

The effect of digital infrastructure on export technological complexity in manufacturing: Empirical evidence from China 2011-2023



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ABSTRACT

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Keywords

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Existing research has mainly focused on export volume or performance, with relatively limited discussion of the impact of technological complexity on manufacturing products. This study utilizes panel data from 30 provincial regions in China from 2011 to 2023 and systematically assesses the impact of digital infrastructure on the technological complexity of manufacturing exports using a fixed-effects panel model and mediation analysis. It further conducts a comprehensive investigation from the perspectives of transmission mechanisms and regional heterogeneity. Empirical results show that digital infrastructure significantly enhances the technological sophistication of manufacturing exports, with a 1% increase in digital infrastructure associated with an average 0.394% rise in export sophistication. The results are statistically significant and robust across various specifications. Besides, heterogeneity analysis highlights that the beneficial influence is particularly evident in both eastern and western regions, accompanied by greater marginal effects in areas characterized by limited digital infrastructure development. Furthermore, the mediation analysis demonstrates that digital infrastructure indirectly enhances export technological complexity by promoting technological progress and human capital accumulation. This study offers empirical evidence for understanding the evolution of manufacturing export competitiveness under the digital economy and provides policy implications for optimizing regional digital infrastructure allocation and promoting high-quality export development.

Contribution/ Originality: This study innovatively quantifies the impact of digital infrastructure on the technological complexity of China's manufacturing exports, revealing its indirect effects through technological progress and human capital accumulation. It further identifies regional heterogeneity, providing empirical evidence and policy implications for optimizing digital infrastructure and enhancing export competitiveness.

1. INTRODUCTION

As the backbone of the real economy, China's manufacturing sector has consistently played a fundamental and strategic role in the national economic system. It serves as a central force in promoting high-quality growth. However, this vital sector, much like its counterparts in other developing and emerging economies, particularly across Asia, is navigating a complex landscape. With the ongoing restructuring of global industrial chains and the continued rise in domestic factor costs, China's manufacturing exports are facing increasingly severe structural challenges. On one hand, the traditional export model dominated by labor-intensive industries can no longer meet the growing international demand for high-tech and high-value-added products. This calls for a strategic shift from "scale-driven" to "quality-driven" export growth [1]. On the other hand, China's industrial chain still exhibits significant external

dependence in mid-to-high-end segments, particularly in areas such as technology, design, and critical equipment [2] resulting in slow enhancement in product complexity and added value. Moreover, global trade has become increasingly uncertain, with frequent occurrences of major disruptions such as intensified trade frictions among major economies, the resurgence of trade protectionism, and the widespread economic shocks triggered by the COVID-19 pandemic [3]. Against this backdrop, it is imperative to explore effective approaches for upgrading the technological content of export commodities, refining the composition of export categories, and advancing the quality of manufacturing exports.

Digital infrastructure has progressively been acknowledged as a pivotal force driving the manufacturing sector toward higher-end, smarter, and greener development. This recognition applies not only to China but also to many emerging and developing economies worldwide, particularly in the dynamic Asian region. Digital infrastructure typically encompasses three major categories network, computing, and integrated application infrastructure including key components such as 5G communication, industrial IoT systems, and cloud-based platforms. These elements are characterized by high connectivity, strong computational power, and deep integration of intelligent technologies, enabling traditional sectors to converge with digital economic frameworks [4].

For China, fostering a strong digital infrastructure system is not merely crucial for overcoming the “low-end lock-in” dilemma while enhancing export quality performance, but also serves as a vital foundation for achieving the strategic goal of becoming a leading manufacturing power. Empirical studies have demonstrated that digital infrastructure particularly broadband expansion and internet penetration is crucial in driving export growth. Advances in broadband infrastructure enhance information transmission efficiency and market responsiveness, thereby facilitating the expansion of urban export trade [5]. The swift spread of internet access functions as a major catalyst for export expansion, especially in strengthening firms’ production organization and market adaptability [6]. Information and communication technology (ICT) infrastructure improves the efficiency of trade activities by enhancing information flows and reducing transaction frictions. Moreover, it helps optimize export structures, particularly by increasing the share of high-technology product exports [7].

This recognition extends beyond China. For instance, studies on ASEAN countries have highlighted the crucial role of ICT in influencing export performance, encompassing both goods and services. Studies based on ASEAN-5 countries show that improvements in ICT infrastructure such as broadband penetration, mobile connectivity, and digital network systems significantly boost both goods and services exports, with notable heterogeneity across countries and export types [8, 9]. Firm-level research from Thailand and Indonesia also confirms that ICT utilization, including basic tools like email and websites, substantially enhances firms’ export engagement and performance [10, 11]. These findings collectively underscore the broader relevance of digital infrastructure in advancing export competitiveness across developing economies in Asia.

Serving as a pivotal catalyst in the ongoing wave of technological and industrial upgrading, digital infrastructure fundamentally redefines how the manufacturing sector evolves. On one hand, it provides essential support for the widespread application of cutting-edge technologies including AI, 5G networks, and cloud-based computing, thereby broadening enterprises’ channels for acquiring external knowledge and technological resources, and effectively expediting shifts in production patterns and the rate of technological progress [12-14]. Meanwhile, digital infrastructure characterized by high speed, large capacity, and freedom from geographical constraints serves as an effective conduit for knowledge and technology circulation, greatly boosting their dissemination across and within regions. This not only strengthens regional cooperation but also amplifies knowledge and technology spillover effects [15] but also facilitates the cross-regional sharing and transfer of frontier knowledge and technology [16] thereby further improving firms’ R&D efficiency.

On the other hand, the advancement of information networks markedly boosts the export capabilities of enterprises, with particularly strong effects observed in manufacturing enterprises with abundant human capital endowments [5]. Moreover, digital infrastructure plays an important role in facilitating human capital accumulation

and quality improvement, Gao [17] and Yao [18] pointed out that digital infrastructure, by expanding the reach and accessibility of educational resources, continuously optimizes the educational foundations and workforce expertise. Meanwhile, the close convergence between digital service industries and the manufacturing domain increases firms' demand for high-skilled talent and accelerates the shift in human capital structure from low-skilled to high-skilled labor, thereby providing sustained momentum toward premium industrial upgrading and the enhancement of export quality in the manufacturing sector, driven by both supply-side and demand-side dynamics.

Although the significant contribution of digital infrastructure to promoting export trade has garnered much attention, existing studies have primarily concentrated on export volume or performance. Far fewer have examined its influence on the technological sophistication of manufactured goods. Moreover, while technological progress and human capital are widely recognized as key drivers of export structure upgrading, systematic investigation into how they mediate the link between digital infrastructure and export complexity remains insufficient. Drawing upon the preceding analysis, this paper selects the manufacturing sectors of 30 Chinese provinces as the empirical sample and applies a fixed-effects panel approach to systematically identify the impact pathways through which digital infrastructure affects the technological complexity of exports. On this basis, our examination further incorporates mediation tests for technological progress and human capital, aiming to uncover the underlying mechanisms by which digital infrastructure shapes the degree of technological complexity in manufacturing exports. The findings are intended to offer theoretical support alongside policy implications to promote region-specific empowerment and optimize the export structure. Crucially, while focusing on China, the insights also hold significant global relevance. They can provide valuable lessons and policy guidance for other developing and emerging economies, especially those in Asia, that are striving to enhance their competitiveness in global value chains and transition towards higher-value-added exports.

2. LITERATURE REVIEW AND THEORETICAL FRAMEWORK

2.1. Literature Review

The literature associated with this study can be classified into three distinct areas. The first concerns the definition and connotation of digital infrastructure. Early studies regarded it as information infrastructure, emphasizing technical attributes and integrative features [19, 20]. With technological advancement, recent research suggests that digital infrastructure has evolved from traditional information systems through mechanisms such as innovation and expansion [21]. It not only retains the utility features of conventional infrastructure but also possesses technological spillover effects enabled by digital technologies [22]. Its core components include network infrastructure, emerging technologies, and computing algorithms [23]. As the cornerstone of the digital economy, digital infrastructure plays a vital role in promoting industrial digital transformation [24] which has attracted considerable attention and emphasis in many emerging Asian economies, including China.

The second category examines the determinants of export technological complexity. Export technological complexity reflects a country's comparative advantage and position in global specialization. In general, a higher level of export complexity implies greater value-added and higher quality of exported commodities, thereby strengthening a country's performance in international markets [25]. Recent research has further identified a range of key determinants. At the macro level, increases in foreign direct investment (FDI), technological diffusion, and human capital have all been empirically shown to enhance export sophistication [26-28]. From a micro perspective, green innovation and technological upgrading significantly contribute to the structural upgrading of exports [29, 30].

The third category focuses on exploring how digital infrastructure impacts export performance. The Internet, as an integral part of digital infrastructure, has been closely associated with export growth. Improved internet penetration enables more small and medium-sized enterprises (SMEs) to participate in export-related operations [31] while also reducing cross-border communication and transactional expenses, thus supporting the enhancement and diversification of export product structures [32]. Moreover, the widespread adoption of ICT has contributed to

economic and technological structural transformation and triggered profound nonlinear social effects [33, 34] fostering the emergence of innovative trade formats, including digital commerce and cross-border online exchanges [35].

In addition, research from other Asian economies has deepened the understanding of how digital infrastructure promotes export performance. Nguyen and Choi [8] found that the expansion of broadband and mobile communication significantly promoted both goods and services exports among ASEAN-5 countries, with stronger effects observed in Singapore and Malaysia. Tee, et al. [9] highlighted that improvements in bilateral ICT development levels can enhance network effects in services trade, although such positive impacts may be offset by high trade costs. At the firm level, Rifin and Naully [11] demonstrated that Indonesian firms' use of email and the presence of a company website were both significantly associated with their likelihood to export. Similarly, Racela and Thoumrungroje [10] showed that ICT tools play a facilitating role in strengthening Thai firms' capabilities for proactive export market development.

However, studies on the underlying mechanisms remain limited. One key pathway is technological progress. Digital infrastructure can enhance firms' total factor productivity (TFP) mainly through better allocation of resources and enhanced coordination among factors, thereby increasing the technological content and value-added in exports [12]. It also lowers the spatial and temporal costs of cross-regional collaboration, thereby expanding firms' access to external knowledge resources and fostering knowledge and technology spillovers [36] thus enhancing firms' R&D efficiency. Vu and Asongu [14] further argue that developing countries can leverage the latecomer advantage in digital infrastructure to accelerate technological imitation, absorption, and transformation, thereby enhancing their technological competitiveness.

Another important channel is human capital enhancement. Advancements in digital infrastructure provide global talent opportunities for advanced online training and experience exchange, thereby enhancing workers' capabilities in R&D and technology absorption, ultimately contributing to an overall improvement in human capital [17]. It has also been shown that the accumulation of human capital, along with its spillover effects, enhances the quality standards of manufactured export goods Forman and Van Zeebroeck [36]. Yao [18] further argues that the optimization of human capital not only improves manufacturing firms' capacity to meet sophisticated technological demands, also strengthens the utilization efficiency of digital infrastructure itself, thereby creating a positive feedback loop that drives the sustained advancement of export technological complexity.

In summary, studies have systematically investigated the positive effects of digital infrastructure on export performance from multiple perspectives. However, most of the existing literature concentrates on how digital infrastructure influences export scale or overall export outcomes, while relatively few have explored its influence on export technological complexity a key indicator of export quality. This research gap is particularly evident in the context of manufacturing and is also of considerable importance for a broader range of emerging economies. Furthermore, the pathways by which digital infrastructure affects export technological complexity are still insufficiently understood. To bridge these gaps, this paper develops a theoretical framework that incorporates "technological progress" and "human capital accumulation" as two mediating pathways, aiming to enrich the theoretical understanding of how digital infrastructure shapes export technological complexity.

2.2. Theoretical Framework

Digital infrastructure fosters greater technological sophistication in manufactured exports primarily through mechanisms such as reducing information and transaction costs, improving production efficiency and responsiveness, and enhancing firms' coordination and supply chain integration capabilities. To begin with, improved digital infrastructure facilitates more efficient data transmission and reduces firms' transaction and communication costs, thereby providing the necessary conditions for participating in high-complexity, technology-intensive export activities. Prior studies indicate that the widespread adoption of digital infrastructure significantly reduces

information acquisition and fixed trade costs, which in turn enhances export activity and expands potential trade opportunities [37]. Additionally, digital infrastructure supports the scaling up of production capacity [5] improves productivity, and lowers unit costs, thereby strengthening firms' supply capacity and responsiveness in export operations. These improvements enable firms to move into export segments characterized by higher technological complexity and greater value-added, thus facilitating an upgrade in the structure and sophistication of export products. In addition, digital infrastructure significantly enhances inter-firm information coordination and supply chain management capabilities, enabling enterprises to more effectively navigate uncertainties associated with the export of technologically complex goods [38]. Based on the above discussion, this study proposes the following hypothesis:

H₁: Digital infrastructure substantially contributes to the improvement of technological complexity in manufacturing exports.

The digital infrastructure exhibits significant heterogeneity in its impact on the technological sophistication of manufacturing exports across different provinces, primarily reflected in two dimensions: regional disparities and varying degrees of digital infrastructure progress. From a regional perspective, the theory of unbalanced development suggests that economic growth is inherently uneven across both spatial and temporal dimensions, with production factors tending to agglomerate from peripheral areas toward central regions. In China, eastern, central, and western provinces differ systematically regarding their stages of economic development, industrial structures, as well as overall development levels. These structural disparities lead to differentiated mechanisms and outcomes in how the digital infrastructure influences the technological sophistication of manufacturing exports across regions [39]. Compared with other areas, more developed eastern provinces possess stronger capacities to attract technology, capital, and skilled labor, which facilitates the optimization of digital infrastructure and consequently enhances the export of high-tech manufacturing products [40].

From the perspective of digital infrastructure development, the expansion of digital infrastructure also follows the law of diminishing marginal returns [41]. In provinces with relatively well-developed digital infrastructure, additional digital investment tends to yield decreasing marginal effects on the technological upgrading of manufacturing exports. Conversely, in provinces with weaker infrastructure, further investment may generate more significant marginal benefits. Therefore, differences in both regional economic characteristics and digital infrastructure development levels jointly shape the heterogeneous impact of digital infrastructure on manufacturing exports across provinces.

H₂: The impact of digital infrastructure on the technological complexity of manufacturing exports exhibits significant heterogeneity across provinces with different regional characteristics and levels of digital development.

Digital infrastructure facilitates technological progress within the manufacturing sector, thereby subsequently promoting the sophistication of export goods, primarily through mechanisms such as improving production efficiency and technological capability, promoting knowledge diffusion and technological iteration, and optimizing factor allocation efficiency. First, digital infrastructure establishes a critical foundational environment enabling the deployment of advanced technologies including AI, cloud platforms, and the industrial Internet, thereby strengthening firms' technological absorptive capacity and production efficiency. By utilizing digital tools to restructure production procedures and improve resource allocation, firms are able to transition from labor-reliant toward tech-intensive export products [12]. Second, the efficient information networks enabled by digital infrastructure reduce the barriers to accessing external knowledge resources and foster inter-firm technological collaboration and knowledge diffusion [42]. In digitally connected environments, firms are more likely to develop learning mechanisms and accelerate technological iteration, thus enhancing the technological content and market competitiveness of export products [13, 14]. Accordingly, the hypothesis below is formulated:

H₃: Digital infrastructure fosters the advancement of technological complexity in manufacturing exports by facilitating technological progress.

Digital infrastructure drives the technological sophistication of manufacturing exports by the intermediary function of human capital via several specific pathways. First, digital infrastructure facilitates the informatization of the education system, significantly expanding the coverage and quality of education while increasing access to knowledge accumulation and skills training for the labor force [43]. This process lays a solid human capital foundation for the structural upgrading of export products in manufacturing firms. Second, platforms built on industrial internet systems, 5G networks, and digital technologies promote high-level online skills training and experience exchange on a global scale [17]. These mechanisms continuously enhance workers' capacity for technology absorption and R&D, thereby strengthening firms' ability to upgrade the technological advancement of exported goods. Third, the convergence between digital services and manufacturing sectors has elevated the need for highly qualified personnel, accelerating the transition of labor quality structures from low-skill to high-skill occupations. This shift provides sustained support for manufacturing firms engaging in high-tech export activities [44]. Building on this foundation, this paper proposes the ensuing hypothesis:

H_{3b}: Digital infrastructure fosters the advancement of technological complexity in manufacturing exports by facilitating human capital.

Figure 1 illustrates the analytical framework highlights the direct and indirect pathways through which digital infrastructure affects export technological complexity within the manufacturing sector.

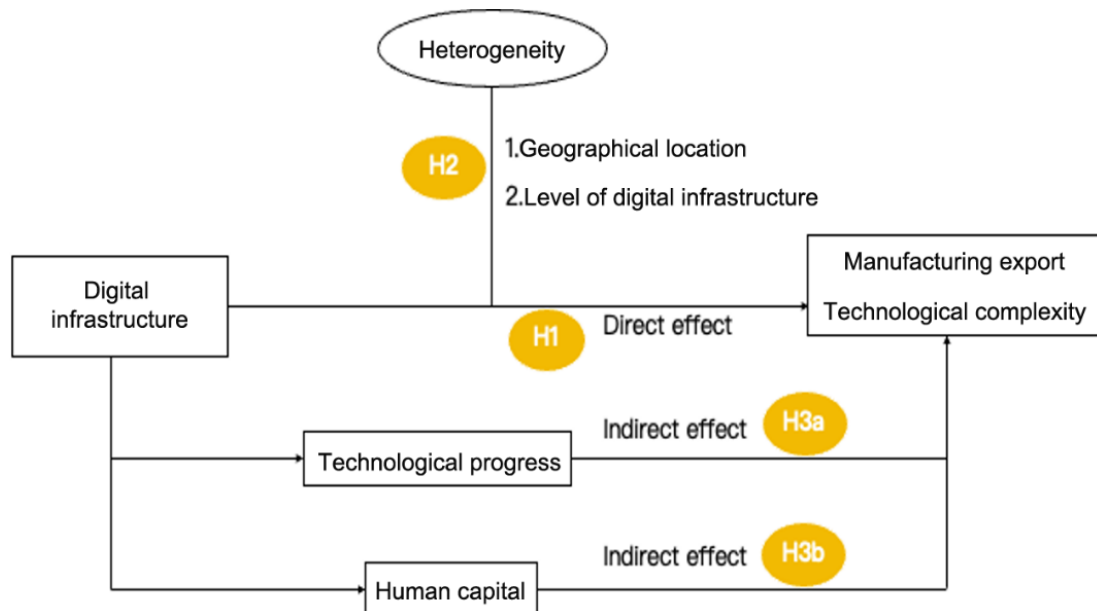


Figure 1. Research framework.

3. METHODOLOGY

3.1. Model Constructing

3.1.1. Fixed Effects Model

In line with Hypothesis H1, the following panel data model is constructed.

$$\ln ETC_{it} = \alpha_0 + \alpha_1 \ln DI_{it} + \alpha_2 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

The subscript i indicates the specific region, and t indicates the time. ETC_{it} reflects the level of technological sophistication in manufacturing exports; DI_{it} captures the extent of digital infrastructure advancement in region i during period t ; X_{it} stands for the control variable vector. μ_i and λ_t correspond to regional and temporal fixed effects, respectively; ε_{it} captures the stochastic disturbance, and α_0 is the constant term. To mitigate potential heteroscedasticity, the relevant variables are transformed using natural logarithms ($\ln$).

3.1.2. Mediation Effect Model

To empirically examine Hypothesis H2, this paper establishes the following mediation model.

$$\ln M_{it} = \beta_0 + \beta_1 \ln DI_{it} + \beta_2 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

$$\ln ETC_{it} = \gamma_0 + \gamma_1 \ln Dig_{it} + \gamma_2 \ln M_{it} + \gamma_3 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

In the Equations 2 and 3, M_{it} denotes the intermediary variable encompassing technological progress and human capital. Definitions for the other variables follow those provided in Equation 1. To evaluate the mediating pathway, this paper adopts the method proposed by Baron and Kenny [45] employing the three-step approach, the Sobel test, and the Bootstrap method.

3.2. Data Sources and Variable Specification

3.2.1. Specification of Variables

Dependent Variable: Export Technological Complexity of the Manufacturing Sector (ETC). This metric is calculated for each province based on the approach developed by Hausmann, et al. [46]. The corresponding computational formula is presented below:

$$PRODY_{jt} = \sum_i \frac{x_{ijt}/X_{it}}{\sum_i (x_{ijt}/X_{it})} Y_{it} \quad (4)$$

$$ETC_{it} = \sum_j \frac{x_{ijt}}{X_{it}} PRODY_{jt} \quad (5)$$

In Equations 4 and 5, the subscripts i , j , and t correspond to region, product type, and year accordingly. $PRODY_{jt}$ represents the degree of technological sophistication in exported manufactured product j ; X_{ijt} denotes the export volume of product j from region i in year t ; X_{it} denotes the overall export volume of region i in year t ; Y_{it} reflects the real per capita GDP for region i ; ETC_{it} captures the technological complexity embedded in manufacturing exports.

Core Independent Variable: Digital Infrastructure (DI). Based on data availability, this study measures digital infrastructure following the approach outlined in Zhao, et al. [47] utilizing a set of indicators representative of internet development conditions, selected indicators encompass internet access rates, mobile phone usage rates, broadband port availability, total length of optical fiber lines, mobile switching capacity, domain name registrations, and webpage quantities. To assign objective weights to each indicator, this paper applies the entropy method to process the raw dataset, which helps mitigate the subjectivity associated with assigning arbitrary weights.

Mediating Variables: (1) Technological Progress (Tfp): Following the approach proposed by Ding, et al. [48] this study adopts the DEA (Data Envelopment Analysis) framework to derive the Malmquist productivity index, treating 30 Chinese provincial-level regions as the basic production units. The output variable is regional GDP, while the input variables include physical capital and human capital. The DEA-Malmquist index approach is employed to estimate provincial-level TFP, which is used as an indicator representing regional technological progress. (2) Human Capital (Hum): This variable is quantified through the enrollment ratio, calculated as the share of students within the overall population, capturing the typical education level among the workforce and the human resource reserve in each region.

Control Variables: (1) Foreign Direct Investment (FDI): Estimated as the proportion of inward FDI relative to provincial GDP, reflecting a region's openness to international capital. (2) Environmental Regulation (Envir): Measured by the proportion of finalized investment for environmental treatment projects to the industrial value added of each region, capturing the stringency of local environmental regulation. (3) Physical Capital Investment (Pci): Denoting the ratio of fixed capital input relative to regional GDP, indicating capital stock intensity across provinces. (4) Financial Development (Fin): Measured using the proportion of overall credit and savings held in financial institutions against provincial GDP, indicating the financial development level across provinces. (5) Per Capita GDP (Pgdp): Calculated as regional GDP divided by the end-of-year resident population, serving as an indicator of regional economic advancement.

3.2.2. Sources of Data and Descriptive Statistics

The analysis is based on panel data from 30 provincial-level regions in China (excluding Hong Kong, Macao, Taiwan, and Tibet) covering the period from 2011 to 2023 as the study timeframe. The primary data sources include the China Statistical Yearbook, Statistical Report on Internet Development, China Industrial Statistical Yearbook, China Customs, the World Development Indicators (WDI) database, and Guoyan Net (DRCnet). The dataset comprises a balanced panel of 30 provinces from 2011 to 2023. Missing values, which were present in only a few provinces for a limited number of years, were imputed using linear interpolation. No other data cleaning procedures were performed.

All variables are available for all years, ensuring the dataset maintains its balanced panel structure. Table 1 reports the summary statistics of the core variables.

Table 1. Summary statistics for main variables.

	Variable	N	Average	Std. dev	Min.	Max.
Dependent variable	lnETC	390	2.1310	0.339	0.65	2.70
Independent variable	lnDI	390	2.5180	0.690	0.64	4.27
Mediating variable	lnTfp	390	2.8378	0.339	2.16	3.96
	lnHum	390	3.0278	0.283	2.09	3.78
Control variable	Fdi	390	1.0512	6.096	0.05	91.45
	Envir	390	3.0248	3.364	0.06	30.99
	Pci	390	0.7772	0.258	0.21	1.48
	Fin	390	3.3354	1.203	1.28	8.16
	Pgdp	390	0.9495	0.466	0.25	2.85

4. RESULT

4.1. Baseline Regression

The regression results in Table 2 assess how digital infrastructure impacts the technological sophistication of manufactured export products. Columns (1) to (6) progressively incorporate control variables to ensure a robust estimation of digital infrastructure's influence.

As demonstrated, lnDI the primary explanatory variable consistently produces a positive estimate and is statistically significant at the 1% level across all model specifications, indicating that improvements in digital infrastructure significantly enhance the technological complexity of manufacturing exports. Specifically, in Column (1), which excludes control variables, the coefficient of lnDI is 0.396. As control variables are added sequentially, the estimated coefficient ranges from 0.367 to 0.394. In the fully specified model (Column 6), the coefficient stabilizes at 0.394, suggesting that a 1% increase in digital infrastructure results in an average 0.394% increase in export technological complexity.

Regarding the control variables, FDI demonstrates a consistently positive and significant influence under all model frameworks, with estimates falling between 0.001 and 0.002. This suggests that a 1% increase in FDI stock leads to a 0.1–0.2% improvement in export technological sophistication. Environmental regulations display a negative and statistically significant coefficient across specifications, with the estimate reaching -0.013 in Column (6). This indicates that a one-unit increase in environmental regulation intensity is associated with a 1.3% decline in export technological complexity, suggesting a potential short-term trade-off between environmental governance and technological upgrading in the manufacturing export sector. Pgdp in Column (6) shows a significantly positive estimate of 0.147, suggesting that a 1% rise in the level of economic development contributes to a 0.147% increase in export complexity.

Other control variables, such as physical capital investment (Pci) and financial development (Fin), do not exhibit significant effects in the current model. Overall, R^2 statistics fall within the 0.802–0.810 interval across specifications,

demonstrating a high degree of model fit. The conclusion remains robust after controlling for various potential confounding factors, lending strong support to this study's hypothesis concerning how digital infrastructure contributes to export technological complexity in the manufacturing sector.

Table 2. Baseline regression results.

	(1)	(2)	(3)	(4)	(5)	(6)
	lnETC	lnETC	lnETC	lnETC	lnETC	lnETC
lnDI	0.396*** (6.078)	0.386*** (5.792)	0.369*** (5.482)	0.367*** (5.382)	0.376*** (5.259)	0.394*** (5.455)
Fdi		0.002*** (2.742)	0.001** (2.212)	0.002** (2.276)	0.002** (2.389)	0.002*** (2.606)
Envir			-0.010* (-1.852)	-0.011** (-1.984)	-0.011** (-1.977)	-0.013** (-2.260)
Pci				0.084 (1.094)	0.079 (1.020)	0.079 (1.019)
Fin					0.013 (0.603)	0.040 (1.460)
Pgdp						0.147* (1.900)
_cons	1.134*** (6.832)	1.158*** (6.833)	1.231*** (7.069)	1.173*** (6.993)	1.111*** (5.347)	0.839*** (3.189)
Year	Yes	Yes	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes	Yes	Yes
N	390	390	390	390	390	390
R ²	0.802	0.803	0.807	0.808	0.808	0.810

Note: Robust t-values are reported in parentheses. *** p<0.01; ** p<0.05; * p<0.1.

4.2. Robustness Checks

To assess the robustness of the baseline regression findings, this paper implements four robustness tests, as shown in Table 3. First, as presented in Column (1), the dependent variable is substituted with export scale (lnY_{ij}) in place of export technological complexity (lnETC) to examine the broader impact of digital infrastructure on manufacturing export capacity.

Findings indicate that lnDI remains significant at the 1% level, implying that digital infrastructure exerts a clearly favorable impact on export scale, thus confirming its overall promoting effect on manufacturing exports. Second, in Column (2), digital infrastructure is re-measured by applying the coefficient of variation method (ln_{di}) to assess the impact. The ln_{di} estimate retains its 1% significance, further demonstrating that the core findings are not dependent on a specific index construction method and are thus robust. Third, in Column (3), all observations from the year 2020 onwards are excluded to control for potential disturbances attributable to the COVID-19 pandemic. The outcome reveals that lnDI retains a favorable and significant estimate, implying that the pandemic did not alter the beneficial influence of digital infrastructure.

Finally, in Column (4), the four municipalities Beijing, Shanghai, Tianjin, and Chongqing are excluded to mitigate potential sample structure bias. The lnDI coefficient continues to be statistically robust, strengthening the consistency and robustness of the results. Taken together, these estimation outcomes under alternative dependent variables, different measurement approaches for the explanatory variable, and adjusted samples are broadly consistent. All findings support the conclusion that digital infrastructure contributes to the advancement of technological sophistication in manufacturing exports, thereby confirming the reliability of the benchmark estimation model.

Table 3. Robustness test results.

	(1)	(2)	(3)	(4)
	lnY _{ij}	lnETC	lnETC	lnETC
lnDI	0.455*** (4.104)		0.358*** (4.345)	0.418*** (5.224)
ln _{di}		0.444*** (5.809)		
Fdi	0.009*** (4.229)	0.002** (2.457)	0.002** (2.561)	-0.008 (-0.104)
Envir	0.010 (1.103)	-0.013** (-2.277)	-0.012** (-2.123)	-0.018*** (-2.904)
Pci	0.765*** (5.235)	0.065 (0.832)	0.147* (1.816)	0.161* (1.726)
Fin	-0.031 (-0.661)	0.039 (1.447)	0.015 (0.470)	0.173*** (3.254)
Pgdp	0.400*** (3.309)	0.162** (2.061)	-0.137 (-1.522)	0.417*** (2.776)
_cons	3.441*** (8.949)	0.625** (2.221)	1.217*** (4.285)	0.073 (0.201)
Year	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
N	390	390	338	270
R ²	0.977	0.812	0.805	0.761

Note: Robust t-values are reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

4.3. Heterogeneity Analysis

To explore the heterogeneous effects of digital infrastructure on the export technological complexity of the manufacturing sector, the sample is classified into two categories according to the regional median level of digital infrastructure namely, high-level and low-level groups. Separate estimations are conducted for each category, with results summarized in Table 4.

Table 4. Heterogeneity analysis by level of digital infrastructure.

	(1)	(2)
	lnETC	lnETC
lnDI	0.530*** (4.146)	0.449*** (5.566)
Fdi	0.001 (1.428)	0.109*** (3.304)
Envir	-0.011* (-1.799)	-0.000 (-0.012)
Pci	0.334*** (2.772)	-0.276*** (-3.409)
Fin	-0.026 (-0.527)	0.029 (1.325)
Pgdp	-0.062 (-0.363)	0.262*** (3.478)
_cons	0.853** (2.083)	0.606* (1.944)
Year	Yes	Yes
Province	Yes	Yes
N	195	195
R ²	0.823	0.862

Note: Robust t-values are reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

The estimation outcomes show that lnDI exhibits a notable and favorable influence within both subgroups. In provinces with relatively low levels of digital infrastructure (Column 1), the estimated coefficient for lnDI is 0.530,

implying that a 1% increase in digital infrastructure is associated with a 0.530% increase in export technological complexity, which reaches significance at the 1% level. In provinces with advanced digital infrastructure (Column 2), the estimated coefficient is 0.449 (meaning a 1% increase in digital infrastructure corresponds to a 0.449% increase in export technological complexity) and remains significant at the 1% level. The findings imply that, regardless of the degree of infrastructure development, digital infrastructure consistently fosters the sophistication of manufactured exports. Notably, the marginal impact of digital infrastructure appears more evident within the low-level group, implying that regions with weaker digital foundations benefit more strongly from improvements in digital infrastructure. These findings highlight that strengthening digital capacity in relatively underdeveloped regions may yield more substantial gains in export competitiveness.

In addition, to investigate how the effect of digital infrastructure differs across regions, this paper conducts group regressions based on China's eastern, central, and western regions. Table 5 displays the estimation outcomes. In the eastern region (Column 1), lnDI exhibits a favorable influence on the technological sophistication in the manufacturing sector, and the coefficient is 0.440, indicating that a 1% increase in digital infrastructure is associated with a 0.440% increase in export technological complexity, playing a clear role in driving export upgrading in eastern China. By contrast, the central region (Column 2) shows a coefficient of 0.119 for lnDI, which is statistically insignificant, implying that the facilitative role of digital infrastructure on export complexity is either unstable or limited in this area. In the western region (Column 3), the coefficient of lnDI reaches 0.592 and is significant at the 1% level, suggesting that a 1% increase in digital infrastructure leads to a 0.592% increase in export technological complexity, highlighting a stronger role of digital infrastructure on technological upgrading in exports. Overall, the effect of digital infrastructure on the technological sophistication of manufactured exports varies significantly across regions. The impact is more evident in China's eastern and western areas, while it appears to be negligible in central areas. Such disparities may stem from heterogeneity in regional development stages, industrial foundations, and digital resource endowments. These results underscore the necessity of tailoring policy design to specific regional contexts. While advancing digital infrastructure construction, greater attention should be paid to regional disparities and coordinated development.

Table 5. Heterogeneity analysis by region.

	(1)	(2)	(3)
	lnETC	lnETC	lnETC
lnDI	0.440*** (4.930)	0.119 (0.904)	0.592*** (4.042)
Fdi	0.001 (1.376)	0.104 (1.514)	-0.055 (-1.450)
Envir	-0.005 (-0.787)	0.009 (0.848)	-0.007 (-1.094)
Pci	-0.463*** (-6.409)	-0.049 (-0.431)	0.505*** (3.484)
Fin	0.044** (2.330)	0.268*** (3.570)	0.018 (0.299)
Pgdp	0.275*** (4.127)	0.756*** (2.911)	-0.341 (-1.193)
_cons	0.671* (1.944)	0.546 (1.024)	0.518 (1.086)
Year	Yes	Yes	Yes
Province	Yes	Yes	Yes
N	143	104	143
R ²	0.892	0.891	0.852

Note: Robust t-values are reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

4.4. Mediation Analysis

To explore the underlying mechanisms through which digital infrastructure affects the technological sophistication in manufacturing exports, this paper incorporates technological progress (lnTfp) and human capital (lnHum) as mediating factors. The classical three-step regression method, Sobel test, combined with Bootstrap test, are employed to assess the mediation effect. Detailed results are presented in Table 6. According to Columns (1) and (2), lnDI significantly promotes technological progress (lnTfp). Specifically, the estimated coefficient for lnDI is 0.234 ($p < 0.01$), implying that a 1% increase in digital infrastructure leads to a 0.234% increase in technological progress. Furthermore, technological progress demonstrates a significant and favorable effect on export technology sophistication (lnETC). Once the mediating factor (technological progress) is included, the direct coefficient for lnDI on lnETC decreases, suggesting that technological progress serves as a partial mediating role within this relationship. The Sobel test validates the significance of this mediation ($Z = 0.123$, $p < 0.01$), with the indirect path through technological progress accounting for 44.19% of the total impact.

Columns (3) and (4) further examine the intermediary role of human capital. The findings demonstrate that digital infrastructure (lnDI) effectively promotes human capital development, with an estimated coefficient of 0.118 ($p < 0.01$). This indicates that a 1% increase in digital infrastructure is associated with a 0.118% increase in human capital. Additionally, human capital shows a significant positive effect on the sophistication of export technology (lnETC). Similar to technological progress, when human capital is included as a mediating variable, the direct coefficient for lnDI on lnETC decreases, suggesting that human capital also acts as a partial mediator in this relationship. As indicated by the Sobel test, the estimated Z-statistic is 0.146, which is statistically significant, and the mediated path through human capital accounts for 20.27% of the overall impact. In summary, digital infrastructure enhances export technological complexity in the manufacturing sector via both direct and indirect channels, operating through the mechanisms of technological progress and human capital accumulation. These findings suggest that advancing digital infrastructure contributes to export competitiveness by fostering innovation and strengthening human capital endowments.

Table 6. Mediation analysis: Mechanisms of technological progress and human capital.

	(1)	(2)	(3)	(4)
	lnTfp	lnETC	lnHum	lnETC
lnDI	0.234*** (4.766)	0.358*** (4.932)	0.118*** (3.710)	0.326*** (4.593)
lnTfp		0.155*** (2.283)		
lnHum				0.003*** (3.211)
Fdi1	0.002 (0.861)	0.002* (1.812)	-0.002*** (-3.573)	-0.013** (-2.319)
Envir	0.003 (1.521)	-0.013** (-2.362)	0.000 (0.191)	-0.011 (-0.151)
k3	0.099** (2.296)	0.063 (0.822)	0.156*** (6.244)	0.082*** (3.217)
Fin	-0.127*** (-5.925)	0.060** (2.063)	-0.073*** (-5.668)	0.336*** (4.072)
Pgdp	0.167*** (2.860)	0.121 (1.484)	-0.329*** (-10.807)	0.575*** (4.585)
_cons	2.425*** (13.397)	0.463 (1.488)	3.166*** (29.494)	-0.981** (-2.104)
Year	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
N	390	390	390	390
R ²	0.925	0.812	0.957	0.820
Sobel Z		0.123*** (3.711)		0.146*** (3.228)
Proportion		44.190%		20.267%

Note: Robust t-values (for regression) and Sobel Z-values (for mediation) are reported in parentheses. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

Furthermore, the mediation effects are validated using the bootstrap technique, with the corresponding findings detailed in Table 7 and Table 8. The 95% confidence intervals of both indirect pathways exclude zero, thereby unequivocally confirming that the mediation effects are statistically significant. Specifically, the indirect effect of $\ln DI$ on $\ln ETC$ through $\ln Tfp$ (technological progress) is 0.1229, and its 95% confidence range is $[0.0554, 0.2168]$; while the indirect path through $\ln Hum$ (human capital) yields a coefficient of 0.1461, with the corresponding 95% CI ranging from $[0.0517, 0.2657]$. Meanwhile, the direct effects in both pathways are also significant, suggesting that digital infrastructure exerts a noteworthy partial mediating effect on the technological complexity of manufacturing exports. These findings provide further empirical support in validating the intermediary roles of technological progress and human capital, highlighting the multi-channel nature of its influence.

Table 7. Bootstrap-based estimation: Technological progress as mediator.

Effect Path	Effect	Coefficient	95% CI
$\ln DI \rightarrow \ln Tfp \rightarrow \ln ETC$	Indirect	0.1229	$[0.0554, 0.2168]$
$\ln DI \rightarrow \ln Tfp \rightarrow \ln ETC$	Direct	0.1552	$[0.0125, 0.3189]$
Mediating effect		Significant	

Table 8. Bootstrap-based estimation: Human capital as mediator.

Effect Path	Effect	Coefficient	95% CI
$\ln X \rightarrow \ln Hum \rightarrow \ln Y$	Indirect	0.1461	$[0.0517, 0.2657]$
$\ln X \rightarrow \ln Hum \rightarrow \ln Y$	Direct	0.5749	$[0.3103, 0.8696]$
Mediating effect		Significant	

5. DISCUSSION

This paper identifies that digital infrastructure substantially improves the technological complexity of manufacturing exports. The finding is consistent with theoretical anticipations concerning the contribution of the digital economy to high-quality development and is additionally supported by empirical evidence from Zhou, et al. [5] and Ganguly and Acharyya [40]. These studies suggest that the developing information infrastructure improves the efficiency of data collection, processing, and transmission, thereby enhancing firms' ability to match supply with demand, optimize production organization, and streamline export processes ultimately contributing to improvements in product technological content and added value. The underlying mechanism may lie in the characteristics of digital infrastructure as a new generation of general-purpose technology, which facilitates information flow, improves the allocation of resources, and strengthens firms' capacity for technology absorption. These functions collectively support the upgrading and optimization of export structures and contribute to the transition toward manufacturing that is more technologically advanced and higher value-added.

Heterogeneity analysis indicates that the influence of digital infrastructure tends to be stronger in areas with relatively weak digital foundations, potentially reflecting the characteristic of "increasing marginal returns to digitalization." In areas with low initial levels of digital development, additional investments are more likely to yield substantial marginal improvements, thereby creating a "latecomer advantage" or catch-up effect. Regionally, the eastern area benefits from its strong digital industrial base and a high capacity for digital integration, enabling digital infrastructure to more effectively drive structural upgrading. In contrast, the western region has gained from concentrated policy investments aimed at addressing digital infrastructure gaps and exhibits strong responsiveness to such inputs, leading to more pronounced marginal benefits from digitalization. The central region appears to lag behind in terms of both digital infrastructure development and policy attention. It lacks the mature industrial support observed in the east and has not benefited from the preferential policies targeting the west, resulting in a limited marginal impact of digital infrastructure. These findings align with existing research suggesting that the "digital dividend" is distributed unevenly across regions [49].

The mediation analysis further reveals that digital infrastructure indirectly enhances export technological complexity through two key pathways: technological progress and human capital accumulation. Research and development, intelligent manufacturing, and innovation diffusion play significant roles in driving the transformation of manufacturing exports. This finding is consistent with the viewpoints proposed by Chang, et al. [12] and Li, et al. [50] who argue that digitalization fosters firms' overall productivity and product complexity via technological progress, thereby advancing industrial value chain transformation. Meanwhile, enhancing human capital stocks also significantly contributes to the improvement of export technological sophistication, aligning with Yao [18] conclusion that "human capital development promotes export sophistication." Overall, the mediation mechanism analysis confirms the internal transmission channels through which digital infrastructure contributes to export upgrading. These findings highlight the necessity of policy initiatives aimed at concurrently advancing technological innovation capabilities and improving human capital endowments.

6. CONCLUSION, IMPLICATION AND LIMITATION

6.1. Summary of Findings

Drawing on provincial panel data from 30 regions in China over the years 2011–2023, this paper conducts an empirical investigation of how digital infrastructure influences the technological sophistication of manufacturing export activities. The findings suggest that digital infrastructure plays a substantial role in advancing the technological complexity of manufactured export goods. This effect remains robust under a variety of tests, including model alterations to both dependent and independent variables, along with the exclusion of specific years and directly administered municipalities. Heterogeneity tests show that the influence of digital infrastructure differs among regions and development stages. Within areas characterized by weaker digital foundations, the marginal effect is more pronounced, suggesting greater potential for improvement in less developed areas. In terms of regional division, significant positive influences are observed in eastern and western regions, whereas the central region shows no statistically notable effect. Mediation analysis further confirms that digital infrastructure indirectly promotes export technological complexity through two key pathways: technological progress and human capital accumulation.

These findings not only corroborate existing studies on the positive role of digital transformation in industrial upgrading [5] but also extend the literature by providing robust empirical evidence specifically on China's regional dynamics and the mediating mechanisms of technological progress and human capital accumulation in the context of manufacturing export technological sophistication.

6.2. Policy Implications

Drawing upon the preceding results, this paper offers specific policy suggestions to guide theory and practice in improving digital infrastructure deployment and strengthening export performance in manufacturing:

(1) Continue strengthening digital infrastructure construction to solidify the foundation for manufacturing transformation. Efforts should be made to accelerate investment in new forms of infrastructure, particularly in broadband networks, the industrial internet, and data centers. Expanding effective investment in these areas will facilitate the comprehensive embedding of digital infrastructure within manufacturing processes and provide solid support for upgrading export competitiveness.

(2) Promote regionally differentiated strategies to unlock the potential of the digital dividend. Targeted fiscal support and resource allocation should be intensified for central and western regions and provinces with weaker foundations. Such measures can help these areas surpass the critical development threshold, enhance the marginal returns of digital infrastructure, and promote coordinated improvement in export quality across regions.

(3) Strengthen digital empowerment mechanisms through the dual drivers of technological progress and human capital accumulation. Alongside infrastructure development, it is crucial to establish institutional environments conducive to the diffusion of innovation and the cultivation of talent. Enhancing research efficiency and educational

standards will optimize factor endowments and reinforce the endogenous competitiveness of the manufacturing sector.

(4) Improve data systems and cross-regional coordination mechanisms. A more comprehensive and standardized statistical and data-sharing system for regional digital infrastructure should be established. Cross-regional cooperation in digital industrial chains should be promoted to foster a unified, open, and competitive digital economy, thereby forming a collective force to enhance export quality.

6.3. Limitations and Future Research

While this study provides valuable insights into the relationship between digital infrastructure and the technological sophistication of manufacturing exports in China, two limitations should be noted. First, the analysis is based on provincial-level data from China, which may constrain the generalizability of the findings to other economies with different institutional and digital development contexts.

Future research could explore cross-country comparisons or examine other developing countries undergoing digital transformation. Second, although this study identifies technological progress and human capital accumulation as key mediating pathways, other mechanisms such as improvements in supply chain efficiency or market access may also play important roles. Further investigation of these channels could enrich the understanding of how digital infrastructure influences export sophistication.

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