from digital technology (Wu et al., 2025), which need to be supported by the intelligent environment in developed areas (Zhang et al., 2025). However, subject of this study is the progress of digital technology, which highlights the technological attributes and has stronger spatial spillover and application inclusiveness (Daud et al., 2024), which can help the backward regions to catch up. This also confirms the inference of Ji et al. (2023) that the use of technology is an effective way for backward regions to narrow the disparity with developed regions.

Table 5. Heterogeneity test outcomes at the regional level

Variables	(1)	(2)	(3)	(4)	(5)
	Eastern region	Central region	Western region	Regions with low economic modernization	Regions with higher economic modernization
DTA	0.1144***	0.1857**	0.2539***	0.3441***	0.1152***
	(0.0312)	(0.0631)	(0.0475)	(0.0731)	(0.0299)
Constant	–2.7269*	–0.3867	0.5117	0.2306	–2.0224
	(1.2597)	(0.2830)	(0.2968)	(0.2269)	(1.6769)
Controls	Yes	Yes	Yes	Yes	Yes
Province_FE	Yes	Yes	Yes	Yes	Yes
Year_FE	Yes	Yes	Yes	Yes	Yes
R^2	0.8237	0.8766	0.7541	0.5212	0.8269
Test for differences in coefficients between groups	(1) and (2) 0.2355, (1) and (3) 0.0059; (2) and (3) 0.3168 (4) and (5) 0.0019				

5.4.3. Heterogeneity test in different stages of digital technology progress

In order to verify H3, according to the threshold regression model, we use the Bootstrap repeated sampling 1000 times to conduct a preliminary existence test on the threshold effect of digital technological progress. Table 6 presents the test results, showing when digital technology progress is taken as the threshold variable, the F value under the single threshold exceeds the critical value of 10% significance level. In contrast, the F value in the double threshold model is below the critical value at 10% significance level, which fails the significance test. It demonstrates the threshold effect of digital technology progress only has a single threshold but not a double threshold. Therefore, the single-threshold regression model of digital technological progress is formulated, with the threshold regression outcomes listed in Table 7. Threshold regression shows that under the definition of economic modernization as the explained variable and digital technology progress as the threshold variable, when digital technology surpasses the threshold value 0.0231, the regression coefficient of digital technology progress is 1.2464, which is significant at the 10% level. When the progress level of digital technology rises to the threshold value 0.0231, the estimated coefficient of digital technology decreases to 0.1281, which is significant at 1% level, specifying that the enhancing effect of digital technology progress on economic modernization is significantly weakened. As the level of digital technological progress improves, the positive promoting effect of digital technology progress on economic modernization presents a nonlinear characteristic of decreasing marginal benefit, which verifies the conjecture. Contrary to Metcalfe's law and network effect theory, this research result does not show the phenomenon of increasing marginal benefits found in existing studies (J. Li et al., 2025; Qiu et al., 2025). It is because that in the process of promoting economic modernization, digital technology, as a technical factor, is more likely to follow the rule of diminishing marginal returns (Jiang et al., 2021). Mwananziche et al. (2023) believed the effects of technological progress could not be fully absorbed by other factors of production, resulting in diminishing marginal returns. However, the views of this study are more consistent with those of Fahmy (2020), that after digital technology reaches a mature state, it will saturate due to technology diffusion, the diffusion process will slow down, and the marginal effect will decrease. The phenomenon of technology saturation is an important influencing factor of diminishing marginal returns.

Table 6. Threshold existence test

Threshold variable (Th)	Threshold number	F value	P value	Critical value			Threshold value
				1%	5%	10%	
DTA	Single threshold	28.41*	0.0600	44.1032	30.3359	24.4419	0.0231
	Double threshold	12.45	0.4070	42.0286	27.5732	23.0017	0.0158

Table 7. Threshold regression results

Variables and statistical parameters		(1)
		ECM
Threshold value	q1	0.0231
DTA·I(Th ≤ q1)		1.2464*
		(0.7096)
DTA·I(Th > q1)		0.1281***
		(0.0186)
Controls		Yes
R^2		0.7731

6. Main conclusions and policy insights

Employing 11-year panel data (2013–2023) from 30 China's provinces, this paper studies the heterogeneity of the impact of digital technology progress on economic modernization, and discusses the dividend differentiation, late-comer advantage and diminishing marginal phenomenon in this impact.

Firstly, the progress of digital technology can stimulate the modernization of China's economy. In the process of economic modernization, the positive effect of digital technology progress has been empirically confirmed. Secondly, this paper deconstructs economic modernization according to the secondary index dimensions of economic modernization, and successively inspects and verifies the stimulative effect of digital technology progress on the subdivision dimensions of economic modernization. Through horizontal comparison and difference test between groups, it is found that the promoting effect of digital technology progress on economic innovation is stronger than its impact on economic modernization and greening, while the impact on economic openness is not significant, and there is an obvious dividend differentiation phenomenon. Thirdly, the regional heterogeneity test reveals that the enhancing effect of digital technology progress on the western region is stronger in comparison to the eastern region, and the promotion effect on the regions with low level of economic modernization is more pronounced than that on regions with high level of economic modernization. Digital technology provides the possibility for backward regions to realize economic modernization and catch up, and there is a late-comer advantage. Finally, we adopt a threshold model to explore the nonlinear relationship between digital technological progress and economic modernization. The outcomes unveil that with the improvement of the level of digital technology progress, its promoting effect on economic modernization is significantly reduced, showing a phenomenon of decreasing "marginal benefit". In order to carry out the research smoothly, we also construct the economic modernization index measurement system from the four dimensions of economic innovation, greening, openness and industrial modernization, and use the entropy method for quantification.

Drawing on the theory analysis and empirical findings of this paper, the subsequent policy insights are put forward. (1) Attach attention to the phenomenon of "consumption increase" in the development of digital technology, encourage digital enterprises to reduce the energy consumption of digital technology progress through dynamic power adjustment and other technologies, and help the green economic transformation. At the same time, we will accelerate the alignment with international trade rules, especially in areas such as digital trade. By facilitating the cross-border flow of digital factors and leveraging the dividend of digital technology progress, we will propel the transformation of economic openness. (2) Encourage backward regions to adopt digital technologies and promote the digital transformation of their industrial systems. We will accelerate the establishment of digital infrastructure in backward regions, serve the comprehensive progress of digital technologies, and promote the economic modernization and transformation of backward areas. (3) Explore new application fields of AI-included digital technologies, enhance the depth of digital technology diffusion, slow down the diminishing marginal benefits caused by digital technology diffusion saturation, and make up for the driving force of economic modernization.

This paper has some limitations, which can serve as future research directions. Firstly, this paper conducts an analysis based on China's 30 provinces as sample for research, and subsequent studies can be carried out from the urban level or the enterprise level. Secondly, regarding the measure of economic modernization, as far as we know, this study is the first one constructed in the existing research, which is not sufficiently perfect in dimension setting and indicator selection. Follow-up research can continuously improve the index measurement system. Thirdly, this study explores the heterogeneity of the impact of digital technology progress on economic modernization, and subsequent research can concentrate on the mechanism analysis of digital technology progress on economic modernization.

Disclosure statement

The authors declare no competing interests.

Data availability statement

Data will be available on reasonable request.

References

Amin, N., Song, H., & Farrukh, M. U. (2022). Does sectoral modernization promote CO_2 emissions? Dynamic panel analysis of selected Asian countries. *Environmental Science and Pollution Research*, *29*(55), 83612–83623. https://doi.org/10.1007/s11356-022-21618-8

Andal, E. G. T. (2022). Industrialisation, state-related institutions, and the speed of energy substitution: The case in Europe. *Energy*, *239*, Article 122274. https://doi.org/10.1016/j.energy.2021.122274

Bai, D. B., Li, M., Wang, Y. Q., Mallek, S., & Shahzad, U. (2024). Impact mechanisms and spatial and temporal evolution of digital economy and green innovation: A perspective based on regional collaboration within urban agglomerations. *Technological Forecasting and Social Change*, *207*, Article 123613. https://doi.org/10.1016/j.techfore.2024.123613

Bellucci, C., Rubínová, S., & Piermartini, R. (2025). Better together: How digital connectivity and regulation reduce trade costs. *Review of International Economics*, *33*(3), 796–814. https://doi.org/10.1111/roie.12807

Belykh, A. A., & Mau, V. A. (2020). Economic reforms in Russia: Theoretical aspects and the practice of XIX-early XX century. *Voprosy Ekonomiki* (1), 18–46.

Chang, H., Ding, Q. Y., Zhao, W. Z., Hou, N., & Liu, W. W. (2023). The digital economy, industrial structure upgrading, and carbon emission intensity – empirical evidence from China's provinces. *Energy Strategy Reviews*, *50*, Article 101218. https://doi.org/10.1016/j.esr.2023.101218

Chen, J., Chen, Y. N., Liang, X. C., Yu, L., Sun, J. L., Luo, X. T., Zhang, M. S., & Wu, Z. Q. (2024). The mitigating effect of new digital technology on carbon emissions: Evidence from China. *Environmental Science and Pollution Research*, *31*(6), 9433–9444. https://doi.org/10.1007/s11356-023-31792-y

Chen, R., Wang, Y. F., Wang, Q., Zhang, L. L., & Xiong, R. X. (2025). Unleashing the digital dividend: Exploring how the digital economy promotes the construction of new urbanization in China's 284 prefecture-level cities? *Economic Analysis and Policy*, *85*, 818–834. https://doi.org/10.1016/j.eap.2024.12.028

Chen, W., Du, X. Y., Lan, W., Wu, W. L., & Zhao, M. R. (2023a). How can digital economy development empower high-quality economic development? *Technological and Economic Development of Economy*, *29*(4), 1168–1194. https://doi.org/10.3846/tede.2023.18784

Chen, W., Zou, W., Zhong, K., & Aliyeva, A. (2023b). Machine learning assessment under the development of green technology innovation: A perspective of energy transition. *Renewable Energy*, *214*, 65–73. https://doi.org/10.1016/j.renene.2023.05.108

Chen, Y., Xu, S. R., Lyulyov, O., & Pimonenko, T. (2023). China's digital economy development: Incentives and challenges. *Technological and Economic Development of Economy*, *29*(2), 518–538. https://doi.org/10.3846/tede.2022.18018

Chen, Z., Zhang, X., & Chen, F. (2021). Do carbon emission trading schemes stimulate green innovation in enterprises? Evidence from China. *Technological Forecasting and Social Change*, *168*, Article 120744. https://doi.org/10.1016/j.techfore.2021.120744

Cheng, K., Chen, H. W., Zhang, F., & Zhang, M. Y. (2023). China's high-quality innovation development from an institutional perspective: Regional differences and convergence. *Technological and Economic Development of Economy*, *29*(6), 1657–1686. https://doi.org/10.3846/tede.2023.20214

Cheng, X. M., Du, A. M., Yan, C. N., & Goodell, J. W. (2025). Internal business process governance and external regulation: How does AI technology empower financial performance? *International Review of Financial Analysis*, *99*, Article 103927. https://doi.org/10.1016/j.irfa.2025.103927

Chotia, V., Khoualdi, K., Broccardo, L., & Yaqub, M. Z. (2025). The role of cyber security and digital transformation in gaining competitive advantage through Strategic Management Accounting. *Technology in Society*, *81*, Article 102851. https://doi.org/10.1016/j.techsoc.2025.102851

Daud, S. N. M., Ahmad, A., & Trinugroho, I. (2024). Financial inclusion, digital technology, and economic growth: Further evidence. *Research in International Business and Finance*, *70*, Article 102361. https://doi.org/10.1016/j.ribaf.2024.102361

Degirmenci, T., Aydin, M., Cakmak, B. Y., & Yigit, B. (2024). A path to cleaner energy: The nexus of technological regulations, green technological innovation, economic globalization, and human capital. *Energy*, *311*, Article 133316. https://doi.org/10.1016/j.energy.2024.133316

Di, Y., Lu, Y., & Razzaq, A. (2025). International differences and dynamic evolution of trade in digitally deliverable services. *Technology in Society*, *81*, Article 102781. https://doi.org/10.1016/j.techsoc.2024.102781

Dong, F., Hu, M. Y., Gao, Y. J., Liu, Y., Zhu, J., & Pan, Y. L. (2022). How does digital economy affect carbon emissions? Evidence from global 60 countries. *Science of The Total Environment*, *852*, Article 158401. https://doi.org/10.1016/j.scitotenv.2022.158401

dos Santos, U. P., & Mendes, P. S. (2023). Regional spillovers of knowledge in Brazil: Evidence from science and technology municipal indicators. *Innovation and Development*, *13*(2), 323–342. https://doi.org/10.1080/2157930X.2021.1978723

Duan, H. Y., & Sun, X. S. (2024). Research on technology spillover of digital economy affecting energy consumption intensity in Beijing-Tianjin-Hebei region. *Sustainability*, *16*(11), Article 4562. https://doi.org/10.3390/su16114562

Eslami, M. H., Pellegrini, L., Lazzarotti, V., Puliga, G., Manzini, R., & Boer, H. (2023). The effect of knowledge collaboration on innovation performance: The moderating role of digital technologies. *International Journal of Technology Management*, *91*(3–4), 162–189. https://doi.org/10.1504/IJTM.2023.128800

Fahmy, H. (2020). Is the sharing economy causing a regime switch in consunitnion? *Journal of Applied Economics*, *23*(1), 281–298. https://doi.org/10.1080/15140326.2020.1750121

Fan, D., Ding, J. Y., Wu, S. H., & Su, Y. Y. (2025). Firewalls or frontlines: Geopolitical tensions and multinationals' digital technology upgrading. *Technological Forecasting and Social Change*, *216*, Article 124147. https://doi.org/10.1016/j.techfore.2025.124147

Galindo-Martín, M.-Á., Castaño-Martínez, M.-S., & Méndez-Picazo, M.-T. (2019). Digital transformation, digital dividends and entrepreneurship: A quantitative analysis. *Journal of Business Research*, *101*, 522–527. https://doi.org/10.1016/j.jbusres.2018.12.014

Gan, C., Zheng, R., & Yu, D. (2011). An empirical study on the effects of industrial structure on economic growth and fluctuations in China. *Economic Research Journal*, *46*(5), 4–16+31.

Gao, J., & Lu, F. (2025). Green public procurement, external pressures and enterprise green transition: Evidence from China. *Journal of Asian Economics*, *98*, Article 101936. https://doi.org/10.1016/j.asieco.2025.101936

Ge, J., Qu, Y. J., & Guo, Y. C. (2025). The impact of digital technology on the innovation efficiency of manufacturing enterprises: Moderating role based on the Chinese context. *Journal of Industrial Integration and Management*, *10*(1), 1–23. https://doi.org/10.1142/S2424862225500010

Gong, W., Ma, R. Y., & Zhang, H. X. (2024). Digital agricultural technology services and farmers' willingness to choose digital production technology in Sichuan province, China. *Frontiers in Sustainable Food Systems*, *8*, Article 1401316. https://doi.org/10.3389/fsufs.2024.1401316

Growiec, J. (2023). Industry 4.0? Framing the digital revolution and its long-run growth consequences. *Gospodarka Narodowa – the Polish Journal of Economics*, *316*(4), 1–16. https://doi.org/10.33119/GN/175243

Guo, X. X., Sun, L. P., Han, S., & Lu, J. B. (2022). Dynamic assessment of China's re-electrification level considering carbon peaking and carbon neutrality goals: A study based on functional data analysis. *Frontiers in Energy Research*, *10*, Article 951140. https://doi.org/10.3389/fenrg.2022.951140

Hong, I., & Ngok, K. (2022). The industrialisation thesis, revisited: Understanding welfare expansion in China through social expenditure data (2000–2019). *Social Policy* & *Administration*, *56*(6), 874–890. https://doi.org/10.1111/spol.12836

Hu, Y., Fisher-Vanden, K., & Su, B. Z. (2020). Technological spillover through industrial and regional linkages: Firm-level evidence from China. *Economic Modelling*, *89*, 523–545. https://doi.org/10.1016/j.econmod.2019.11.018

Ismail, N. W. (2021). Digital trade facilitation and bilateral trade in selected Asian countries. *Studies in Economics and Finance*, *38*(2), 257–271. https://doi.org/10.1108/SEF-10-2019-0406

Jafarli, H. (2023). Problems of modernization of the structure of the national economy taking into account global economic conditions. *Baltic Journal of Economic Studies*, *9*(2), 1–7. https://doi.org/10.30525/2256-0742/2023-9-2-1-7

Ji, Z., Zhao, L., Song, X., & Gao, X. (2023). Digital economy impact on inclusive green growth: Intermediary and spatial spillover effects in China. *Environmental Science and Pollution Research*, *30*(59), 123657–123678. https://doi.org/10.1007/s11356-023-30898-7

Jiang, Q., Li, J. Z., Si, H. Y., & Su, Y. Y. (2022). The impact of the digital economy on agricultural green development: Evidence from China. *Agriculture-Basel*, *12*(8), Article 1107. https://doi.org/10.3390/agriculture12081107

Jiang, W. M., Fan, J., & Tian, K. L. (2021). Input-output production structure and non-linear production possibility frontier. *Journal of Systems Science* & *Complexity*, *34*(2), 706–723. https://doi.org/10.1007/s11424-020-9079-y

Jones, E. (2023). Digital disruption: Artificial intelligence and international trade policy. *Oxford Review of Economic Policy*, *39*(1), 70–84. https://doi.org/10.1093/oxrep/grac049

Kamoyo, M., Masamha, T., & Chikazhe, L. (2025). Remote e-learning model in the post COVID-19 era; building a resilient higher education strategy. *Cogent Education*, *12*(1), Article 2498854. https://doi.org/10.1080/2331186X.2025.2498854

Kayanja, W., Kyambade, M., & Kiggundu, T. (2025). Exploring digital transformation in higher education setting: The shift to fully automated and paperless systems. *Cogent Education*, *12*(1), Article 2489800. https://doi.org/10.1080/2331186X.2025.2489800

Klingenberg, C. O., Borges, M. A. V., & Antunes, J. A. d. V. (2022). Industry 4.0: What makes it a revolution? A historical framework to understand the phenomenon. *Technology in Society*, *70*, Article 102009. https://doi.org/10.1016/j.techsoc.2022.102009

Kovács, G., & Bartók, L. (2024). Metamorphoses: The relationship between the banking system and economic modernization in II. in post-World War II France. *Public Finance Quarterly-Hungary*, *70*(2), 31–64. https://doi.org/10.35551/PFQ_2024_2_2

Lei, C., Tao, D. U., Difan, W. U., & Chengrui, L. A. I. (2024). Can digital financial inclusion promote the nighttime economy? – New evidence from Chinese counties' nighttime lighting data and threshold model. *Technological and Economic Development of Economy*, *30*(6), 1553–1571. https://doi.org/10.3846/tede.2024.22245

Li, B., & Zhou, C. (2024). Robot adoption and urban total factor productivity: Evidence from China. *Technological and Economic Development of Economy*, *30*(5), 1330–1351. https://doi.org/10.3846/tede.2024.21102

Li, J., Wang, Y. N., Zhang, S. H., & Sheng, X. C. (2025). Digital economy, fiscal decentralization, and carbon emission intensity: Evidence from China. *Sustainable Futures*, *9*, Article 100522. https://doi.org/10.1016/j.sftr.2025.100522

Li, Y., Li, N., & Li, Z. B. (2023). Evolution of carbon emissions in China's digital economy: An empirical analysis from an entire industry chain perspective. *Journal of Cleaner Production*, *414*, Article 137419. https://doi.org/10.1016/j.jclepro.2023.137419

Li, Z., Shao, S., Shi, X., Sun, Y., & Zhang, X. (2019). Structural transformation of manufacturing, natural resource dependence, and carbon emissions reduction: Evidence of a threshold effect from China. *Journal of Cleaner Production*, *206*, 920–927. https://doi.org/10.1016/j.jclepro.2018.09.241

Li, Z.-G., Wu, Y., & Li, Y.-K. (2024). Technical founders, digital transformation and corporate technological innovation: empirical evidence from listed companies in China's STAR market. *International Entrepreneurship and Management Journal*, *20*(4), 3155–3180. https://doi.org/10.1007/s11365-023-00852-7

Liang, S., & Tan, Q. (2024). Can the digital economy accelerates China's export technology upgrading? Based on the perspective of export technology complexity. *Technological Forecasting and Social Change*, *199*, Article 123052. https://doi.org/10.1016/j.techfore.2023.123052

Liao, C.-S., & Li, X. (2024). The impact of R&D efficiency on economic growth in China: Non-linear threshold effects. *Technological and Economic Development of Economy*, *30*(5), 1205–1228. https://doi.org/10.3846/tede.2024.20166

Liu, G., & Liu, B. (2023). How digital technology improves the high-quality development of enterprises and capital markets: A liquidity perspective. *Finance Research Letters*, *53*, Article 103683. https://doi.org/10.1016/j.frl.2023.103683

Liu, H., & Li, X. (2025). How digital technology can improve new quality productive forces? – Perspective of total factor agricultural carbon productivity. *Journal of Asian Economics*, *98*, Article 101921. https://doi.org/10.1016/j.asieco.2025.101921

Liu, J., Yu, Q., Chen, Y., & Liu, J. (2022). The impact of digital technology development on carbon emissions: A spatial effect analysis for China. *Resources*, *Conservation and Recycling*, *185*, Article 106445. https://doi.org/10.1016/j.resconrec.2022.106445

Liu, J., Wang, Q. B., & Wei, C. Y. (2024a). Unleashing green innovation in enterprises: The transformative power of digital technology application, green human resource, and digital innovation networks. *Systems*, *12*(1), Article 11. https://doi.org/10.3390/systems12010011

Liu, J., Feng, X., Liu, J., & Yamaka, W. (2024b). Digital economy and industrial structure transformation: Mechanisms for high-Quality development in China's agriculture and rural areas. *Agriculture-Basel*, *14*(10), Article 1769. https://doi.org/10.3390/agriculture14101769

Liu, Y., Jiang, R., Zhang, Y., Dai, J. J., & Cheng, J. (2024). Mitigating digital trade barriers: Strategies for enhancing national value chains performance. *International Review of Economics* & *Finance*, *95*, Article 103485. https://doi.org/10.1016/j.iref.2024.103485

Lu, D., Hui, E. C. M., Shen, J., & Shi, J. (2024). Digital industry agglomeration and urban innovation: Evidence from China. *Economic Analysis and Policy*, *84*, 1998–2025. https://doi.org/10.1016/j.eap.2024.10.047

Lu, H., Pan, Y., Fan, R., & Guan, W. (2025). Green credit policy and heavily polluting enterprises' green transition. *International Review of Financial Analysis*, *103*, Article 104162. https://doi.org/10.1016/j.irfa.2025.104162

Lu, T., & Zhu, Z. (2021). Will AI reduce labor income share – A test based on fixed effect model and panel quantile model. *Journal of Shanxi University of Finance and Economics*, *43*(11), 29–41.

Lyu, Y., Wang, W., Wu, Y., & Zhang, J. (2023). How does digital economy affect green total factor productivity? Evidence from China. *Science of The Total Environment*, *857*, Article 159428. https://doi.org/10.1016/j.scitotenv.2022.159428

Ma, R., & Lin, B. (2025). The impact of digital technology innovation on energy-saving and emission reduction based on the urban innovation environment. *Journal of Environmental Management*, *375*, Article 124176. https://doi.org/10.1016/j.jenvman.2025.124176

Ma, R., Lin, Y., & Lin, B. (2023). Does digitalization support green transition in Chinese cities? Perspective from Metcalfe's Law. *Journal of Cleaner Production*, *425*, Article 138769. https://doi.org/10.1016/j.jclepro.2023.138769

Meng, X., & Wu, C. (2024). Empirical evidence on digitization enabling the transition to a green economy in China. *Environmental Science and Pollution Research*, *31*, 51790–51805. https://doi.org/10.1007/s11356-024-34613-y

Miao, Z. Y. (2022). Industry 4.0: Technology spillover impact on digital manufacturing industry. *Journal of Enterprise Information Management*, *35*(4–5), 1251–1266. https://doi.org/10.1108/JEIM-02-2021-0113

Michelotto, F., & Joia, L. A. (2024). Organizational digital transformation readiness: An exploratory investigation. *Journal of Theoretical and Applied Electronic Commerce Research*, *19*(4), 3283–3304. https://doi.org/10.3390/jtaer19040159

Mignamissi, D., & Nguekeng, B. (2022). Trade openness-industrialization nexus revisited in Africa. *Economic Change and Restructuring*, *55*(4), 2547–2575. https://doi.org/10.1007/s10644-022-09401-8

Mwananziche, J., Myovella, G., Karacuka, M., Haucap, J., & Moshi, G. (2023). Is digitalization a booster for economic growth in Africa? Short run and long run evidence from Tanzania. *Telecommunications Policy*, *47*(10), Article 102679. https://doi.org/10.1016/j.telpol.2023.102679

Narula, S., Tamvada, J. P., Kumar, A., Puppala, H., & Gupta, N. (2024). Putting digital technologies at the forefront of industry 5.0 for the implementation of a circular economy in manufacturing industries. *IEEE Transactions on Engineering Management*, *71*, 3363–3374. https://doi.org/10.1109/TEM.2023.3344373

Navickienė, O., Meidutė-Kavaliauskienė, I., Činčikaitė, R., Morkūnas, M., & Valackienė, A. (2023a). Modernisation of a country in the context of social environmental sustainability: Example of Lithuania. *Sustainability*, *15*(4), Article 3689. https://doi.org/10.3390/su15043689

Navickienė, O., Meidutė-Kavaliauskienė, I., Činčikaitė, R., Morkūnas, M., & Valackienė, A. (2023b). The expression of the country's modernisation in the context of economic environmental sustainability: The case of Lithuania. *Sustainability*, *15*(13), Article 10649. https://doi.org/10.3390/su151310649

Nunn, N., & Qian, N. (2014). US food aid and civil conflict. *American Economic Review*, *104*(6), 1630–1666. https://doi.org/10.1257/aer.104.6.1630

Oyetade, K., Zuva, T., & Harmse, A. (2025). Integrating Industry 4.0 technologies into IT education. *Cogent Education*, *12*(1), Article 2479195. https://doi.org/10.1080/2331186X.2025.2479195

Pan, X. F., & Yuan, J. H. (2024). Global value chain, GVC, biased technological change and reginal total factor productivity differences. *Technological Forecasting and Social Change*, *206*, Article 123538. https://doi.org/10.1016/j.techfore.2024.123538

Perilla Jiménez, J. R. (2024). Income per-capita across-countries: Stories of catching-up, stagnation, and laggardness. *Journal of Applied Economics*, *27*(1), Article 2339701. https://doi.org/10.1080/15140326.2024.2339701

Philippart, M. H. (2022). Success factors to deliver organizational digital transformation: A framework for transformation leadership. *Journal of Global Information Management*, *30*(8), 1–17. https://doi.org/10.4018/JGIM.304068

Pu, Z., Qian, Y., & Liu, R. (2025). Is digital technology innovation a panacea for carbon reduction? *Technological and Economic Development of Economy*, *31*(2), 496–524. https://doi.org/10.3846/tede.2024.22208

Qiu, Y., Liu, W., & Wu, J. (2025). Digital economy and urban green innovation: from the perspective of environmental regulation. *Journal of Environmental Planning and Management*, *68*(2), 267–289. https://doi.org/10.1080/09640568.2023.2244668

Ramirez, P. (2021). Technological revolutions, socio-technical transitions and the role of agency: Värmland's transition to a regional bio-economy. *Regional Studies*, *55*(10–11), 1642–1651. https://doi.org/10.1080/00343404.2021.1957810

Ross, P., & Maynard, K. (2021). Towards a 4th industrial revolution. *Intelligent Buildings International*, *13*(3), 159–161. https://doi.org/10.1080/17508975.2021.1873625

Sadik-Zada, E. R. (2021). Natural resources, technological progress, and economic modernization. *Review of Development Economics*, *25*(1), 381–404. https://doi.org/10.1111/rode.12716

Shang, Y. J., Lee, H., & Ma, J. H. (2025). A study on the spatial effects of the digital economy on regional economic growth in China. *Sustainability*, *17*(5), Article 2259. https://doi.org/10.3390/su17052259

Shi, T., Qiao, Y. R., Zhou, Q., & Zhang, J. G. (2022). The regional differences and random convergence of urban resilience in China. *Technological and Economic Development of Economy*, *28*(4), 979–1002. https://doi.org/10.3846/tede.2022.16721

Skripnuk, D. (2020). Analysis of the regional modernization processes in a global context with an example of the Russian northern regions. *International Journal of System Assurance Engineering and Management*, *11*, 100–110. https://doi.org/10.1007/s13198-019-00895-6

Song, M. L., Peng, L. C., Shang, Y. P., & Zhao, X. (2022). Green technology progress and total factor productivity of resource-based enterprises: A perspective of technical compensation of environmental regulation. *Technological Forecasting and Social Change*, *174*, Article 121276. https://doi.org/10.1016/j.techfore.2021.121276

Su, X., & Wang, Y. Y. (2025). Factor conditions and capability building of artificial intelligence empowered digital transformation in the banking sector: A case study of a Chinese bank. *International Journal of Technology Management*, *97*(2–3). https://doi.org/10.1504/IJTM.2025.143587

Takpara, M. M., Djiogap, C. F., Kouty, M., & Sawadogo, B. (2024). Effect of trade facilitation on economic complexity in selected African countries. *African Development Review-Revue Africaine De Developpement*, *36*(4), 568–580. https://doi.org/10.1111/1467-8268.12786

Tan, L., Yang, Z., Irfan, M., Ding, C. J., Hu, M. J., & Hu, J. (2024). Toward low-carbon sustainable development: Exploring the impact of digital economy development and industrial restructuring. *Business Strategy and the Environment*, *33*(3), 2159–2172. https://doi.org/10.1002/bse.3584

Tang, H., Yao, Q., Boadu, F., & Xie, Y. (2023). Distributed innovation, digital entrepreneurial opportunity, IT-enabled capabilities, and enterprises' digital innovation performance: A moderated mediating model. *European Journal of Innovation Management*, *26*(4), 1106–1128. https://doi.org/10.1108/EJIM-08-2021-0431

Tang, T., Jiang, X., Zhu, K., Ying, Z., & Liu, W. (2024). Effects of the promotion pressure of officials on green low-carbon transition: Evidence from 277 cities in China. *Energy Economics*, *129*, Article 107159. https://doi.org/10.1016/j.eneco.2023.107159

Thakur, P., & Wilson, V. H. (2024). Circular innovation ecosystem: A multi-actor, multi-peripheral and multi-platform perspective. *Environment Development and Sustainability*, *26*(6), 14327–14350. https://doi.org/10.1007/s10668-023-03196-y

Tsou, H. T., & Chen, J. S. (2023). How does digital technology usage benefit firm performance? Digital transformation strategy and organisational innovation as mediators. *Technology Analysis & Strategic Management*, *35*(9), 1114–1127. https://doi.org/10.1080/09537325.2021.1991575

Vărzaru, A. A. (2022). Assessing artificial intelligence technology acceptance in managerial accounting. *Electronics*, *11*(14), Article 2256. https://doi.org/10.3390/electronics11142256

Wang, H., & Sun, H. (2025). New energy pilot policy, financial subsidies and green technology progress. *International Journal of Hydrogen Energy*, *115*, 400–409. https://doi.org/10.1016/j.ijhydene.2025.01.406

Wang, J., Dong, K., Dong, X., & Taghizadeh-Hesary, F. (2022a). Assessing the digital economy and its carbon-mitigation effects: The case of China. *Energy Economics*, *113*, Article 106198. https://doi.org/10.1016/j.eneco.2022.106198

Wang, J., Ma, X. W., Zhang, J., & Zhao, X. (2022b). Impacts of digital technology on energy sustainability: China case study. *Applied Energy*, *323*, Article 119329. https://doi.org/10.1016/j.apenergy.2022.119329

Wang, L., Luo, G.-L., Sari, A., & Shao, X.-F. (2020). What nurtures fourth industrial revolution? An investigation of economic and social determinants of technological innovation in advanced economies. *Technological Forecasting and Social Change*, *161*, Article 120305. https://doi.org/10.1016/j.techfore.2020.120305

Wang, S., Shu, W., & Cui, L. (2024). Green finance policy and green economic transformation. *International Review of Financial Analysis*, *96*, Article 103785. https://doi.org/10.1016/j.irfa.2024.103785

Wang, X., Wang, Z., & Li, G. (2025). Barriers to digital services trade: Evaluation of their restrictiveness with application of Brier Score. *Oeconomia Copernicana*, *16*(1), 197–245. https://doi.org/10.24136/oc.3435

Wang, Y., Shi, M., Liu, J., Huang, H., & Yu, K. (2025). Environmental pollution management effects of technological convergence between digital and real economy industries: A perspective of tripartite co-governance by company, government, and public. *Journal of Cleaner Production*, *501*, Article 145201. https://doi.org/10.1016/j.jclepro.2025.145201

Wang, Y., & Li, L. (2024). Digital economy, industrial structure upgrading, and residents' consumption: Empirical evidence from prefecture-level cities in China. *International Review of Economics & Finance*, *92*, 1045–1058. https://doi.org/10.1016/j.iref.2024.02.069

Wang, Z.-Z., Xu, S.-Q., & Guan, Y.-J. (2025). Impact of the innovation promotion strategy on digital technology diffusion in regional innovation ecosystems. *Technology Analysis & Strategic Management*, *37*(13), 3946–3962. https://doi.org/10.1080/09537325.2024.2426743

Wu, B., Ma, W. X., & Zhao, Q. (2025). Digital economy and urban green transformation. *International Review of Financial Analysis*, *104*, Article 104286. https://doi.org/10.1016/j.irfa.2025.104286

Xia, W., Ruan, Z., Ma, S., Zhao, J., & Yan, J. (2025). Can the digital economy enhance carbon emission efficiency? Evidence from 269 cities in China. *International Review of Economics & Finance*, *97*, Article 103815. https://doi.org/10.1016/j.iref.2024.103815

Yang, C.-H. (2023). External technological sources, subsidies and firm productivity in China. *Applied Economics*, *55*(47), 5572–5590. https://doi.org/10.1080/00036846.2022.2140113

Ye, L. (2025). Digital economy and high-quality agricultural development. *International Review of Economics & Finance*, *99*, Article 104028. https://doi.org/10.1016/j.iref.2025.104028

Yu, H., Wang, J., Xu, J., & Ding, B. (2024). Does digital economy agglomeration promote green economy efficiency? A spatial spillover and spatial heterogeneity perspective. *Environment, Development and Sustainability*, *27*, 7379–7406. https://doi.org/10.1007/s10668-023-04197-7

Yu, Y., Liu, D., & Dai, Y. (2024). Carbon emission effect of digital economy development: Impact of digital economy development on China's carbon dioxide emissions. *Clean Technologies and Environmental Policy*, *26*, 2707–2720. https://doi.org/10.1007/s10098-024-02751-z

Zhang, L., Mu, R., Zhan, Y., Yu, J., Liu, L., Yu, Y., & Zhang, J. (2022). Digital economy, energy efficiency, and carbon emissions: Evidence from provincial panel data in China. *Science of The Total Environment*, *852*, Article 158403. https://doi.org/10.1016/j.scitotenv.2022.158403

Zhang, T., & Zhang, R. (2024). The spatial effect of low-carbon development of regional industries driven by the digital economy: Evidence from Chinese cities. *Humanities & Social Sciences Communications*, *11*(1), Article 706. https://doi.org/10.1057/s41599-024-03215-x

Zhang, X., Wan, G., Zhang, J., & He, Z. (2019). Digital economy, financial inclusion, and inclusive growth. *Economic Research Journal*, *54*(8), 71–86.

Zhang, X., Xu, Y. Y., & Ma, L. (2023). Information technology investment and digital transformation: The roles of digital transformation strategy and top management. *Business Process Management Journal*, *29*(2), 528–549. https://doi.org/10.1108/BPMJ-06-2022-0254

Zhang, X., Yu, Q., Liu, J., He, Y., & Xu, A. (2024). The application of industrial robots and changes in capital-labour income disparity in China. *Economic Analysis and Policy*, *84*, 42–56. https://doi.org/10.1016/j.eap.2024.08.020

Zhang, Y. (2023). The development of enterprise management innovation in the digital economy era based on the Schumpeter model. *Applied Mathematics and Nonlinear Sciences*, *8*(2), 1695–1704. https://doi.org/10.2478/amns.2023.1.00156

Zhang, Y. (2021). The regional disparity of influencing factors of technological innovation in China: Evidence from high-tech industry. *Technological and Economic Development of Economy*, *27*(4), 811–832. https://doi.org/10.3846/tede.2021.14828

Zhang, Y., Su, Y., & Wang, S. (2025). Digital economy and entrepreneurial vitality: Unveiling the impact and mechanisms through the lens of smart cities. *Scientific Reports*, *15*(1), Article 14228. https://doi.org/10.1038/s41598-025-98014-y

Zhang, Z., Jin, J., Li, S., & Zhang, Y. (2023). Digital transformation of incumbent firms from the perspective of portfolios of innovation. *Technology in Society*, *72*, Article 102149. https://doi.org/10.1016/j.techsoc.2022.102149

Zhao, Y., Zhao, X., & Yang, J. (2024). Coupling coordination and influencing factors between digital village development and agricultural and rural modernization: Evidence from China. *Agriculture-Basel*, *14*(11), Article 1901. https://doi.org/10.3390/agriculture14111901

Zheng, C., Wang, Z.-a., Pan, S., Chen, X., & Jia, S. (2023). Does financial structure still matter for technological innovation when financial technology and financial regulation develop? *Technological Forecasting and Social Change*, *194*, Article 122747. https://doi.org/10.1016/j.techfore.2023.122747

Zhou, Y., Yang, Q. J., & Lu, S. (2023). Research on the identification and formation mechanism of the main path of digital technology diffusion: Empirical evidence from China. *Technology in Society*, *75*, Article 102398. https://doi.org/10.1016/j.techsoc.2023.102398

Zhu, Y., Deng, J., Wang, M., Tan, Y., Yao, W., & Zhang, Y. (2022). Can agricultural productive services promote agricultural environmental efficiency in China? *International Journal of Environmental Research and Public Health*, *19*(15), Article 9339. https://doi.org/10.3390/ijerph19159339