Digital Transformation, R&D Internationalization, and Corporate Innovation Quality

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Abstract—**Digital transformation thoroughly dredges the access channels of international innovation networks and facilitates the global transfer of enterprises' R&D activities. However, there is limited research focusing on the relevance of digital transformation toward R&D internationalization, especially exploring the possible role of R&D internationalization as an enabling mechanism for businesses to participate in high-quality innovation activities under digital circumstances. Drawing on the empirical dataset of Chinese A-share-listed manufacturing enterprises in Shanghai and Shenzhen from 2012 to 2021, this study develops a mediating and multiple mediating effect model to examine how digital transformation increases the level of corporate innovation quality. The findings verify the promoting effect of digital transformation on corporate innovation quality. It is also observed that this positive impact of digitalization is more prominent in non-SOEs, enterprises that face lesser financial constraints, and those obtaining fewer government subsidies. Further investigation confirms that R&D internationalization, innovation resource, and power boundary mediate the relationship between digital transformation and corporate innovation quality. The discoveries provide an opportunity to extend R&D internationalization towards explanations of corporate high-quality innovation in the digital environment.**

Keywords—**digital transformation, Innovation quality, R&D internationalization, a mediating and multiple mediating effect model**

I. INTRODUCTION

Enterprise digital transformation uses the new generation of informative technologies to revolutionize traditional production and management modes, greatly helping them to achieve cost reduction, energy saving, and efficiency improvement. Digital transformation holds crucial significance on technological innovation, serving as both the source and solution for corporate sustainable development. Recently, the Chinese government has placed growing emphasis on implementing digital-driven development strategies (Wu *et al.*, 2022) to harness the spillover effects of the fourth scientific and technological revolution. The 20th National Congress of the Communist Party of China (CPC) points out that "under the theme of promoting high-quality development and using new-generation information technologies as a new growth engine, we will accelerate the construction of manufacturing power and digital China". Concurrently, the "14th Five-Year Plan" (FYP) also contends to forge an additional advantage of the digital economy, empowering manufacturing enterprises to upgrade and undergo digital transformation. Successful digital practice is an essential strategic choice for enterprises' sustainable

innovation and economic growth. In this sense, only when corporate entities fully use the outcomes of digital technologies will they gain innovative edges over their competitors.

After reviewing extant scholarly documents, it is found that there exists a wealth of insightful explorations and discussions regarding how innovation performance is influenced by digital transformation. Some investigations have discovered that digital transformation can eliminate the impediments to corporate innovation (Niu *et al.*, 2023) and improve the financial availability and operational flexibility of enterprises (Tian *et al.*, 2022). The adoption and integration of digital platforms are refashioning enterprises' dynamic capabilities and driving business model innovation (Xie *et al.*, 2022; Matarazzo *et al.*, 2021). Digitalization is increasingly becoming a main focus of competition and cooperation between countries and enterprises. However, knowledge is heavily lacking on the correlation between digital transformation and the quality of corporate innovation, and more focused and specific questions need to be analyzed in the future.

Amid the rapid advancement of the digital economy, an increasing number of enterprises are beginning to expand their R&D efforts internationally to source fresh expertise and technical solutions. It can be seen that the R&D internationalization strategy presents innovative behaviors within corporations in the digital background. Some research indicates that the mutual integration of digital technologies and internationalization strategies could assist enterprises in harnessing and recombining what is available at hand (Vadana *et al.*, 2021), and upgrading the value-creation capabilities in the global market. More importantly, this transformation and upgrading towards digitalization is fundamentally altering the nature of corporate innovation and giving impetus to the connection between enterprises and the external environment. Enterprises can implement their R&D activities abroad as they move toward digital transformation, which makes it possible to trigger innovation breakthroughs and technological revolutions. This allows them to get involved in research innovation activities at the frontier of the industry and market, thus increasing and even changing their core competitive skills.

The springboard theory from emerging markets is the theoretical foundation for this research, which highlights that Multinational Corporations (MNCs) from those economies can exploit international expansion as a critical springboard to conquer the inferiority of latecomers in the global market (Luo and Tung, 2007). This theory has a proper "fit" with the

enterprise R&D internationalization strategy in China. On the one hand, internationalizing R&D activities can increase the accessibility of global innovative resources for corporations, which has gradually emerged as an effective path in looking for the technological progress of the business. By doing so, enterprises can integrate different location-specific advantages into research activities and contribute to achieving favorable innovation outcomes (Hurtado-Torres *et al.*, 2018). On the other hand, the independence of firms in the industrial chain networks is affected when pushing R&D internationalization; that is, the power boundaries related to the market discourse rights may lead to change accordingly. When corporate entities undertake international R&D collaboration with local customers, competitors, universities, and public institutions (Oxley and Sampson, 2004), the weak position of enterprises in the global innovation network can be improved.

Some research on "digital transformation and corporate innovation" has accumulated a significant amount of analysis and investigation. The related mediating mechanisms between them are primarily from the perspective of analyst attention, financial constraint, corporate governance, and internal control quality (Niu *et al.*, 2023; Zhao *et al.*, 2023). However, based on digitalization, the resultant effect of R&D internationalization affecting corporate innovation is largely neglected. As a consequence, does digital transformation directly increase corporate innovation quality? If so, what is the possible role of R&D internationalization behind this effect? Whether this effect of digitalization present heterogeneous characteristics across different property rights, financing constraints, and government subsidies?

To address the aforementioned question, taking the sample of A-share-listed manufacturing enterprises in Shanghai and Shenzhen, this study surveys empirically whether enterprise digital transformation increases innovation quality and its potential influencing mechanisms of action. The marginal contributions can be summarized as the following three-fold: (1) Distinguished from previous research, this study carries out a systematic analysis of how digital transformation agitates corporate innovation quality through the lens of R&D internationalization. The findings make certain incremental contributions to the investigation of the innovative aftermath of enterprise digital transformation. (2) This study adequately unpacks the multiple mediating paths between digital transformation and corporate innovation quality. It not only proposes the mediating effect of R&D internationalization, but also inspects the differential chain impact mechanisms of R&D internationalization touching corporate innovation quality from two aspects: innovation resources and power boundaries. The research conclusions supplement new empirical evidence for manufacturing enterprises to seek the avenue of R&D internationalization-driven innovation. (3) This study extends the determinants that affect innovation quality to the domain of R&D internationalization. By linking R&D internationalization with technological innovation, this study scrutinizes that it can exert implications on corporate innovation quality via the "resource effect" and the "boundary effect".

II. Theoretical Background and Research Hypotheses

A. Digital Transformation and Corporate Innovation Quality

There is no agreement on the impact of digital transformation affecting corporate innovation quality. Some researchers suggest that enterprise digital transformation has enabled the development of innovation performance by reducing financial restrictions, improving corporate governance (Niu *et al.*, 2023). Whereas others argue that digital development modes have little positive impact, or even a negative connection with innovation performance (Usai *et al.*, 2021). Therefore, it remains unclear whether digital transformation can elevate the quality of corporate innovation.

This study conjectures that enterprise digital transformation brings a "bright" stimulating effect to their innovation quality. First and foremost, digitalization acts as an important driving force in optimizing and reforming organizational processes. The strategic imperatives arising from digital technologies not only create novel business models but also cause organizational processes to transition into an agile architecture with minimal levels of hierarchy (Verhoef *et al.*, 2021). The digital platform-based capabilities structures radically promote sustainability-oriented innovation (Wang *et al.*, 2023). Therefore, highly digitized businesses can efficiently capture significant volumes of cutting-edge technological innovation outcomes. Second, digital transformation is instrumental in enhancing the informational environment of enterprises and expediting the flow of informative factors. Based on the connectivity and communication features of digital technologies, enterprises attract more scrutiny from market analysts, promoting the information disclosure of corporate governance, decision-making, and profitability (Chen *et al.*, 2021). Among them, the diffusion of innovative information helps enterprises transmit a favorable message to external investors, which is conducive to elevating the ability to acquire financial resources and providing solid guarantees for R&D activities. Third, the borders between internal and external organizations are gradually blending as the penetration ratio of digital technologies increases. An open and flexible innovation atmosphere is established by integrating the features of reprogrammability and data homogenization offered by emerging technologies (Yoo *et al.*, 2012), enabling different participants to break communication barriers and improve the sharing of resources and information among themselves. Also, the property of digital affordances urges enterprises to convert to a multi-party collaborative entrepreneurial ecosystem (Autio *et al.*, 2018), which incurs radical innovation in cooperation patterns between them.

Hypothesis 1. A positive relationship exists between digital transformation and corporate innovation quality.

B. Mediating Role of R&D Internationalization

According to the foregoing discussion, digital transformation indeed empowers enterprises in the manufacturing industry to achieve great enhancement of innovation quality. However, how digital transformation

promotes corporate innovation quality still requires further exploration from scholars. In this vein, the internationalization strategy associated with R&D is gradually attracting attention from the academic community. Some studies indicate that against the backdrop of the digital economy, the presence of overseas R&D networks is important for elucidating how corporate technological diversification influences innovation performance (Li and Wang, 2021). Thus, this study advances the theoretical research on innovative paybacks of digital transformation by focusing on internationalization strategies related to R&D activities.

Actually, the increasing positivity of enterprise digital transformation will create more opportunities for international learning and networking (Alcácer *et al.*, 2016; Yu *et al.*, 2022), and stimulate them to get involved in the multi-agent innovation ecology system. Also, the connectivity between enterprises and the international world can be significantly enhanced owing to the application of different emerging technologies (Brynjolfsson and McAfee, 2017), which enables enterprises to utilize global open resources and then convert them into firm-specific advantages (Luo, 2021; Verbeke and Hutzschenreuter, 2021). Digital resource richness not only strengthens enterprises' management capabilities but also markedly promotes their international performance (Bertello *et al.*, 2021). In this regard, this study speculates that R&D internationalization is a reasonable alternative for enterprises to exacerbate the quality of their innovations in the digital era.

R&D internationalization appertains to the practice of multinational enterprises, which invest in overseas R&D institutions and integrate them into a universal network (Berry, 2020). This geographic R&D expansion allows enterprises to collaborate with partners from different backgrounds and improve their technological innovation skills. The various strategic advantages of enhancing foreign R&D international intensity are motivating enterprises to transmit their technological centers to other countries (Khasawneh and Dasouqi, 2017). For example, Un and Rodríguez (2018) believe that conducting overseas R&D activities plays a fundamental bridging role in increasing the cross-border knowledge reserve of overseas subsidiaries. Consistent with this, Tang *et al.* (2019) also acknowledge that R&D internationalization is an essential means of international market expansion, which has important implications for organizational learning capabilities and external resource allocation. Moreover, the R&D internationalization strategy of (eMNCs) provides evidence to unravel the springboard theory, which suggests that enterprises can obtain advanced technologies and knowledge from overseas to boost significantly their innovation performance (Hurtado-Torres *et al.*, 2018). As a priority strategy, R&D internationalization can overcome regional restrictions and ensure enterprises keep up with the forefront of industry and technology development. In such an international process, enterprises can get access to different resources beyond their home market and use them to augment innovation performance (Hsu *et al.*, 2015).

Hypothesis 2. Digital transformation accelerates the progress of R&D internationalization, thus bringing about corporate innovation quality promotion.

C. Multiple Mediating Role of R&D Internationalization, Innovation Resource and Power Boundary

Advancing digital transformation improves enterprise innovation resources and expands their power boundaries. Firstly, digital transformation has a direct impact on innovation resources. Existing studies have confirmed that the drive for businesses to undertake digital development modes is very strong because they are able to access technicians and R&D investment (Chen and Kim, 2023). After experiencing digital transformation, corporations become more adaptable and efficient and create new value propositions for innovation ecosystems (Feliciano-Cestero *et al.*, 2023). As a result, enterprises that actively participate in digital practices can enhance financing capabilities and reduce financing constraints, which is beneficial to technological processes and innovation (Niu *et al.*, 2023).

Secondly, digital transformation positively affects firms' power boundaries. The communication efficiency and quality between businesses and other economic entities can be enhanced by digitalization, acquiring more valuable information feedback (Ji *et al.*, 2023). Embedding digital technologies into organizational structure pushes enterprises to construct their innovation cooperation networks (Tang *et al.*, 2023). With the in-depth implementation of digital transformation, the effect of collaborative innovation between enterprises and external partners is significantly strengthened (Wan *et al.*, 2022). Digital technologies empower enterprises to connect with a variety of businesses in the upstream and downstream (Ji *et al.*, 2023). More importantly, the power boundary resulting from market influence will be expanded, which reflects the influence and independence of an enterprise in the industrial chain.

Hypothesis 3a. Digital transformation increases innovation resources, which can promote corporate innovation quality.

Hypothesis 3b. Enterprise digital transformation expands organizational power boundaries and then enhances their innovation quality.

Furthermore, this study considers that R&D internationalization affects enterprise innovation resources and power boundaries. On the one hand, the behavior of R&D internationalization generates resource superiority. Businesses internationalizing their R&D activities can acquire globally divergent knowledge and improve productivity performance (Mavroudi *et al.*, 2023). An international trunk of R&D teams brings the benefits of a collision of thoughts and complementary skills, improving the innovation capabilities of enterprises (Xu *et al.*, 2021). Implementing R&D internationalization has easier access to locally-bound characteristic resources, such as scientific talents and skilled R&D personnel (Mavroudi *et al.*, 2023), and expands avenues for value creation and capture. On the other hand, R&D internationalization brings about the expansion of power boundaries. The advancement of R&D internationalization helps enterprises use location-specific advantages to augment their innovation performance (Nieto and Rodríguez, 2011). R&D internationalization provides effective channels for corporations to interact with local suppliers, R&D institutions, and customers (Li and Wang, 2021). It means that firms can learn about scientific and technological advancements from university-industry

collaborations and forge alliances with suppliers to improve process efficiency (Asimakopoulos *et al.*, 2020), thus increasing the competitiveness in the international market.

Hypothesis 3c. Digital transformation increases R&D internationalization, which accumulates diverse innovation resources, and finally improves corporate innovation quality.

Hypothesis 3d. Digital transformation increases R&D internationalization, thereby expanding power boundaries, and ultimately improving corporate innovation quality.
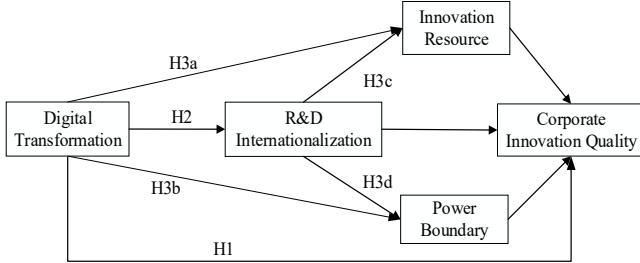

Fig. 1. Research framework and theoretical hypotheses.

III. RESEARCH METHODOLOGY

A. Sample Selection and Data Source

This study takes Chinese A-share manufacturing enterprises that are published in the Shanghai and Shenzhen Stock Exchange as the research object, and the period spans from 2012 to 2021. To asseverate the representativeness of the sample, this study further processes the consequent screening criteria: (1) exclude enterprises with the names of ST, ST*, or PT; (2) delete the enterprises that go public in 2021 and beyond; (3) eliminate enterprises delisted before 2014; (4) remove enterprises issuing B-shares and H-shares simultaneously. After matching sample data and deleting missing values of some variables, this study finally yields 16,488 valid observations covering 2,466 companies during the sample period. Specifically, this study take advantage of Python software to collect the enterprises' annual report from Cninfo Web, and then make use of textual analysis to obtain the data of independent variable digital transformation. The left-over data are mainly assembled from the Chinese Research Data Services and Chinese Stock Market and Accounting Research databases. All continuous variables in this study are winsorized at the 1% and 99% levels.

B. Variable Definitions

1) Dependent variable

Referring to prior research (Niu *et al.*, 2023), this paper logarithmically processes the total application counts for invention patents to measure corporate innovation quality. In general, there are three different types of patent, namely, model patent, design patent, and invention patent. Compared with the first two, the number of invention patents has the natural advantage of representing technological novelty (Hsu *et al.*, 2015), so as to effectively reflect the factual situation of corporate innovation. The specific calculation equation is shown as follows:

$$INV = \log(1 + InventionPatents) \qquad (1)$$

2) Independent variable

Python software is a typical technique for text analysis method, which is used to collect and arrange textual

information from annual reports of enterprises. Henceforth, This study determines to take advantage of this tool to obtain data on enterprise digital transformation. Following previous research (Niu *et al.*, 2023), the first is to select and construct two-dimensional keyword terms to evaluate the level of enterprise digital transformation. Among them, one refers to the underlying digital technologies, which consist of artificial intelligence, big data, cloud computing, and blockchain. The other is linked to the practice application level, such as smart healthcare as well as intelligent customer service, etc. In this study, we combine these two-dimensional keyword terms to construct a digital transformation dictionary. Then, fleece *Jieba Chinese test segmentation technology* in Python to extract keywords about digital transformation in annual reports. Based on this, the indicator of digital transformation (*Dig*) represented by the keyword frequency can be calculated. In addition, this study has taken logarithmic processing on the data concerned about digitalization because of the potential right-skewing problem. The specific formula structure is presented in model (2):

$$Dig = \log(1 + digtalkeywards\_count) \qquad (2)$$

3) Mediating variables

(1) R&D internationalization

The main proxy for R&D internationalization is the total volume of overseas R&D subsidiaries of an enterprise in a given year. Following existing studies (Hsu *et al.*, 2015; Zhong *et al.*, 2022), the R&D subsidiary is elucidated by the qualitative textual description of its business scope, and the relevant information originates from the CSMAR database. More specifically, if the textual description of a subsidiary's business scope includes some keywords such as "R&D", "innovation", "technology", "scientific research" or other ways, this subsidiary will be recognized as an R&D subsidiary.

(2) Innovation resource and power boundary

Based on the theoretical analysis, this study posits that R&D internationalization encourages the growth of corporate innovation quality by strengthening the absorptive capability of innovation resources and expanding the influential scope of the power boundary. In the empirical examination, this study uses R&D investment to measure the abundant extent of innovation resources (*FI*), which is calculated by the ratio of R&D expenditure to operating revenues. In the meantime, this study uses one minus the sales proportion of the firm's top five sellers to measure the power boundary (*Power*). The higher the value of the *Power* variable, the wider the power boundary of an enterprise.

4) Control variables

This study further controls for a series of enterprise characteristic factors that influence digital transformation, R&D internationalization, and corporate innovation quality, including firm age (*lnAge*), expressed by the natural logarithm of the years from an enterprise going public; firm size (*Asset*), measured by the total asset of an enterprise; financial leverage (*Lev*), measured by the proportion of the total liabilities to the total assets of an enterprise; ownership concentration (*Con10*); calculated by the ratio of top ten shareholders; firm growth (*Growth*), represented by the

proportion of net profit on operating revenue; duality (*Duality*), when the chairman and the managing director are the same people, then the value of *Duality* is 1, and 0 otherwise; firm value (*QB*), reflected by Tobin Q value.

C. Regression Models

1) Constructing basic regression model

Model (3) is used to examine whether enterprise digital transformation increases innovation quality. The coefficient α_1 reflects the total effect of digital transformation on corporate innovation quality. If α_1 is positive and significant, it suggests that enterprises conducting a digital-driven development strategy can realize the intention of high-quality innovation.

$$INV_{i,t} = \alpha_0 + \alpha_1 Dig_{i,t,} + \alpha_2 Control_{i,t} + u_i + u_{t,j} + \varepsilon_{it} \quad (3)$$

where the sub-indexes *i*, *t*, and *j* stand for the enterprise, the time, and the province' location, respectively. $INV_{i,t}$ refers to the innovation quality of enterprise *i* in the year *t*; the core explanatory variable $Dig_{i,t}$ denotes the level of enterprise digital transformation. $Control_{i,t}$ means a series of controlled variables in correlation with enterprise characteristics, including *lnAge*, *Asset*, *Lev*, *Con10*, *Growth*, *Duality*, *QB*. This study further adds the firm fixed effect (u_i) and the year and province joint fixed effects ($u_{j,t}$) into the regression model. ε_{it} represents the disturbance term.

2) Constructing a mediating effect model

In order to further clarify the influencing channel of digital transformation on the innovation quality of manufacturing enterprise, the stepwise regression model is used to demonstrate the mediating effect of R&D internationalization, namely, "digital transformation→R&D internationalization→innovation quality", as shown in models (4)–(5).

$$RDI_{i,t} = \beta_0 + \beta_1 Dig_{i,t} + \beta_2 Control_{i,t} + u_i + u_{t,j} + \varepsilon_{it} \quad (4)$$

$$INV_{i,t} = \gamma_0 + \gamma_1 Dig_{i,t} + \gamma_2 RDI_{i,t} + \gamma_3 Control_{i,t} + u_i + u_{t,j} + \varepsilon_{it} \quad (5)$$

W the coefficient β_1 of the model (4) suggests the effect of digital transformation on the mediator variable, R&D internationalization. The coefficient γ_2 of the model (5) denotes the effect of the mediator variable, R&D internationalization, on innovation quality after controlling the impact of digital transformation. In addition, the coefficient of γ_1 in the model (5) reflects the direct effect of digital transformation on innovation quality after the influence of R&D internationalization is controlled. If the test result shows that β_1 and γ_2 are significant and the sign of $\beta_{1*}\gamma_2$ (which is not equal to 0) and γ_1 are the same, then it conveys that there exists a mediating effect, otherwise, it is a masking effect.

3) Constructing a multiple mediating effect model

This study employs a multiple mediating effect model to estimate the chain impact mechanisms of digital transformation affecting corporate innovation quality. Firstly, models (6)–(7) are used to analyze two parallel mediating effects of innovation resource and power boundary, which refers to "digital transformation→innovation resource→ innovation quality" as well as "digital transformation→ power boundary → innovation quality". Secondly, models (8)–(9) simultaneously introduce R&D internationalization, innovation resource, and power boundary variables to examine the chain influencing paths of enterprise digital technology revolution, including "digital transformation→ R&D internationalization→innovation resource→ innovation quality" (*Path1*) and "digital transformation→ R&D internationalization→ power boundary →innovation quality" (*Path2*).

$$FI_{i,t} / Power_{i,t} = a_0 + a_1 Dig_{i,t} + a_2 Control_{i,t} + u_i + u_{t,j} + \varepsilon_{it} \quad (6)$$

$$INV_{i,t} = b_0 + b_1 Dig_{i,t} + b_2 FI_{i,t} / Power_{i,t} + b_3 Control_{i,t} + u_i + u_{t,j} + \varepsilon_{it} \quad (7)$$

$$FI_{i,t} / Power_{i,t} = \varphi_0 + \varphi_1 Dig_{i,t} + \varphi_2 RDI_{,t} + \varphi_3 Control_{i,t} + u_i + u_{t,j} + \varepsilon_{it} \quad (8)$$

$$INV_{i,t} = \lambda_0 + \lambda_1 Dig_{i,t} + \lambda_2 RDI_{i,t} + \lambda_3 FI_{i,t} / Power_{i,t} + \lambda_4 Control_{i,t} + u_i + u_{t,j} + \varepsilon_{it} \quad (9)$$

Among them, $FI_{i,t}$ denotes the level of innovation resource possessed by an enterprise, while $Power_{i,t}$ represents the scale of organizational power boundary. The mediating effect of these two variables is the coefficient interaction term of models (6)–(7), namely, $a_1 b_2$. At the same time, this study uses the coefficients in models (4), (8), and (9) to calculate the chain impact of *Path1* and *Path2*, and the corresponding effect value is $\beta_1 \varphi_2 \lambda_3$.

IV. EMPIRICAL TEST AND RESULT ANALYSIS

A. Digital Transformation and Corporate Innovation Quality

In accordance with model (3), this study Operates the Least Square method (OLS) to test the promotion effect of digital transformation on corporate innovation quality, and Table 1 represents the corresponding regression results. Column (1) does not control for any influencing variables and fixed effects, which examines the only effect of the core explanatory variable *Dig* on corporate innovation quality. Columns (2)–(4) further include the enterprise characteristic variables, the firm fixed effect together with the year and province joint fixed effects in that order. The coefficients of *Dig* are as follows: 0.3147, 0.2749, 0.0868, and 0.0709, all of them significantly passing the *t*-test within 1%, that is, digital transformation is positively related to corporate innovation quality. Each unit increase of corporate digital transformation variable will improve their innovation quality level by 0.3147, 0.2749, 0.0868, and 0.0709 units. The above conclusions indicate that the development of enterprise digitalization will help enhance innovation quality, and hypothesie1 is verified. This study has argued that the digital-driven strategy is an effective vehicle to advance the layout for corporate innovation. The existence of digital technologies promoting effect enables enterprises to not only improve internal governance level but also optimize resource allocation efficiency when organizing innovation activities.

Table 1. Results of the direct impact of digital transformation on corporate innovation quality

Variables	(1) INV	(2) INV	(3) INV	(4) INV
Dig	0.3147*** (0.0087)	0.2749*** (0.0077)	0.0868*** (0.0100)	0.0709*** (0.0102)
lnAge		−0.0887 (0.0865)	3.7059*** (0.1524)	1.5953*** (0.3307)
Asset		0.0044*** (0.0001)	0.0034*** (0.0002)	0.0032*** (0.0002)
Lev		0.8169*** (0.0646)	0.3985*** (0.0775)	0.4103*** (0.0789)
Con10		−0.0052*** (0.0007)	0.0023** (0.0011)	0.0009 (0.0011)
Growth		0.8122*** (0.0728)	0.2635*** (0.0607)	0.2786*** (0.0608)
Duality		−0.0607** (0.0203)	0.0158 (0.0226)	0.0240 (0.0227)
QB		−0.0172** (0.0074)	−0.0151** (0.0060)	−0.0055 (0.0069)
_cons	2.0230*** (0.0144)	1.8622*** (0.1158)	−2.0820*** (0.1922)	0.2114 (0.3663)
Firm FE	NO	NO	YES	YES
Year×Province FE	NO	NO	NO	YES
N	16,488	16,488	16,465	16,464
Adjust_R^2	0.0768	0.2473	0.7527	0.7566

Notes: Robust standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

B. Robustness Tests

1) Measurement error

(1) Alternative measure of digital transformation

According to the idea of Fang *et al.* (2023, this study reconstructs the metrics for digital transformation (*Dig_sen*) using the sentence ratio of digital transformation in an annual report. The result in column (1) of Table 2 suggests that the direct effect of digital transformation on corporate innovation quality is still significantly positive at the 1% level, which is statistically in obedience to previous discoveries.

(2) Dimension decomposition of corporate innovation quality

This study appropriates an alternative measure of corporate innovation quality by dividing the it into two sub-dimensions: namely, "autonomous innovation" (*INV_ZU*)

and "collaborative innovation" (*INV_HZ*). In this way, the relationship between digital transformation and different types of high-quality innovation activities can be clearly examined. The results of replacing the dependent variable are shown in columns (2) and (3) of Table 2. Obviously, there is no obvious difference in the significance and coefficient, which effectively confirms the assumption that corporate innovation quality can be raised through the application of digital technologies.

2) Omitting variables

Following previous practice (Fang *et al.*, 2023), column (4) in Table 2 further controls for the positive and negative text intonation in the annual report (*Test_P*, *Test_N*). Evidently, the coefficient of *Dig* suggests that digital transformation is still significantly positive related to innovation quality ($β = 0.0623$, $p < 0.01$), which is the same as the baseline regression.

3) Instrumental variable method

This study utilizes the instrumental variables least squares (IV-2SLS) method to mitigate the possible endogeneity problem arising out of reverse causality. Following existing literature (Niu *et al.*, 2023), this study selects the year-province average of digital transformation as an instrumental variable (*Average_p*) and re-estimates the regression model with the same controls. Also, the robust standard errors clustered is set at the prefecture-level cities. The second-stage regression result represented in column (5) of Table 2 suggests that the estimated coefficient of digital transformation on corporate innovation quality passes the *t*-test at the level of 1%, and the direction is positive, supporting our expectations.

4) The lagged effects of digital transformation

Columns (6)–(7) of Table 2 further take into account the lagged effects of digital transformation on innovation quality, where the estimated coefficients of different lagged effects (*L.Dig*, *L2.*Dig) remain significantly positive at the 1% and 5% level, respectively. The findings affirm that enterprise digital transformation is a precious catalyst for achieving high-quality innovation, and this promoting effect of digital transformation may last for one year to two years.

Table 2. Results of robustness tests between digital transformation and corporate innovation quality.

Variables	Measurement Error			Omitting Variables	IV-2SLS Method	The Lagged Effects	
	(1) INV	(2) INV-ZU	(3) INV-HZ	(4) INV	(5) INV	(6) INV	(7) INV
Dig_sen	5.6318*** (1.6138)						
Dig		0.0701*** (0.0107)	0.0375*** (0.0086)	0.0623*** (0.0101)	0.0605*** (0.0233)		
L.Dig						0.0432*** (0.0116)	
L2.Dig							0.0310** (0.0125)
_cons	0.2519 (0.3659)	0.4052 (0.3875)	−0.4893 (0.3208)	0.9391** (0.4316)	-	1.0632** (0.4849)	1.2326** (0.6123)
Controls	YES	YES	YES	YES	YES	YES	YES
Firm FE	YES	YES	YES	YES	YES	YES	YES
Year×Province FE	YES	YES	YES	YES	YES	YES	YES
N	16,464	16,464	16,464	16,464	16,464	13,007	10,894
Adjust_R^2	0.7562	0.7394	0.6697	0.7583	0.0293	0.7727	0.7837

Notes: Robust standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

C. Heterogeneity Analysis

1) The analysis of ownership heterogeneity

Columns (1)–(2) of Table 3 conduct the heterogeneity analysis based on different ownership. The research results of a grouped regression suggest that the technological innovation effect of enterprise digital transformation is asymmetric. Although the coefficients under different ownership are both significant and positive at the 1% and 5% confidence levels, the findings are still comparable. The absolute value of the coefficient for non-state-owned enterprises is 0.0696, which is much higher than 0.0454 for state-owned enterprises. Specifically, for every unit addition to the digital transformation index of the non-stated-owned and stated-owned enterprise, corporate innovation quality will expand by 0.0696 and 0.0454 units, respectively. As can be seen, the promoting impact of digitalization on corporate innovation quality is mainly reflected in non-SOEs, which are more likely to capitalize on different digital technologies to ennoble corporate sustainable development.

Table 3. Results of heterogeneity analysis based on different ownership, financial constraints and government subsidy

Variables	INV					
	Ownership		Financial constraint		Government subsidy	
	(1) SOEs	(2) non-SOEs	(3) FCH	(4) FCL	(5) GSH	(6) GSL
Dig	0.0454** (0.0204)	0.0696*** (0.0118)	0.0377 (0.0237)	0.0586** (0.0248)	0.0131 (0.0288)	0.0730*** (0.0148)
_cons	−0.5954 (0.9560)	0.4082 (0.4142)	2.9523 (2.6735)	−1.1651 (1.1739)	0.6597 (1.1500)	−0.8036 (0.5937)
Controls	YES	YES	YES	YES	YES	YES
Firm FE	YES	YES	YES	YES	YES	YES
Year×Province FE	YES	YES	YES	YES	YES	YES
N	3,849	12,557	3,860	4,103	2,447	8,406
Adjust_R^2	0.8289	0.7230	0.8088	0.7946	0.8340	0.7331

Notes: Robust standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

2) The analysis of financial constraint heterogeneity

The level of digital transformation may vary among enterprises confronted with different financial constraints. Thus, the research selections are further divided into two groups: high financial constraints (FCH) and low financial constraints (FCL), and the heterogeneous impacts of digital transformation on corporate innovation quality of different financial constrictions are examined. Columns (3)–(4) in Table 3 show that the regression coefficient of FCL enterprises is greater than FCH enterprises. Among them, the *Dig* coefficient of FCL business is 0.0586, which is significant. However, the technological innovation effect of digital transformation is not evident for those firms faced with higher financial constraints. The findings emphasize that the positive impact of digital transformation on corporate innovation quality will decrease as their financial constraints increase.

3) The analysis of government subsidy heterogeneity

In enterprises with different degrees of government subsidy, the impact of digital transformation on corporate innovation quality may differ. The estimated coefficient of *Dig* in column (5) of Table 3 shows that digital transformation has no significant impact in the case of higher government subsidies. Conversely, column (6) of Table 3 indicates that digital transformation positively affects corporate innovation quality in the low-government subsidies sample ($\beta = 0.0730$), which passes the 1% significance level test. With every unit increase in the digital transformation of those enterprises that obtain lower government subsidies, there will be an increment in their innovation quality by 0.0730 units. The fewer government subsidies an enterprise possesses, the better its innovation performance is.

D. Mechanism Analysis

1) Examination of the mediating effect of R&D internationalization

According to the mediating effect model, we apply it in this study to examine the mediator hypotheses of digital transformation affecting corporate innovation quality. Columns (1)–(2) of Table 4 suggest that R&D internationalization increases with the mushrooming of digital transformation, thereby enhancing corporate innovation quality. The results in column (1) reflect the extent to which digital transformation influences R&D internationalization, and the coefficient of *Dig* on *INV* is positive and significant ($\beta = 0.0154$, $p < 0.05$), suggesting that increases in international R&D investments are associated with increases in the degree of digital transformation. Moreover, column (2) reports the joint influences of digital transformation and R&D internationalization on corporate innovation quality. Among them, the direct effect of digital transformation on corporate innovation quality is 0.0703 ($p < 0.01$), while the indirect effect of R&D internationalization on corporate innovation quality is 0.0370 ($p < 0.05$), both of which pass the significance test at the 1% and 5% levels, respectively. The above findings validate the hypothesis 2: digital transformation maximizes the value of corporate innovation by increasing the scale of the R&D internationalization inputs.

Table 4. Results of mediating impact mechanisms of R&D internationalization

Variables	(1) RDI	(2) INV
Dig	0.0154** (0.0074)	0.0703*** (0.0102)
RDI		0.0370** (0.0119)
_cons	−0.5089* (0.2951)	0.2303 (0.3657)
Controls	YES	YES
Firm FE	YES	YES
Year×Province FE	YES	YES
N	16,464	16,464
Adjust_R2	0.8114	0.7568

Notes: Robust standard errors in parentheses; $^{*} p < 0.1$, $^{**} p < 0.05$, $^{***} p < 0.01$.

2) Examination of the multiple mediating effect of R&D internationalization and innovation resource

Columns (1)–(4) in Table 5 identify the chain impact mechanisms through which digital transformation can improve corporate innovation quality: by implementing an R&D internationalization strategy, thereby accumulating diverse innovation resources. Column (1) takes innovation resource as the dependent variable, and the coefficient of digital transformation is significantly positive ($\beta = 0.0007$, $p < 0.05$). Also, the results in column (2) show that the regression coefficients of innovation resource and digital transformation on corporate innovation quality are 4.4196 and 0.0679, and they are significant at the 1% level. Enterprise digital transformation can change the dilemma of poor innovation quality by increasing innovation resource inputs. Innovation resources mediate the relationship between digital transformation and innovation quality. Columns (3)–(4) are the validation of the chain mediating effect of R&D internationalization and innovation resources. From the above consequences, the value of the chain mediating effect is 0.0001, indicating that the "resource effect" of R&D internationalization promotes the positive implication of digital transformation on corporate innovation quality.

Table 5. Results of multiple impact mechanisms of R&D internationalization, innovation resource, and power boundary

Variables	R&D Internationalization and Innovation Resource				R&D Internationalization and Power Boundary			
	(1) FI	(2) INV	(3) FI	(4) INV	(5) Power	(6) INV	(7) Power	(8) INV
Dig	0.0007** (0.0002)	0.0679*** (0.0101)	0.0007** (0.0002)	0.0674*** (0.0101)	0.0023* (0.0013)	0.0705*** (0.0102)	0.0022* (0.0013)	0.0699*** (0.0102)
RDI			0.0012** (0.0004)	0.0317** (0.0116)			0.0047** (0.0017)	0.0363** (0.0119)
FI		4.4196*** (0.4313)		4.3860*** (0.4317)				
Power						0.1578** (0.0799)		0.1518* (0.0799)
_cons	0.0885*** (0.0093)	−0.1796 (0.3660)	0.0891*** (0.0093)	−0.1605 (0.3654)	0.6317*** (0.0489)	0.1117 (0.3691)	0.6341*** (0.0489)	0.1340 (0.3686)
Controls	YES	YES	YES	YES	YES	YES	YES	YES
Firm FE	YES	YES	YES	YES	YES	YES	YES	YES
Year×Province FE	YES	YES	YES	YES	YES	YES	YES	YES
N	16,464	16,464	16,464	16,464	16,464	16,464	16,464	16,464
Adjust_R2	0.8085	0.7596	0.8087	0.7597	0.8236	0.7567	0.8238	0.7568

Notes: Robust standard errors in parentheses; $^{*} p < 0.1$, $^{**} p < 0.05$, $^{***} p < 0.01$.

3) Examination of the multiple mediating effect of R&D internationalization and power boundary

This study holds that there exists another influencing mechanism for enterprises to improve technological innovation efficiency, namely, R&D internationalization can improve corporate innovation quality through the organizational power boundary expansion pathway. To delve further into the above impact mechanism, the remaining section of Table 5 examines the chain impact effect of R&D internationalization and power boundaries. As shown in columns (5)–(6), the coefficient values of digital transformation and power boundary are all significantly positive, and the mediating effect of the *Power* variable is 0.0004. The results have proved that enterprise digital transformation can expand the scope of their power boundary, while the extension of the organizational power boundary leads to an increase in the quality of corporate innovation.

In addition, columns (7)–(8) discover that R&D internationalization and power boundary play a positive and significant chain mediating effect between digital transformation and corporate innovation quality; the estimated coefficients pass the significance tests ($\beta = 0.0047$, $p < 0.05$; $\beta = 0.0363$, $p < 0.05$; $\beta = 0.1518$, $p < 0.1$). They manage to establish an interaction between the two tides of digital transformation and corporate innovation quality, revealing the international path where enterprises seize the opportunities to carry out collaborative innovation, establish their research network, and subsequently enhance competitive edges and performance gains. In other words, enterprises can effectively accelerate the international pace and rhythm of the R&D aspect through digital transformation, which makes it easier to release the facilitating effect of enterprises' market power and ultimately help them improve innovation capabilities.

V. CONCLUSIONS AND LIMITATION

A. Research Conclusions

This study utilizes a dataset of Chinese manufacturing

enterprises over the period of 2012–2021 to comprehensively investigate the impact of digital transformation on corporate innovation quality and its mechanism from an R&D internationalization perspective. The main results are as follows. To begin with, the finding reports that there is a positive relationship between digital transformation and corporate innovation quality, implying that successive digital efforts will be rewarded with more high-quality innovation outcomes. This conclusion remains consistent after various robustness tests, including measurement error, omitting variables, the endogeneity analysis, and lagged effects. The research further reveals that the technological innovation effect of digital transformation exhibits multi-dimensional heterogeneity, exerting a stronger positive influence on the innovation quality of non-SOEs, businesses with lower financial constraints, and those receiving fewer government subsidies.

Furthermore, this study establishes a mediating and multiple mediating effect model to examine the international paths through which corporate innovation quality increases with the growth in the size of digital transformation. The findings demonstrate that building on the mediating role of R&D internationalization, digital transformation can notably bolster corporate innovation quality. Enterprise R&D internationalization not only augments innovation resource availability but also broadens organizational power boundaries, thus positively playing a chain mediating effect in corporate innovation quality.

B. Limitations and Future Research

Some limitations of this study are as follows: Firstly, although the manufacturing industry is a typical representative of Chinese enterprises, the single-industry R&D international behavior of the research limits the generalization of our results to other industries. Thus, future research is required to re-examine our research hypothesis in different industries or even all enterprises. Secondly, under the condition that the data about R&D internationalization and digital transformation variables is available, future research should try to change the measurement methods of these indicators from other perspectives. Thirdly, this study has examined the influencing paths from R&D internationalization, innovation resource, and power boundary, future research could be extended by including other international attributes and contextual factors based on the current theoretical framework.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTION

Wu did the writing of paper, and conducted the software to formal analysis; Xi was also involved in writing, supervision, and funding acquisition; Li made data collection and additional adjustments; all authors had approved the final version.

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