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Research on the impact of top management team digitalization awareness of a firm's innovation output

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Abstract

This study, using panel-fixed effect and mediating effect models, examines the digitalization awareness of TMTs in Chinese listed companies from 2007 to 2021, analysing its impact on firms' innovation output, substantive innovation, and strategic innovation. Our findings indicate that TMTs' digitalization awareness significantly boosts innovation output, particularly substantive innovation. But it does not have a significant positive impact on strategic innovation. This impact is achieved through increased research and development (R&D) investment and information transparency. Furthermore, we observe that the positive impact of digitalization awareness on innovation output and substantive innovation is more significant when a firm has a high asset-liability ratio and is state-owned. However, when the proportion of largest shareholder shares is relatively high, the positive impact of digitalization awareness on innovation output and substantive innovation is relatively muted. After several tests, such as endogenity treatment of instrumental variables, model replacement, and firm fixed effects, the research conclusions in this article are still valid. These conclusions offer valuable insights for firms seeking to enhance their innovation output and for further research on TMT digitalization awareness.

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1. Introduction

Digital development has been a hot issue for the Chinese government and enterprises in recent years. In actuality, the government has issued a series of laws and regulations aimed at promoting the digitalization of enterprises. One example is the "Special Action Plan for Digital Empowerment of Small and Medium-Sized Enterprises" that was implemented in March 2020. This plan enhanced the support for digital resource services such as network, computing, and security, as well as the sharing, development, and utilization of data resources. In September 2020, the Notice on Accelerating the Digital Transformation of State-Owned Enterprises accelerated the digital transformation of state-owned enterprises and established a closed-loop management mechanism for digital transformation. In January 2022, the 14th Five-Year Plan for the Development of the Digital Economy vigorously accelerated the promotion of digital industrialization, and improved the governance system of the digital economy. In November 2022, the "Guide to Digital Transformation of Small and Medium-Sized Enterprises" helped small and medium-Sized enterprises promote digital transformation scientifically and efficiently.

In terms of theory, the existing studies mainly focus on enterprise digital transformation, but there are few literature studies on the digital awareness of top management teams (Zhang, Su, & Tong, 2023). The literature on the influencing factors of firm innovation output mainly focuses on macro policies, Confucian culture, product market competition, bank credit, firm characteristics, and executive team characteristics(Chemmanur, Kong, Krishnan, & Yu, 2019; Cho, Halford, Hsu, & Ng, 2016). Few studies have investigated the impact of digital awareness of TMT on company innovation output. So, how does TMT's digital awareness affect company's innovation output?

This article utilizes the annual report data of Chinese listed companies from 2011 to 2021 and empirically tests the impact and mechanism of digital awareness of executive teams on company innovation output using panel fixed effects (FE) model and a mediating effect model.

The main contributions of this paper include: Firstly, this paper conducts a text analysis of the Management Discussion and Analysis (MD&A) section of annual financial reports; the key words related to digitalization are captured, and the measurement indicators of TMT's digitalization awareness are constructed. In the past, questionnaires and other methods were mainly used to measure the characteristics, consciousness, or cognition of TMT, which was subjective, but the text analysis method is more objective and accurate to measure the digitalization awareness of TMT, which provides new methods and ideas for the research on digitalization awareness. Secondly, the paper distinguishes between substantive and strategic innovation in terms of the innovation output. The impact factor of innovation output is then studied empirically, considering the perspective of the TMT's digitalization awareness. This extends the existing research literature on the influencing factors of a company's innovation output, providing a more comprehensive understanding of how digitalization awareness affects innovation output and its impact (Cho et al., 2016). Thirdly, from the influencing mechanisms of R&D investment and information transparency, the impact of TMT's digitalization awareness on the innovation output is studied, and the research depth is expanded to provide relevant research for the future.

2. Theoretical Analysis and Research Hypothesis Development

In this paper, the term "TMT's awareness of digitalization" refers to the top management team's recognition and ability to acknowledge the significance of digitalization and take appropriate actions. As technology rapidly evolves and digital transformation accelerates, it is essential for the TMT to possess a sense of digitalization to adapt to the dynamically changing business environment and leverage digital technology to generate greater value.

2.1. Theoretical Analysis of TMT's Digitalization Awareness and Corporate Innovation Output

The upper echelons theory suggests that the heterogeneity of TMT has an important impact on the decision-making, such as the gender and age of TMT (Bamber, Jiang, & Wang, 2010; Yim, 2013). The cognition, attitude, and other characteristics of the top management team (TMT) are integral to its profile, and they significantly impact firm decision-making. Prior research has established that TMT heterogeneity and corporate culture exert distinct effects on product innovation and management innovation (Huffman & Hegarty, 1993). The technical orientation of TMT has improved the firm's R&D expense intensity (Daellenbach, McCarthy, & Schoenecker, 1999). Existing research on the influencing factors of firms' innovation output has primarily focused on government subsidies (Guo, Guo, & Jiang, 2016) religious culture (Adhikari & Agrawal, 2016; Ozgen, Nijkamp, & Poot, 2013) bank competition (Benfratello, Schiantarelli, & Sembenelli, 2008)chief executive officer(CEO)'s gender, age, and other characteristics (Cho et al., 2016) executive risk-taking, technical characteristics, pilot, etc (Hirshleifer, Low, & Teoh, 2012; Sunder, Sunder, & Zhang, 2017; Ting, Wang, Yang, & Tuan, 2021). However, there is limited literature that examines the impact of TMT's digitalization awareness on corporate innovation output. Therefore, this paper aims to fill this research gap by exploring the relationships between TMT's digitalization awareness and corporate innovation output.

So, how does TMT's digitalization awareness affect the firm's innovation output? Firstly, according to cognitive theory, when the senior management team or CEO lacks sufficient understanding of certain areas, there will be no strategic layout in these areas, and a lot of resources will not be invested in these areas (Cho et al., 2016; Khazanchi, Lewis, & Boyer, 2007). Conversely, if TMT or CEO focuses on certain areas, they will give a lot of support in terms of strategy, management, policies, and resources, and the company will be rapidly improving in these areas. Digital development has indeed been a pivotal topic for the Chinese government and companies in recent years. With the rapid advancement of technology, digitalization has become a key driver of economic growth and transformation. The Chinese government has been actively promoting digitalization strategies to enhance productivity, innovation, and competitiveness. Similarly, companies in China have been investing in digital technologies to stay abreast of the changing business environment and capture new opportunities. Therefore, it is essential to understand the role of TMT's digitalization awareness in driving innovation output and its impact on the company's performance. This paper aims to fill this knowledge gap by exploring the relationships between TMT's digitalization awareness and corporate innovation output. When the TMT has a stronger sense of digitalization, they pay more

attention to digital development, which can provide more human, financial, materials, and other resources for the company's digital development (Li, Maggitti, Smith, Tesluk, & Katila, 2013).When the company has more R&D capital for digitalization, its innovation ability will be stronger, which will improve innovation levels and patent output (Chemmanur et al., 2019). Secondly, the theory of information asymmetry suggests that when there is a significant gap in information availability between a company and its external stakeholders, it can create challenges in obtaining useful resources, such as funds, from external sources. When information asymmetry is high, external stakeholders may have difficulty assessing a company's true performance and potential, leading to a decrease in the availability of resources and an increase in financing costs. This can hinder a company's ability to pursue innovative opportunities and limit its growth potential. Therefore, reducing information asymmetry through effective communication and transparency can enhance a company's access to external resources, enabling it to pursue innovative projects and expand its operations (Dierkens, 1991). The stronger TMT or CEO's awareness of digitalization, the more willing they are to communicate with the outside through digital means, which improves the company's information transparency. The more transparent the company's information, the more willing creditors, such as banks, are to lend money to firm, and the lower the cost of debt financing (Bertomeu, Beyer, & Dye, 2011). Suppliers and customers will also trust the company more, and the company will be able to obtain more commercial credit, which will ease the firm's level of financing constraints (Wei & Zee, 1997), which in turn improves the company's R&D capabilities (He & Wintoki, 2016).

Some scholars divide the company's innovation output into two categories: substantive innovation and strategic innovation (Hu, Jin, Ni, Peng, & Zhang, 2023). Substantive innovation is mainly based on invention patents, which can enable firms to form core technologies in this field, thereby improving core competitiveness in this field, while strategic innovation is mainly based on appearance and utility model patents, which do not constitute the core technology in this field and cannot help firms form core advantages and core competitiveness in this field. When TMT or CEO has a stronger sense of digitalization, the higher the attention to substantive innovation, and the greater the investment of resources in substantive innovation, which in turn improves the company's substantive innovation output (Liao, Chen, Weng, & Zhu, 2023).Of course, as substantive innovation increases, so does strategic innovation. In summary, this paper proposes the following research hypotheses:

H_1: TMT's awareness of digitalization exerts a significant positive impact on firm's innovation output.

H_{1a}: TMT's awareness of digitalization exerts a significant positive impact on firm's substantive innovation output.

H_{1b}: TMT's awareness of digitalization exerts a significant positive impact on firm's strategic innovation output.

H_2: TMT's awareness of digitalization has significantly elevated the firm's R&D investment level. This heightened investment has subsequently boosted the company's (substantive, strategic) innovation output.

H_3: TMT's awareness of digitalization increases the information transparency, which in turn improves the firm's (substantive, strategic) innovation output.

2.2. Theoretical Analysis of the Moderating Effect of Asset-Liability Ratio

The asset-to-liability ratio is a significant metric for assessing a company's long-term solvency. It offers insights into the relationships between a company's assets and its liabilities. A higher asset-liability ratio generally suggests a larger proportion of assets relative to liabilities (Rauh & Sufi, 2010).The stronger the TMT's awareness of digitalization, the more R&D investment the company makes, and the more R&D funds are needed. The company's own funds generally cannot meet the needs of R&D funds, and it needs to borrow from external creditors such as banks, and firm's asset-liability ratio increases, thereby meeting firm's R&D needs and improving the firm's innovation output (Kong, 2023). At the same time, the stronger TMT's awareness of digitalization, the more funds are invested in digitalization. Due to the high risks and potential rewards associated with firm innovation, along with the extended nature of the cycle, there is increased uncertainty about future returns. As a result, creditors such as banks are reluctant to lend funds to such projects based on the uncertain nature of the returns. This reluctance to lend ultimately lowers the company's asset-liability ratio and hinders its ability to finance innovative endeavours, leading to reduced innovation output. In summary, this paper proposes the following competing hypotheses:

H_{4a}: As the asset-liability ratio increases, the positive impact of TMT's digitalization awareness on both substantive and strategic innovation output becomes more evident.

H_{4b}: Conversely, as the asset-liability ratio decreases, the positive impact of TMT's digitalization awareness on both substantive and strategic innovation output becomes less apparent.

2.3. Theoretical Analysis of the Shareholding Ratio of the Largest Shareholder Moderating Effect

Some studies have shown that the shareholding ratio of the largest shareholder has a double-edged sword effect (Boateng & Huang, 2017).On the one hand, the largest shareholder will actively supervise the firm's TMT on behalf of small and medium-sized shareholders, improve the level of corporate governance and information disclosure, and improve the TMT's awareness of digitalization, thereby improving the firm's financing ability, reducing debt financing costs, and then providing more financial support for the innovation and promoting the firm's innovation output (Kedia, Rajgopal, & Zhou, 2017). Conversely, the largest

shareholder may collude with management to "hollow out" the company to the detriment of its own benefit (Ho, Huang, & Karuna, 2020). Therefore, it does not necessarily encourage the TMT's awareness of digitalization, which reduces information transparency, reduces the company's financing ability, increases debt financing costs, and then restricts the firm's innovation output. In summary, this paper proposes the following competing hypotheses:

H5a: As the shareholding ratio of the largest shareholder increases, the positive impact of TMT's digitalization awareness on both substantive and strategic innovation output becomes more significant.

H5b: Conversely, when the shareholding ratio of the largest shareholder is lower, the positive impact of TMT's digitalization awareness on both substantive and strategic innovation output becomes less significant.

2.4 Theoretical Analysis of the Moderating Effect of Property Rights

The nature of property rights categorizes the sample into state-owned enterprises and non-state-owned enterprises. State-owned enterprises (SOEs) intrinsically possess close connections with banks and government departments. On one hand, state-owned enterprises not only pursue economic interests, but also bear additional social responsibilities, which can potentially hinder their performance (Su & Xue, 2023). If the government requires SOEs to play a leading role in digital development, it will strengthen the awareness of digitalization among the TMT of SOEs, which in turn will improve innovation output (Wang & Jiang, 2021). On the other hand, if the government does not require SOEs to play a leading role in digital development, it will weaken the TMT digitalization awareness of SOEs, which in turn will reduce the company's innovation output (Dong, Meng, Firth, & Hou, 2014). In summary, this paper posits the following competing hypotheses:

H6a: When the company is a state-owned enterprise, the positive impact of TMT's digitalization awareness on both substantive and strategic innovation output is more significant.

H6b: Conversely, when the company is a non-state-owned enterprise, the positive impact of TMT's digitalization awareness on both substantive and strategic innovation output is more evident.

3. Modelling and Basic Statistical Analysis

3.1. Modelling and Variable Definition

3.1.1. Sample Selection

Drawing from a sample of Chinese listed companies spanning the years 2007 to 2021, this study examines how the TMT's awareness of digitalization impacts innovation output. The sample selection process is as follows: Initially, samples of companies that are currently designated as special treatment (ST) or *ST are excluded. Subsequently, samples of financial and listed companies in the current year are also excluded. Afterwards, any samples with missing variable values are eliminated. Finally, 34,368 year-company matching samples were obtained. The data on TMT's digitalization awareness are derived from the text analysis of the management discussion and analysis (MD&A) in the annual report, and the other data are from the China Research Data Service Platform (CRDSP).

3.1.2. Modelling

To verify hypotheses H1*, H2*, H3*, H4*, H5*, and H6*, panel fixed effects models are constructed. In comparison to panel random effects and OLS (ordinary least squares) models, panel fixed effects models effectively address the issue of omitted variables. These variables may be constant over time but vary among individuals, or vice versa—they may be constant across individuals but change over time. By incorporating fixed effects, the models can more accurately estimate the impact of the independent variables on the dependent variable, thereby enhancing the reliability of the hypothesis testing. Equation 1 is proposed to be used to test hypotheses H1, H1a, and H1b.

$$innov_{i,t} = \alpha_0 + \alpha_1 * dfmda_{i,t} + \alpha_2 * size_{i,t} + \alpha_3 * level_{i,t} + \alpha_4 * mb_{i,t} + \alpha_5 * roa_{i,t} + \alpha_6 * shrcr1_{i,t} + \alpha_7 * djg_{i,t} + \alpha_8 * ip_{i,t} + \alpha_8 * big4_{i,t} + \alpha_9 * dual_{i,t} + \alpha_{10} * state_{i,t} + \alpha_{11} * year_{i,t} + \alpha_{12} * ind_{i,t} + \mu \quad (1)$$

The "innov" variable in Equation 1 shows the output of innovation. It includes things like the number of patent applications (Npat), the number of invention patent applications (Ninv), the number of patent citations (Cited), the number of appearance patent applications (Ndes), and the number of utility model patent applications (Nuti). Dfmda is an independent variable that indicates TMT's awareness of digitalization. The control variables in the model include firm size (Size), asset-liability ratio (Level), market capitalization book ratio (Mb), return on assets (Roa), shareholding ratio of the largest shareholder (Shrcr1), total number of board of directors, board of supervisors, and shareholders' meeting (Djg), shareholding ratio of institutional investors (Is), whether the company uses the services of the big4 accounting firms (Big4), whether the chairman and general manager are the same person (Dual), whether the company is a state-owned enterprise (State), and dummy variables for year and industry to control for any potential confounding effects (Sunder et al., 2017).

To empirically test the mediating effects of R&D investment (H2) and information transparency (H3), additional Equations 2 and 3 were constructed.

$$rdp(itrans)_{i,t} = \alpha_0 + \alpha_1 * dfmda_{i,t} + \alpha_2 * size_{i,t} + \alpha_3 * level_{i,t} + \alpha_4 * mb_{i,t} + \alpha_5 * roa_{i,t} + \alpha_6 * shrcr1_{i,t} + \alpha_7 * djg_{i,t} + \alpha_8 * ip_{i,t} + \alpha_8 * big4_{i,t} + \alpha_9 * dual_{i,t} + \alpha_{10} * state_{i,t} + \alpha_{11} * year_{i,t} + \alpha_{12} * ind_{i,t} + \mu \quad (2)$$

$$inovo_{i,t} = \alpha_0 + \alpha_{11} * dfmda_{i,t} + \alpha_{12} * rdp(itrans)_{i,t} + \alpha_2 * size_{i,t} + \alpha_3 * level_{i,t} + \alpha_4 * mb_{i,t} + \alpha_5 * roa_{i,t} + \alpha_6 * shrcr1_{i,t} + \alpha_7 * djg_{i,t} + \alpha_8 * ip_{i,t} + \alpha_8 * big4_{i,t} + \alpha_9 * dual_{i,t} + \alpha_{10} * state_{i,t} + \alpha_{11} * year_{i,t} + \alpha_{12} * ind_{i,t} + \mu \quad (3)$$

In Equations 2 and 3, the mediating variables are R&D investment (rdp) and information transparency (itrans).

To test the moderating effects of the asset-liability ratio (H4*), the shareholding ratio of the largest shareholder (H5*), and the nature of property rights (H6*), a fourth Equation 4 is established.

$$inovo_{i,t} = \alpha_0 + \alpha_{11} * dfmda_{i,t} + \alpha_{12} * dfmda_{i,t} * level(shrcr1/state)_{i,t} + \alpha_2 * size_{i,t} + \alpha_3 * level_{i,t} + \alpha_4 * mb_{i,t} + \alpha_5 * roa_{i,t} + \alpha_6 * shrcr1_{i,t} + \alpha_7 * djg_{i,t} + \alpha_8 * ip_{i,t} + \alpha_8 * big4_{i,t} + \alpha_9 * dual_{i,t} + \alpha_{10} * state_{i,t} + \alpha_{11} * year_{i,t} + \alpha_{12} * ind_{i,t} + \mu \quad (4)$$

3.1.3. Variable Definitions

Table 1 shows the definitions of dependent variables, independent variables, mediating variables, and control variables.

Table 1. Definitions of dependent variables, independent variables and other variables.

Name	Definitions
Npat	Innovation output is measured as the total number of patents applied for by the firm in the current year.
Ninv	Substantial innovation output 1, the total number of invention patents applied for by firm in the current year.
Ndes	Strategic innovation output1, the total number of appearance patents applied for by firm in the current year.
Nuti	Strategic innovation output 2, the total number of utility model patents applied for by firm in the current year.
Cited	Substantial innovation output2 is measured as the number of citations of the firm's patents.
Dfmda	TMT digitalization awareness, management discussion and analysis (MD&A) in the annual report for text analysis, using artificial intelligence, cloud computing, big data, block chain, digital applications and other keywords to capture, measured by the total number of keywords.
Size	Firm scale, the total assets of firm are taken as the natural logarithm.
Level	Asset-liability ratio, divided by total liabilities by total assets.
Mb	Market capitalization-to-book ratio is the ratio of a firm's market capitalization to its book value at the end of the year.
Roa	Return on assets (ROA) is a financial performance measure that represents the profit generated by a firm from its total assets.
Shrcr1	The shareholding ratio of the largest shareholder is the proportion of shares held by the largest shareholder in a company. It is calculated by dividing the number of shares held by the largest shareholder by the total number of shares outstanding.
Djg	The total number of meetings, which includes board meetings, board of supervisor's meetings, and general meetings of shareholders, is often measured using the natural logarithm.
Is	Institutional investor shareholding, the total number of shares held by institutional investors divided by the total number of shares outstanding.
Big4	Whether a company is one of the four major international accounting firms can be denoted using a binary value: 1 if the company is a member of the Big Four, and 0 otherwise.
Dual	If the chairman and the general manager are the same person, the value is 1; otherwise, the value is 0.
State	If the company is a state-owned enterprise, the value is 1; otherwise, the value is 0.
Ind	Dummy variable for industry.
Year	Dummy variable for year.
Rdp	R&D expenditure, R&D expenditure as a percentage of principal operating revenue.
Itrans	Information transparency, the level of transparency of firm information published by the Shanghai and Shenzhen stock exchanges.

3.2. Descriptive Statistical Analysis of Variables

Table 2 is a descriptive statistical analysis of the variables. The mean value of the number of patent applications (Npat) was 18.79, and the standard deviation of the sample was 253.3, indicating a high degree of variation among the companies' patent application numbers. The maximum value was 16,934, while the

minimum was 0, indicating that the majority of companies did not apply for patents. Therefore, the number of patent applications among the companies in the sample varied significantly. The mean value of the number of invention patent applications (Ninv) was 5.938, indicating a typical level of patent applications in the sample. However, the standard deviation of 99.06 highlights a significant variation among the companies' patent application numbers. The maximum value reached 8,214, while the minimum was 0, indicating that the number of patent applications among the companies in the sample varied widely. The mean value of the number of design patent applications (Ndes) was 0.515, the standard deviation was 7.635, and the maximum and minimum values were 556 and 0, respectively, indicating that most companies did not apply for design patents, and the number of design patent applications among the companies in the sample varied significantly. The mean value of the number of utility patent applications (Nuti) is 1.955, indicating a typical level of utility patent applications in the sample. However, the standard deviation of 22 highlights a significant variation among the companies' utility patent application numbers. The maximum value reached 1,710, while the minimum was 0, indicating that the number of utility patent applications among the companies in the sample varied widely. In conclusion, most companies do not apply for utility patents, and the number of utility model patent applications for each firm varies significantly.

The mean value of the number of patents Cited (Cited) was 69.80, but the standard deviation was as high as 823.3, indicating a wide variation in the number of patents cited by different companies. The maximum value reached 58,794, while the minimum was 0, highlighting the significant differences in patent citation practices among the companies in the sample. The mean value of Dfmda was 0.831, with a standard deviation of 1.141. The maximum and minimum values were 4.317 and 0, respectively, indicating that the Dfmda values also varied widely among different companies. The average asset-liability ratio (Level) of the companies in the sample was 0.415, with a standard deviation of 0.204. The maximum and minimum values were 0.870 and 0.050, respectively, indicating that the asset-liability ratio of Chinese listed companies is generally high, but there is still significant variation among different companies. The mean value of return on assets (Roa) is 0.053, with a standard deviation of 0.041. The minimum and maximum values are 0 and 0.208, respectively, indicating that the return on assets of Chinese listed companies is generally low. The mean value of the shareholding ratio of the largest shareholder (Shrcr1) is 0.353, with a standard deviation of 0.15. The minimum and maximum values are 0.088 and 0.75, respectively, indicating that the shareholding ratio of the largest shareholder of Chinese listed companies is relatively high. The mean value of institutional investor shareholding (Is) is 0.363, with a standard deviation of 0.243. The minimum and maximum values are 0 and 0.879, respectively, indicating that the shareholding ratio of institutional investors in Chinese listed companies is also relatively high. The mean value of dual is 0.274, with a standard deviation of 0.446. The maximum and minimum values are 1 and 0, respectively, indicating that approximately 27.4% of Chinese listed companies have the same person serving as chairman and general manager. The mean value of state-owned enterprises is 0.326, with a standard deviation of 0.469. The maximum and minimum values are 1 and 0, respectively, indicating that approximately 32.6% of listed companies are state-owned enterprises.

Table 2. Results of descriptive statistical.

Variable	Sample	Mean	Std.	Min.	25th	Median	75th	Maxi.
Npat	34,368	18.790	253.300	0	0	0	0	16934
Ninv	34,368	5.938	99.060	0	0	0	0	8214
Ndes	34,368	0.515	7.635	0	0	0	0	556
Nuti	34,368	1.955	22	0	0	0	0	1710
Cited	34,368	69.800	823.300	0	0	0	18	58794
Dfmda	34,368	0.831	1.141	0	0	0	1.386	4.317
Size	34,368	22.110	1.305	19.740	21.16	21.910	22.850	26.160
Level	34,368	0.415	0.204	0.050	0.250	0.409	0.569	0.870
Mb	34,368	0.617	0.243	0.116	0.432	0.616	0.799	1.156
Roa	34,368	0.053	0.0410	0	0.022	0.044	0.073	0.208
Shrcr1	34,368	0.353	0.150	0.088	0.235	0.334	0.456	0.750
Djg	34,368	2.709	0.370	1.792	2.485	2.708	2.944	3.584
Is	34,368	0.363	0.243	0	0.141	0.360	0.556	0.879
Big4	34,368	0.062	0.241	0	0	0	0	1
Dual	34,368	0.274	0.446	0	0	0	1	1
State	34,368	0.326	0.469	0	0	0	1	1

3.3. Grouping Test of Mean and Median Difference (TMT Digitalization Awareness Grouping)

The results of the TMT digitization awareness grouping test are shown in Table 3. Panel A is the result of the grouping test of the innovation output, and the mean values of Npat, Ninv, Ndes, Nuti, and Cited are 11.63, 3.106, 0.350, 1.438, and 43.54, respectively, in the sample group with low TMT awareness of digitalization. In the sample group with high TMT digitalization awareness, the mean values of Npat, Ninv, Ndes, Nuti, and Cited were 31.85, 11.11, 0.815, 2.900, and 117.7, respectively, and the T values of the mean

difference test were -20.221***, -8.002***, -0.464***, -1.462*** and -74.190***, respectively. The findings suggest that TMT's awareness of digitalization is significantly and positively associated with various indicators of the company's innovation output, aligning with the hypotheses. The medians for Npat, Ninv, Ndes, Nuti, and Cited were 0, 0, 0, 0, and 0, respectively. In the sample group with high digitalization awareness of TMT, the mean values of Npat, Ninv, Ndes, Nuti, and Cited were 0, 0, 0, 0 and 1, respectively, and the Z-values of the median difference test were 98.645***, 92.523***, 167.613***, 52.232*** and 221.821***, respectively. The results indicate that the TMT's awareness of digitalization is strongly and positively associated with indicators of innovation output, aligning with the initial hypothesis.

In Panel B, compared with the sample group with a higher awareness of TMT digitalization, mean and median values of Size, Roa, Djg, and Is, Big4, Dual in the sample of a lower awareness of TMT digitalization are small, and they are significant differences.

In contrast, the mean and median values of level, mb, shrcr1, and state in the sample group with low TMT digitalization awareness are higher than those in the group with higher TMT digitalization awareness, with significance levels ranging from 1% to 10%.

Table 3. Group test results of Dfmda.

Variable	TMT's awareness of digitalization (Low)			TMT's awareness of digitalization (High)			Mean difference (T)	Median difference (Z)
	N	Mean	Median	N	Mean	Median		
Panel A dependent variable								
Npat	22205	11.630	0	12163	31.850	0	-20.221***	98.645***
Ninv	22205	3.106	0	12163	11.110	0	-8.002***	92.523***
Ndes	22205	0.350	0	12163	0.815	0	-0.464***	167.613***
Nuti	22205	1.438	0	12163	2.900	0	-1.462***	52.232***
Cited	22205	43.540	0	12163	117.700	1	-74.190***	221.821***
Panel B controls variables								
Size	22205	22.040	21.850	12163	22.230	22.040	-0.185***	114.603***
Level	22205	0.422	0.418	12163	0.402	0.391	0.020***	67.998***
Mb	22205	0.625	0.627	12163	0.601	0.594	0.025***	68.744***
Roa	22205	0.052	0.0430	12163	0.054	0.046	-0.002***	34.013***
Shrcr1	22205	0.358	0.340	12163	0.344	0.321	0.014***	55.936***
Djg	22205	2.700	2.708	12163	2.726	2.708	-0.027***	14.147***
Is	22205	0.358	0.351	12163	0.372	0.377	-0.014***	28.797***
Big4	22205	0.060	0	12163	0.065	0	-0.005*	3.679*
Dual	22205	0.250	0	12163	0.318	0	-0.068***	182.251***
State	22205	0.358	0	12163	0.267	0	0.091***	295.667***

Note: *, and *** in the table represent correlation at the 10%, and 1% significance levels, respectively.

3.4. Pearson and Spearman Correlation Analysis of Variables

We can see the results of Pearson and Spearman correlation tests on Table 4 to see how innovation output (Npat, Ninv, Ndes, Nuti, and Cited) and TMT digitalization awareness (Dfmda) are related. The table highlights the correlation coefficients and significance levels for each variable pair, providing insights into the relationships between these variables.

The results of Pearson correlation analysis are shown in the triangle region in the lower left, and the results of Spearman correlation analysis are shown in the triangle region in the upper right. The results from Pearson and Spearman correlation analysis Table 4 indicates that innovation output variables (Npat, Ninv, Ndes, Nuti, and Cited) exhibit a significant positive correlation with TMT digitalization awareness (Dfmda) at the 1% significance level.

The correlation coefficient between the company's innovation output and the control variables is less than 0.3, indicating that there is no significant multicollinearity issue among innovation output, TMT digitalization awareness, and the control variables. This suggests that the relationships between these variables are independent and not strongly influenced by multicollinearity.

Among the control variables, the company's innovation output is significantly positively correlated with the firm's size, asset-liability ratio, market capitalization-to-book ratio, and institutional investor shareholding ratio, whether it is significantly negatively correlated with Big4, Dual, and State is at the 10% level, but there is no significant correlation with other variables.

Table 4. Pearson and Spearman correlation analysis among variables.

Variable	Serial number	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Npat	(1)	1	0.643***	0.412***	0.516***	0.238***	0.069***	-0.008	-0.081***
Ninv	(2)	0.784***	1	0.442***	0.679***	0.207***	0.064***	-0.065***	-0.116***
Ndes	(3)	0.103***	0.093***	1	0.573***	0.080***	0.086***	-0.053***	-0.073***
Nuti	(4)	0.136***	0.099***	0.494***	1	0.113***	0.045***	-0.091***	-0.101***
Cited	(5)	0.359***	0.214***	0.020***	0.012*	1	0.079***	0.075***	-0.048***
Dfmda	(6)	0.049***	0.055***	0.040***	0.032***	0.040***	1	0.063***	-0.098***
Size	(7)	0.111***	0.074***	0.006	0.019***	0.122***	0.032***	1	0.498***
Level	(8)	0.032***	0.021***	-0.005	-0.001	0.050***	-0.109***	0.494***	1
Mb	(9)	0.025***	0.002	-0.023***	-0.017**	0.032***	-0.114***	0.517***	0.353***
Roa	(10)	0.007	0.013*	0.028***	0.026***	-0.008	0.037***	-0.120***	-0.395***
Shrcr1	(11)	0.005	-0.006	0.009	0.0099	-0.006	-0.110***	0.191***	0.063***
Djg	(12)	0.007	0.004	0.002	-0.005	0.028***	0.041***	0.183***	0.236***
Is	(13)	0.041***	0.025***	0.015**	0.019***	0.044***	-0.018***	0.461***	0.223***
Big4	(14)	0.075***	0.036***	0.016**	0.015**	0.114***	-0.012*	0.348***	0.107***
Dual	(15)	0.013*	0.018**	0.022***	0.019***	0.010	0.117***	-0.169***	-0.165***
State	(16)	0.019***	0.003	-0.020***	-0.024***	0.031***	-0.157***	0.344***	0.301***
Variable		(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
Npat	(1)	-0.048***	0.046***	-0.024***	-0.013*	-0.004	-0.004	0.044***	-0.035***
Ninv	(2)	-0.067***	0.063***	-0.032***	-0.027***	-0.033***	-0.014**	0.054***	-0.077***
Ndes	(3)	-0.054***	0.054***	-0.012*	-0.003	-0.019***	-0.011*	0.048***	-0.065***
Nuti	(4)	-0.054***	0.050***	-0.028***	-0.011*	-0.054***	-0.029***	0.057***	-0.088***
Cited	(5)	-0.026***	0.038***	-0.010	0.001	0.039***	0.026***	0.039***	-0.043***
Dfmda	(6)	-0.097***	0.061***	-0.094***	0.020***	0.012*	-0.001	0.115***	-0.152***
Size	(7)	0.489***	-0.142***	0.148***	0.168***	0.452***	0.278***	-0.179***	0.326***
Level	(8)	0.354***	-0.436***	0.057***	0.230***	0.226***	0.108***	-0.166***	0.299***
Mb	(9)	1	-0.322***	0.162***	0.091***	-0.017**	0.139***	-0.112***	0.209***
Roa	(10)	-0.351***	1	0.076***	-0.075***	-0.008	0.016**	0.097***	-0.182***
Shrcr1	(11)	0.172***	0.071***	1	-0.013*	0.258***	0.125***	-0.051***	0.217***
Djg	(12)	0.096***	-0.075***	-0.017**	1	0.024***	0.036***	-0.016**	0.017**
Is	(13)	-0.001	0.027***	0.273***	0.023***	1	0.182***	-0.176***	0.331***
Big4	(14)	0.142***	0.021***	0.137***	0.038***	0.195***	1	-0.059***	0.152***
Dual	(15)	-0.114***	0.081***	-0.058***	-0.015**	-0.176***	-0.059***	1	-0.289***
State	(16)	0.216***	-0.158***	0.218***	0.017**	0.332***	0.152***	-0.289***	1

Note: *, **, and *** in the table indicate correlation at the 10%, 5%, and 1% significance levels, respectively.

4. Analysis of the Empirical Results of the Impact of TMT's Digitalization Awareness on the Company's Innovation Output

4.1. Basic Regression Analysis: Panel Fixed-Effect Model Regression

Table 5 presents the outcomes of a fixed-effect panel regression analysis examining the influence of TMT's digitalization awareness on the company's innovation output. The results in column (1) reveal a strongly positive correlation between TMT's digitalization awareness (Dfmda) and the total number of patent applications (Npat) at the 1% significance level. Furthermore, the regression coefficient carries significant economic implications. An increase of 1 unit in standard deviation of TMT's digitalization awareness translates into a surge of 1744.78 in the total number of patent applications, amounting to approximately 92.857 times the average Npat. Table 5 shows the outcomes of a fixed-effect panel regression analysis that looked at how TMT's awareness of digitalization affected different types of innovation. The outcomes in column (2) indicate a significant positive correlation between TMT's digitalization awareness (Dfmda) and invention patent applications (Ninv) at the 1% significance level. Furthermore, the regression coefficient carries significant economic implications. An increase of 1 unit in standard deviation of TMT's digitalization awareness leads to an increase of 309.76 in the total number of invention patent applications, which is approximately 52.166 times the average Ninv. Columns (3) and (4) indicate that TMT's awareness of digitalization is negatively associated with Ndes and Nuti, although the relationships are not statistically significant. Column (5) reveals a significant positive correlation between TMT's digitalization awareness (Dfmda) and the number of patents cited (Cited) at the 1% level. Additionally, the regression coefficient carries significant economic implications. An increase of 1 unit in standard deviation of TMT's digitalization awareness leads to an increase of 17,800.08 in the number of patents cited, which is approximately 255.02 times the average Cited. The above results support the assumptions H1 and H1a, but do not support H1b. It shows that the TMT's digitalization awareness has improved innovation output (number of patent

applications), mainly improved the company's high-quality innovation output (the number of invention patent applications and the number of patents cited), but did not improve the company's low-quality innovation output (design and utility patents).

Table 5. Regression analysis of the impact of TMT's digitalization awareness on innovation output.

Variable	(1)	(2)	(3)	(4)	(5)
	Npat	Ninv	Ndes	Nuti	Cited
Dfmda	6.888***	3.127***	-0.091	-0.099	21.620***
	(3.385)	(3.778)	(-1.529)	(-0.657)	(3.943)
Size	3.651	2.754**	-0.036	-0.032	14.411
	(1.062)	(1.971)	(-0.358)	(-0.125)	(1.557)
Level	-9.714	-5.776	1.155***	2.148**	7.582
	(-0.717)	(-1.048)	(2.924)	(2.132)	(0.208)
Mb	6.327	-1.289	-0.462	-1.542*	103.024***
	(0.578)	(-0.289)	(-1.449)	(-1.895)	(3.492)
Roa	29.199	9.867	0.031	-3.048	305.261**
	(0.616)	(0.512)	(0.023)	(-0.866)	(2.391)
Shrcr1	-5.065	-4.777	0.428	2.271	-37.363
	(-0.239)	(-0.554)	(0.693)	(1.441)	(-0.654)
Djg	-3.190	-1.497	0.071	0.001	-2.007
	(-0.664)	(-0.766)	(0.509)	(0.003)	(-0.155)
Is	-11.290	-6.227*	-0.054	0.408	97.872***
	(-1.265)	(-1.715)	(-0.206)	(0.615)	(4.070)
Big4	-6.521	-4.721	0.709**	1.073	1.453
	(-0.552)	(-0.982)	(2.059)	(1.222)	(0.046)
Dual	-4.006	0.209	-0.168	-1.181***	16.573
	(-0.880)	(0.113)	(-1.264)	(-3.492)	(1.352)
State	-17.598**	-10.464***	-0.141	-0.349	65.027***
	(-1.983)	(-2.899)	(-0.545)	(-0.531)	(2.720)
Constant	-59.465	-44.554	0.408	1.138	-360.908*
	(-0.867)	(-1.596)	(0.204)	(0.223)	(-1.952)
Year/Ind	Control	Control	Control	Control	Control
Number	34368	34368	34368	34368	34368
Overall_R2	0.003	0.003	0.003	0.005	0.009
F value	3.849	3.373	3.543	5.809	10.611

Note: *, **, and *** in the table indicate correlation at the 10%, 5%, and 1% significance levels, respectively. In parentheses is the value of the t-statistical.

4.2. Empirical Test of the Impact Mechanism of R&D Expenses

Table 6 presents the results of the mediating effect of TMT's digitalization awareness on the company's innovation output through R&D expenses (inputs). As indicated in Table 5, there is no significant correlation between the company's low-quality innovation output (the number of appearance patents and utility patents) and the TMT's digitalization awareness. Therefore, it can be inferred that the mediating effect of R&D expenses on the relationships between TMT's digitalization awareness and the company's innovation output is not significant in this case. This suggests that while TMT's digitalization awareness may have a positive impact on high-quality innovation outputs (such as invention patents and cited patents), it does not significantly influence low-quality outputs through R&D expenses. This paper does not need to examine the mediating effect of TMT's digitalization awareness on the low-quality innovation output.

The results in column (1) of Table 6 indicate a significant positive correlation between TMT's digitalization awareness and R&D expenses at the 1% level. This suggests that TMT's digitalization awareness has led to increased investment in R&D. There is a big positive relationship between TMT's awareness of digitalization and innovation output (number of patent applications) (coefficient of 10.2327, t value of 6.767) and R&D expenses (input; coefficient of 1.3968, t value of 3.229). When combined with the results from Table 5 and Table 6, it appears that R&D expenses play a partial mediating role in the impact of TMT's digitalization awareness on innovation output. The Sobel, Goodman-1, and Goodman-2 tests provide Z values of 3.214, 3.212, and 3.215, respectively, indicating that some of the mediating effects of R&D expenses are significant at the 1% level. The ratio of the mediating effect to the total effect is 0.0766279, and the proportion of the mediating effect to the direct effect is 0.08298703. Furthermore, to avoid the requirement of normal distribution on the Sobel test, the Bootstrap cycle 1000 times method is used to re-test the mediating effect model. The Z-value of the indirect effect r(ind_eff) is 6.41, and the Z-value of the direct effect r(dir_eff) is 3.14. These findings support the hypothesis that R&D investment plays a partial mediating

role in the impact of TMT's digitalization awareness on innovation output (number of patent applications), and support hypothesis H2.

The results in column (3) of Table 6 indicate TMT's digitalization awareness significantly positively influences high-quality innovation output (the number of invention patent applications) at the 1% level. This suggests that TMT's digitalization awareness has a positive impact on high-quality innovation outputs. Column (3) also shows that high-quality innovation output is significantly positively correlated with R&D expenses (input) at the 1% level. When combined with the results from Table 5 and Table 6, it appears that R&D expenses play a partial mediating role in the impact of TMT's digitalization awareness on high-quality innovation output. The Sobel, Goodman-1, and Goodman-2 tests provide Z values of 2.682, 2.68, and 2.683, respectively, indicating that some of the mediating effects of R&D expenses are significant at the 1% level. The ratio of the mediating effect to the total effect is 0.05604844, and the proportion of the mediating effect to the direct effect is 0.05937639. Furthermore, to avoid the requirement of normal distribution on the Sobel test, the Bootstrap cycle 1000 times method is used to re-test the mediating effect model. The Z-value of the indirect effect r(ind_eff) is 4.38, and the Z-value of the direct effect r(dir_eff) is 3.66. These findings support the hypothesis that R&D expenses play a partial mediating role in the impact of TMT's digitalization awareness on high-quality innovation output (the number of invention patent applications) and support hypothesis H2.

Table 6. Empirical test results of R&D expenses impact channel.

Variable	(1)	(2)	(3)	(4)
	Rdp	Npat	Ninv	Cited
Dfmda	0.608***	10.233***	4.682***	33.598***
	(32.715)	(6.767)	(7.880)	(6.899)
Rdp	-	1.397***	0.457***	8.686***
		(3.229)	(2.691)	(6.235)
Size	0.180***	27.857***	8.844***	97.359***
	(7.961)	(15.347)	(12.401)	(16.655)
Level	-4.798***	-5.799	2.062	10.866
	(-42.638)	(-0.627)	(0.567)	(0.365)
Mb	-2.997***	-30.276***	-15.497***	-53.994*
	(-27.592)	(-3.441)	(-4.482)	(-1.905)
Roa	-5.897***	30.996	20.994	-4.221
	(-11.984)	(0.784)	(1.352)	(-0.033)
Shrcr1	-0.867***	-16.993*	-6.290	-168.779***
	(-7.012)	(-1.714)	(-1.615)	(-5.286)
Djg	0.168***	-10.368***	-3.811**	2.314
	(3.392)	(-2.610)	(-2.442)	(0.181)
Is	-0.648***	-13.854*	-5.887**	-34.399
	(-7.135)	(-1.903)	(-2.058)	(-1.467)
Big4	0.293***	41.890***	4.183*	273.549***
	(3.859)	(6.891)	(1.751)	(13.972)
Dual	0.473***	11.458***	4.131***	47.978***
	(11.783)	(3.551)	(3.259)	(4.618)
State	-0.239***	1.092	-0.495	4.918
	(-5.547)	(0.316)	(-0.365)	(0.443)
Constant terms	-0.755	-546.022***	-169.569***	-1970.258***
	(-1.623)	(-14.658)	(-11.585)	(-16.423)
Year/Ind	Control	Control	Control	Control
N	34368	34368	34368	34368
Adj-R2	0.452	0.024	0.015	0.042
F-number	628.479	18.315	10.985	32.343
Sobel test		Z= 3.214,***	Z= 2.682,***	Z= 6.125,***
Goodman-1 (Aroian) test		Z= 3.212,***	Z= 2.68,***	Z= 6.122,***
Goodman-2 test		Z= 3.215,***	Z= 2.683,***	Z= 6.128,***
Proportion of total effect that is mediated		0.077	0.056	0.136
Ratio of indirect to direct effect		0.083	0.059	0.157
Bootstrap 1000 times test		r(ind_eff), Z= 6.410,*** r(dir_eff), Z=3.140,***	r(ind_eff), Z=4.380,*** r(dir_eff), Z=3.660,***	r(ind_eff), Z= 5.140,*** r(dir_eff), Z=2.070,**

Note: *, **, and *** in the table indicate correlation at the 10%, 5%, and 1% significance levels, respectively. In parentheses is the value of the t-statistical.

The results in column (4) of Table 6 suggest that TMT's digitalization awareness significantly positively influences high-quality innovation output (the number of patents cited) at the 1% level. This correlation indicates that TMT's digitalization awareness has a positive impact on high-quality innovation outputs. Additionally, column (4) shows that high-quality innovation output is significantly positively correlated with R&D expenses (input) at the 1% level. When combined with the results from Table 5 and Table 6, it appears that R&D expenses play a partial mediating role in the impact of TMT's digitalization awareness on high-quality innovation output. The Sobel, Goodman-1, and Goodman-2 tests provide Z values of 6.125, 6.122, and 6.128, respectively, indicating that some of the mediating effects of R&D expenses are significant at the 1% level. The ratio of the mediating effect to the total effect is 0.13582684, and the proportion of the mediating effect to the direct effect is 0.15717549. Furthermore, to avoid the requirement of normal distribution on the Sobel test, the Bootstrap cycle 1000 times method is used to re-test the mediating effect model. The Z-value of the indirect effect r(ind_eff) is 5.14, and the Z-value of the direct effect r(dir_eff) is 2.07. These findings support the hypothesis that R&D expenses play a partial mediating role in the impact of TMT's digitalization awareness on high-quality innovation output (the number of patents cited), and support hypothesis H2.

4.3. An Empirical Test of the Impact Mechanism of Information Transparency

The results presented in Table 7 demonstrate the mediating effect of TMT's digitalization awareness on innovation output through information transparency.

Firstly, column (1) reveals that TMT's awareness of digitalization has a significant positive impact on information transparency at the 1% level. This suggests that as TMT's awareness of digitalization increases, the company's information transparency also improves.

Second, column (2) shows that there is a significant positive correlation between the company's innovation output as measured by the quantity of patent applications and both TMT's digitalization awareness at the 1% level and information transparency at the 5% level. The coefficient for TMT's digitalization awareness is 12.3301, with a t-value of 6.231, indicating a strong relationship.

When combining these results with those from column (1) of Table 5, and columns (1) and (2) of Table 6, it becomes evident that information transparency plays a partial mediating role in the relationship between TMT's digitalization awareness and innovation output. In other words, TMT's digitalization awareness influences innovation output partly through its effect on information transparency.

To further validate this mediating effect, Sobel, Goodman-1, and Goodman-2 tests were conducted. The Z-values obtained from these tests (Z = 2.228, Z = 2.216, and Z = 2.241, respectively) confirm the significance of the mediating effect at the 1% level. Additionally, the proportion of the mediating effect to the total effect was found to be 0.02103932, while the proportion of the mediating effect to the direct effect was 0.02149149.

To ensure robustness, the mediating effect model was re-tested using the Bootstrap method with 1000 iterations. The results from this analysis also support the mediating role of information transparency, with a Z-value of 3.36 for the indirect effect and 3.66 for the direct effect.

Overall, these results strongly support hypothesis H3 by showing that information transparency plays a part in how TMT's digitalization awareness affects innovation output.

The (3) and (4) columns are the regression results of the mediating effect with the dependent variables Ninv and Cited, which are consistent with the results in (2) column. The results indicate that information transparency plays a partial mediating role in the impact of TMT's digitalization awareness on Ninv and Cited and support hypothesis H3.

Table 7. Empirical test results of the information transparency impact mechanism.

Variable	(1)	(2)	(3)	(4)
	Itrans	Npat	Ninv	Cited
Dfmda	0.034***	12.330***	5.336***	41.433***
	(9.012)	(6.231)	(6.721)	(6.422)
Itrans	-	7.904**	2.558*	22.605**
		(2.300)	(1.855)	(2.018)
Size	0.139***	36.716***	11.210***	111.776***
	(28.743)	(14.038)	(10.683)	(13.109)
Level	-0.422***	-12.326	2.588	1.641
	(-17.654)	(-0.965)	(0.505)	(0.039)
Mb	-0.072***	-42.765***	-18.608***	-105.071***
	(-3.247)	(-3.626)	(-3.932)	(-2.733)
Roa	2.166***	11.273	21.474	-262.142
	(21.125)	(0.205)	(0.974)	(-1.464)
Shrcr1	0.258***	-23.514*	-8.833	-263.739***
	(9.879)	(-1.693)	(-1.585)	(-5.826)
Djg	-0.093***	-15.876***	-6.154***	-1.415
	(-9.149)	(-2.927)	(-2.828)	(-0.080)

Is	0.139***	-23.729**	-8.053**	-59.815*
	(7.290)	(-2.350)	(-1.987)	(-1.817)
Big4	0.094***	68.623***	6.036	432.154***
	(5.336)	(7.356)	(1.613)	(14.210)
Dual	0.014*	13.779***	4.675***	59.851***
	(1.759)	(3.223)	(2.726)	(4.295)
State	0.079***	1.000	-1.049	3.292
	(8.346)	(0.200)	(-0.523)	(0.202)
Constant	-0.177*	-724.277***	-216.229***	-2198.251***
	(-1.784)	(-13.713)	(-10.204)	(-12.768)
Year/Ind	Control	Control	Control	Control
N	23924	23924	23924	23924
Adj-R2	0.151	0.028	0.015	0.041
F	94.316	15.164	8.101	21.985
Sobel test		Z= 2.228,**	Z= 1.817,*	Z=1.969,**
Goodman-1 (Aroian) test		Z= 2.216,**	Z= 1.807,*	Z= 1.958,**
Goodman-2 test		Z= 2.241,**	Z= 1.828,*	Z=1.981,**
Proportion of total effect that is mediated		0.021	0.016	0.018
Ratio of indirect to direct effect		0.021	0.016	0.018
Bootstrap 1000 times test		r(ind_eff), Z= 3.360,*** r(dir_eff), Z= 3.660,***	r(ind_eff), Z= 2.750,*** r(dir_eff), Z= 3.910,***	r(ind_eff), Z= 3.460,*** r(dir_eff), Z= 3.560,***

Note: *, **, and *** in the table indicate correlation at the 10%, 5%, and 1% significance levels, respectively. In parentheses is the value of the t-statistical.

4.4. An Empirical Test of the Moderating Effect of the Asset-Liability Ratio

Based on the theoretical review, this paper empirically tests the moderating effects of TMT's digitalization awareness on innovation output, including asset-liability rate, shareholding ratio of the largest shareholder, and property rights.

Table 8 shows the moderating effect of the asset-liability ratio on the impact of TMT's digitalization awareness on innovation output. As you can see in Column (1), the level of digitalization awareness of TMT (Dfmda) has a 1% positive effect on innovation output (number of patent applications) at the 1% level (coefficient 6.884, t-value 3.384).The multiplier term of Dfmda*Level significantly positively influences innovation output at the 1% level (coefficient 38.718, t-value 4.706), indicating that when the asset-liability ratio is higher, the positive impact of TMT's digitalization awareness on innovation output is more obvious, which played a "strengthening" role, H4a is supported, H4b is not supported. Column (2) shows that the digitalization awareness of TMT (Dfmda) significantly positively affects high-quality innovation output at the 1% level (coefficient 3.125, t-value 3.778). The multiplier term of Dfmda*Level significantly positively affects high-quality innovation output at the 1% level (coefficient 16.971, t value 5.072), indicating that when the asset-liability ratio is higher, the positive impact of TMT's digitalization awareness on high-quality innovation output is more obvious, H4a is supported, H4b is not supported. Column (3) shows that TMT's digitalization awareness (Dfmda) significantly positively influences high-quality innovation output at the 1% level (coefficient 21.616, t-value 3.942).The multiplier term of Dfmda*Level significantly positively influences high-quality innovation output at the 10% level (coefficient 42.391, t value 1.912), indicating that when the asset-liability ratio was higher, the positive impact of TMT's digitalization awareness on high-quality innovation output (the number of patents cited) wasmore obvious. H4a is supported; H4b is not supported.

Table 8. Results of asset-liability ratio moderating effect.

Variable name	**(1)**	**(2)**	**(3)**
	Npat	**Ninv**	**Cited**
Dfmda	6.884***	3.125***	21.616***
	(3.384)	(3.778)	(3.942)
Dfmda* Level	38.718***	16.971***	42.391*
	(4.706)	(5.072)	(1.912)
Size	3.298	2.599*	14.025
	(0.960)	(1.860)	(1.515)
Level	-1.463	-2.159	16.617
	(-0.107)	(-0.388)	(0.451)
Mb	3.543	-2.509	99.976***
	(0.323)	(-0.563)	(3.384)
Roa	21.478	6.482	296.808**

Variable name	(1)	(2)	(3)
	Npat	Ninv	Cited
	(0.453)	(0.336)	(2.324)
Shrcr1	-6.789	-5.533	-39.251
	(-0.320)	(-0.641)	(-0.687)
Djg	-3.582	-1.668	-2.436
	(-0.746)	(-0.854)	(-0.188)
Is	-11.551	-6.341*	97.587***
	(-1.294)	(-1.748)	(4.058)
Big4	-6.366	-4.654	1.622
	(-0.539)	(-0.968)	(0.051)
Dual	-4.270	0.094	16.284
	(-0.939)	(0.051)	(1.328)
State	-16.208*	-9.855***	66.548***
	(-1.826)	(-2.730)	(2.782)
Constant	-44.295	-37.815	-332.603*
	(-0.643)	(-1.350)	(-1.792)
Year/Ind	Control	Control	Control
N	34368	34368	34368
Overall_R2	0.004	0.004	0.009
F	4.555	4.235	10.344

Note: *, **, and *** in the table indicate correlation at the 10%, 5%, and 1% significance levels, respectively. In parentheses is the value of the t-statistical.

4.5. An Empirical Test of the Shareholding Ratio of the Largest Shareholder Moderating Effect

Table 9 shows the moderating effect of shrcr1 on the impact of TMT's digitalization awareness on innovation output. Column (1) shows that TMT's digitalization awareness (Dfmda) significantly positively affects innovation output at the 1% level (coefficient 6.550, t value 3.193). The multiplier term of Dfmda*shrcr1 is negatively correlated but not significant (coefficient -14.893, t-value -1.319), H5a and H5b are not supported. Column (2) shows that high-quality innovation output (number of invention patent applications) significantly positively affects TMT's digitalization awareness (Dfmda) at the 1% level (coefficient 2.947, t-value 3.533), and significantly negatively affects Dfmda*shrcr1 at the 10% level (coefficient -7.901, t-value -1.721). It shows that when shrcr1 is higher, the positive impact of TMT's digitalization awareness on high-quality innovation output is less obvious, which plays a "weakening" role, supporting H5b and not supporting H5a. Column (3) shows that high-quality innovation output (number of patents Cited) significantly positively affects TMT's digitalization awareness (Dfmda) at the 1% level (coefficient 19.202, t-value 3.475), and significantly negatively affects Dfmda*shrcr1 at the 1% level (coefficient -106.395, t-value -3.499).It shows that when shrcr1 is higher, the positive impact of TMT's digitalization awareness on high-quality innovation output (number of patents cited) is less obvious, which plays a "weakening" role, supporting H5b and not supporting H5a.

Table 9. The results of the shrcr1 moderating effect.

Variable	(1)	(2)	(3)
	Npat	Ninv	Cited
Dfmda	6.550***	2.947***	19.202***
	(3.193)	(3.533)	(3.475)
Dfmda* Shrcr1	-14.893	-7.901*	-106.395***
	(-1.319)	(-1.721)	(-3.499)
Size	3.287	2.561*	11.810
	(0.953)	(1.827)	(1.272)
Level	-9.825	-5.834	6.791
	(-0.725)	(-1.058)	(0.186)
Mb	7.118	-0.869	108.672***
	(0.649)	(-0.195)	(3.679)
Roa	30.116	10.353	311.810**
	(0.636)	(0.537)	(2.443)
Shrcr1	-7.729	-6.191	-56.397
	(-0.363)	(-0.714)	(-0.982)
Djg	-3.143	-1.471	-1.665
	(-0.654)	(-0.753)	(-0.129)
Is	-9.845	-5.461	108.193***
	(-1.095)	(-1.493)	(4.466)
Big4	-6.470	-4.694	1.816
	(-0.547)	(-0.977)	(0.057)

Variable	(1)	(2)	(3)
	Npat	Ninv	Cited
Dual	-4.033	0.195	16.380
	(-0.886)	(0.105)	(1.336)
State	-17.634**	-10.483***	64.765***
	(-1.987)	(-2.905)	(2.709)
Constant	-46.266	-37.990	-289.538
	(-0.670)	(-1.352)	(-1.556)
Year/Ind	Control	Control	Control
Number	34368	34368	34368
Overall_R2	0.003	0.003	0.009
F	3.768	3.357	10.677

Note: *, **, and *** in the table indicate correlation at the 10%, 5%, and 1% significance levels, respectively. In parentheses is the value of the t-statistical.

4.6. An Empirical Test of the Moderating Effect of Property Rights

Table 10 shows the moderating effect of state on TMT's digitalization awareness on innovation output. Column (1) shows that TMT digitalization awareness (Dfmda) significantly positively affects innovation output, but not significantly (coefficient 3.020, t-value 1.316), and is significantly positively affects by Dfmda*State correlated at the 1% level (coefficient 1.995, t-value 3.649), indicating that when firm is stated, the positive impact of TMT's digitalization awareness on high-quality innovation output is more obvious, which plays a "strengthening" role, supporting H6a and not supporting H6b. Column (2) shows that TMT's digitalization awareness (Dfmda) significantly positively affects high-quality innovation output at the 5% level (coefficient 2.242, t value 2.402), and significantly negatively affects Dfmda*State at the 5% level (coefficient 3.203, t-value 2.053), indicating that when firm is state-owned, the positive impact of TMT's digitalization awareness on high-quality innovation output is more obvious, which plays a "strengthening" role, supporting H6a but not supporting H6b. Column (3) shows that digitalization awareness of TMT (Dfmda) significantly positively affects high-quality innovation output at the 1% level (coefficient 20.009, t-value 3.236), and is positively correlated with Dfmda. *State (coefficient is 5.831, t value is 0.564), not supporting H6a and H6b.

Table 10. Results of the state moderating effect.

Variable	(1)	(2)	(3)
	Npat	Ninv	Cited
Dfmda	3.020	2.242**	20.009***
	(1.316)	(2.402)	(3.236)
Dfmda* State	13.995***	3.203**	5.831
	(3.649)	(2.053)	(0.564)
Size	4.727	3.000**	14.859
	(1.371)	(2.139)	(1.599)
Level	-8.627	-5.527	8.035
	(-0.636)	(-1.002)	(0.220)
Mb	3.117	-2.023	101.686***
	(0.284)	(-0.453)	(3.436)
Roa	23.605	8.587	302.930**
	(0.498)	(0.445)	(2.372)
Shrcr1	-8.305	-5.519	-38.713
	(-0.391)	(-0.639)	(-0.677)
Djg	-3.242	-1.508	-2.029
	(-0.675)	(-0.772)	(-0.157)
Is	-12.593	-6.525*	97.330***
	(-1.410)	(-1.796)	(4.044)
Big4	-6.255	-4.661	1.563
	(-0.529)	(-0.969)	(0.049)
Dual	-4.066	0.196	16.548
	(-0.894)	(0.106)	(1.350)
State	-15.340*	-9.947***	65.968***
	(-1.725)	(-2.750)	(2.752)
Constant	-73.895	-47.856*	-366.920**
	(-1.075)	(-1.712)	(-1.981)
Year/Ind	Control	Control	Control
Number	34,368	34,368	34,368
Overall_R2	0.004	0.003	0.009
F	4.214	3.406	10.215

Note: *, **, and *** in the table indicate correlation at the 10%, 5%, and 1% significance levels, respectively. In parentheses is the value of the t-statistical.

5. Robustness Test

In order to solve endogeneity problems such as missing variables and reverse causality in the model, this paper will use the two-stage model of instrumental variables, the panel random effect and OLS model, the substitution of independent variables, the firm-level fixed-effect model, and the double clustering model to test the robustness.

5.1. A Two-Stage Regression Analysis of Instrumental Variable (The Mean Value of the Digitalization Awareness of TMT of Other Companies in the Same Region and Same Year)

Table 11 presents the two-stage regression results of the instrumental variables used to address endogeneity issues.In this paper, Durbin-Wu-Hausman test results show that the Prob>chi2 of all models is equal to 0.000, indicating all models have endogeneity problems. As recommended by Shen and Hou (2021)we utilize the mean value of digitalization awareness among TMTs of other publicly traded companies within the same region and year (Dfmdayr) as an instrumental variable. The results of a series of instrumental variable tests are as follows:

The Anderson test produces a P-value of 0.000, indicating the absence of under-identification issues with the instrumental variables. The Cragg-Donald Wald F statistics from the tests are greater than the critical value of 16.38 in all instances, indicating that the instrumental variable is not weakly identified. Furthermore, the Sardan test confirms that the equation is exactly identified, indicating that the instrumental variable does not suffer from over-identification issues.

Additionally, the results from the first stage of regression reveal a significant positive correlation between Dfmda and Dfmdayr at the 1% significance level (coefficient: 0.695, t-value: 26.939). This finding aligns with the principle of correlation between instrumental variables, providing further validation for the chosen instrumental variable.

Columns (2) to (4) contain the results of the second-stage regression analysis. Column (2) highlights the regression results for the impact of TMT's digitalization awareness on the total number of patent applications. The analysis reveals a significant positive correlation at the 1% level, with a coefficient of 48.554 and a t-value of 5.885. This supports Hypothesis H1, which posits a positive relationship between TMT's digitalization awareness and innovation output.

Columns (3) and (4) are the results of second-stage regression with dependent variables Ninv and Cited. The research results show that TMT's awareness of digitalization exerts a significant positive impact on firm's substantive innovation output, indicating that after instrumental variable regression, H1a is still valid.

Table 11. Two-stage regression of instrumental variables (mean of the TMT digitalization awareness of other companies in the same region and same year).

Variable	(1)	(2)	(3)	(4)
	First stage	Second stage		
	Dfmda	Npat	Ninv	Cited
Dfmda	-	48.554***	10.108***	111.023***
		(5.885)	(3.143)	(4.201)
Dfmdayr	0.695***	-	-	-
	(26.939)			
Size	0.218***	23.055***	8.256***	89.318***
	(22.753)	(10.705)	(9.835)	(12.947)
Level	-0.091**	-1.580	1.314	-9.517
	(-2.383)	(-0.167)	(0.356)	(-0.314)
Mb	-0.334***	-14.419	-14.191***	-41.219
	(-10.874)	(-1.463)	(-3.695)	(-1.306)
Roa	-0.306**	46.763	21.512	-10.205
	(-2.291)	(1.160)	(1.369)	(-0.079)
Shrcr1	-0.359***	-15.046	-6.234	-169.462***
	(-6.025)	(-1.494)	(-1.588)	(-5.252)
Djg	0.102***	-16.999***	-4.666***	-9.558
	(7.587)	(-3.966)	(-2.793)	(-0.696)
Is	-0.154***	-10.167	-5.546*	-31.645
	(-6.153)	(-1.367)	(-1.912)	(-1.328)
Big4	-0.041	45.532***	4.776**	282.880***
	(-1.221)	(7.358)	(1.980)	(14.272)
Dual	0.001	9.304***	3.982***	46.571***
	(0.093)	(2.805)	(3.080)	(4.383)
State	-0.128***	5.623	0.073	11.935
	(-5.128)	(1.542)	(0.051)	(1.022)
Cons	-4.343***	-430.484***	-154.682***	-1756.903***
	(-22.685)	(-9.350)	(-8.619)	(-11.913)
Year/Ind	Control	Control	Control	Control
N	34,255	34,255	34,255	34,255

Variable	(1)	(2)	(3)	(4)
	First stage	Second stage		
	Dfmda	Npat	Ninv	Cited
Adj (Overall) -R2	0.261	0.006	0.012	0.034
Durbin–Wu–Hausman test		chi2 (1) = (b-B) [(V_b-V_B) ^ (-1)] (b-B) = 21.680; Prob > chi2 = 0.000	chi2 (1) = (b-B) [(V_b-V_B) ^ (-1)] (b-B) = 2.640; Prob > chi2 = 0.104	chi2 (1) = (b-B) [(V_b-V_B) ^ (-1)] (b-B) = 7.730; Prob > chi2 =0.005
Anderson's test (Insufficient identification)		P-value = 0.000	P-value = 0.000	P-value = 0.000
Cragg-Donald test (Weak instrumental variable)		1177.994 >16.380	1177.994 >16.380	1177.994 >16.380
Sardan test (Over-identification)		0.000, equation exactly identified	0.000, equation exactly identified	0.000, equation exactly identified

Note: *, **, and *** in the table indicate correlation at the 10%, 5%, and 1% significance levels, respectively. In parentheses is the value of the t-statistical.

5.2. Model Substitution: Panel Random Effects and Mixed OLS Models

To eliminate the influence of model selection bias, this study aims to replace the panel fixed-effect regression model with a panel random-effects model and a mixed OLS model (Wang, Shen, Tang, Wu, & Ma, 2021).

Table 12 shows the results of the panel random effects test, and column (1) shows that the TMT digitalization awareness (Dfmda) is significantly positively correlated with the total number of patent applications (Npat) at the 1% level (coefficient 10.2843, t value 6.751), supporting hypothesis H1. Column (2) shows that TMT's digitalization awareness (Dfmda) significantly positively affects Ninv at the 1% level (coefficient 4.9604, t-value 8.477), supporting the hypothesis H1a. Based on Column (3) it can be seen that TMT digitalization awareness (Dfmda) has a 1% level of positive effect on the number of patents Cited (Cited) (coefficient 24.3975, t-value 5.136), which supports the hypothesis H1a.

Table 12. Regression results of panel random and OLS model.

Variable	Panel random effect			OLS model		
	(1)	(2)	(3)	(4)	(5)	(6)
	Npat	Ninv	Cited	Npat	Ninv	Cited
Dfmda	10.284*** (6.751)	4.960*** (8.477)	24.398*** (5.136)	11.082*** (7.441)	4.960*** (8.477)	38.879*** (8.102)
Size	26.651*** (13.984)	8.927*** (12.527)	55.449*** (8.426)	28.108*** (15.498)	8.927*** (12.527)	98.925*** (16.929)
Level	-13.672 (-1.459)	-0.132 (-0.037)	-17.893 (-0.584)	-12.501 (-1.386)	-0.132 (-0.037)	-30.811 (-1.060)
Mb	-28.963*** (-3.258)	-16.867*** (-4.932)	47.123* (1.749)	-34.462*** (-3.959)	-16.867*** (-4.932)	-80.025*** (-2.853)
Roa	27.645 (0.694)	18.297 (1.181)	250.854** (2.126)	22.759 (0.577)	18.297 (1.181)	-55.444 (-0.436)
Shrcr1	-16.282 (-1.542)	-6.686* (-1.718)	-109.627*** (-2.832)	-18.2040* (-1.837)	-6.6864* (-1.718)	-176.3088*** (-5.523)
Djg	-8.863** (-2.203)	-3.734** (-2.393)	0.042 (0.003)	-10.133** (-2.551)	-3.734** (-2.393)	3.774 (0.295)
Is	-13.658* (-1.849)	-6.183** (-2.163)	50.346** (2.279)	-14.759** (-2.028)	-6.183** (-2.163)	-40.026* (-1.707)
Big4	41.348*** (6.339)	4.317* (1.807)	153.372*** (6.525)	42.299*** (6.959)	4.317* (1.807)	276.092*** (14.097)
Dual	9.885*** (2.991)	4.348*** (3.436)	31.210*** (2.991)	12.119*** (3.764)	4.348*** (3.436)	52.091*** (5.021)
State	0.399 (0.106)	-0.604 (-0.446)	24.432* (1.649)	0.759 (0.220)	-0.604 (-0.446)	2.844 (0.256)
Constant terms	-522.2985*** (-13.237)	-169.9148*** (-11.608)	-1178.1774*** (-8.198)	-547.0763*** (-14.685)	-169.9148*** (-11.608)	-1976.8117*** (-16.469)
Year/Ind	Control	Control	Control	Control	Control	Control
Number	34,368	34,368	34,368	34,368	34,368	34,368
Overall_R2	0.024	0.014	0.038	0.024	0.014	0.041

Note: *, **, and *** in the table indicate correlation at the 10%, 5%, and 1% significance levels, respectively. In parentheses is the value of the t-statistical.

Table 12 shows the results of panel OLS regression, and table (4) shows that digitalization awareness (Dfmda) of TMT significantly positively affects Npat at the level of 1% (coefficient 11.0819, t value 7.441), supporting hypothesis H1. The results of column (5) show that TMT's digitalization awareness (Dfmda) significantly positively affects Ninv at the 1% level (coefficient 4.9604, t-value 8.477), supporting the hypothesis H1a. Column (6) shows that TMT digitalization awareness (Dfmda) significantly positively affects the number of patents Cited (Cited) at the 1% level (coefficient 38.8791, t-value 8.102), supporting the hypothesis H1a.

5.3. Results of Independent Variables Replacement

Table 13 shows the results of the test of replacing the TMT digitalization awareness (Dfmda) with the TMT digital technology awareness (Mdacx), and Table 1 shows that the TMT digitalization awareness (Mdacx) significantly positively affects Npat at the 1% level (coefficient 9.6129, t-value 4.132), supporting the hypothesis of H1. The results in column (2) show that the level of awareness of digitalization among managers has a positive and significant effect on Ninv at the 1% level (coefficient 4.3011, t-value 4.546), which supports the hypothesis H1a. Columns (3) and (4) show that management's awareness of digitalization can't significantly positively affect Ndes and Nuti, and do not support the hypothesis of H1b. Column (5) shows that management's awareness of digitalization (Mdacx) significantly positively affects the number of Cited patents (Cited) at the 1% level (coefficient 18.3031, t-value 2.919), supporting the hypothesis H1a.

Table 13. Regression results of independent variable substitution.

Variable	(1)	(2)	(3)	(4)	(5)
	Npat	Ninv	Ndes	Nuti	Cited
Mdacx	9.613***	4.301***	-0.033	0.091	18.303***
	(4.132)	(4.546)	(-0.490)	(0.529)	(2.919)
Size	3.248	2.584*	-0.049	-0.073	15.566*
	(0.945)	(1.848)	(-0.494)	(-0.286)	(1.680)
Level	-9.948	-5.882	1.159***	2.154**	6.726
	(-0.734)	(-1.067)	(2.935)	(2.138)	(0.184)
Mb	6.759	-1.112	-0.439	-1.477*	100.669***
	(0.617)	(-0.250)	(-1.376)	(-1.815)	(3.413)
Roa	32.663	11.401	0.043	-2.957	308.860**
	(0.689)	(0.591)	(0.031)	(-0.839)	(2.418)
Shrcr1	-4.384	-4.491	0.453	2.343	-39.427
	(-0.207)	(-0.520)	(0.732)	(1.486)	(-0.690)
Djg	-3.189	-1.491	0.064	-0.017	-1.080
	(-0.665)	(-0.764)	(0.457)	(-0.047)	(-0.084)
Is	-10.759	-5.997*	-0.044	0.441	97.451***
	(-1.205)	(-1.652)	(-0.169)	(0.665)	(4.050)
Big4	-6.431	-4.684	0.712**	1.082	1.202
	(-0.544)	(-0.974)	(2.067)	(1.232)	(0.038)
Dual	-4.065	0.183	-0.168	-1.182***	16.491
	(-0.893)	(0.099)	(-1.264)	(-3.495)	(1.345)
State	-17.744**	-10.535***	-0.132	-0.332	63.725***
	(-2.000)	(-2.920)	(-0.512)	(-0.503)	(2.666)
Constant	-51.410	-41.149	0.676	1.945	-383.304**
	(-0.749)	(-1.474)	(0.338)	(0.381)	(-2.072)
Year/Ind	Control	Control	Control	Control	Control
N	34,368	34,368	34,368	34,368	34,368
Overall_R2	0.003	0.003	0.003	0.005	0.009
F	4.074	3.629	3.459	5.802	10.327

Note: *, **, and *** in the table indicate correlation at the 10%, 5%, and 1% significance levels, respectively. In parentheses is the value of the t-statistical.

5.4. Firm-Level Fixed-Effect Regression Analysis

Table 14 displays the findings of Chemmanur and Tian (2018) firm-level fixed-effect regression analysis. As indicated in (1), TMT's digitalization awareness (Dfmda) significantly positively affects the total number of patent applications (Npat) at the 1% level. The regression analysis supports Hypothesis H1, as the coefficient of 11.082 and t-value of 2.916 indicate a positive relationship between TMT's digitalization awareness and innovation output.

The results of column (2) show that TMT's digitalization awareness (Dfmda) significantly positively affects Ninv at the 1% level (coefficient 4.960, t-value 3.050), supporting the hypothesis of H1a. Column (3)

shows that TMT's digitalization awareness (Dfmda) significantly positively affects the number of patents Cited (Cited) at the 1% level (coefficient 38.879, t-value 3.392), supporting the hypothesis H1a.

Table 14. Results of firm-level fixed-effect regression analysis and double cluster regression.

Variable	Firm-level fixed-effect(Reghdfe)			Double cluster (Firm and year)		
	(1)	(2)	(3)	(4)	(5)	(6)
	Npat	Ninv	Cited	Npat	Ninv	Cited
Dfmda	11.082***	4.960***	38.879***	7.943***	3.679***	19.820*
	(2.916)	(3.050)	(3.392)	(3.241)	(3.411)	(1.680)
Size	28.108***	8.927***	98.924***	26.963***	8.306***	80.314***
	(3.878)	(2.831)	(4.148)	(3.824)	(2.991)	(2.704)
Level	-12.501	-0.132	-30.810	-11.368	0.775	1.142
	(-1.203)	(-0.050)	(-0.765)	(-0.980)	(0.223)	(0.024)
Mb	-34.462**	-16.867**	-80.025**	-40.608***	-17.333***	-133.562**
	(-2.320)	(-2.419)	(-1.975)	(-2.663)	(-2.893)	(-2.122)
Roa	22.759	18.297	-55.444	14.418	19.565	-165.714
	(0.506)	(1.158)	(-0.321)	(0.310)	(1.078)	(-1.083)
Shrcr1	-18.204	-6.686	-176.309	-15.377	-6.237	-138.056
	(-0.800)	(-1.210)	(-1.627)	(-0.725)	(-1.341)	(-1.349)
Djg	-10.133**	-3.734	3.774	-10.228*	-3.460	7.436
	(-1.991)	(-1.452)	(0.387)	(-1.920)	(-1.501)	(0.443)
Is	-14.759	-6.183*	-40.025	-22.305*	-7.905**	-71.511
	(-1.274)	(-1.709)	(-1.174)	(-1.824)	(-2.134)	(-1.481)
Big4	42.299	4.317	276.092*	43.014	4.643	287.399*
	(1.603)	(0.574)	(1.931)	(1.634)	(0.639)	(1.890)
Dual	12.119*	4.348	52.091**	13.300**	4.660*	48.491*
	(1.766)	(1.423)	(1.985)	(2.071)	(1.731)	(1.665)
State	0.759	-0.604	2.844	-0.526	-1.053	9.557
	(0.124)	(-0.305)	(0.095)	(-0.098)	(-0.584)	(0.363)
Constant	-553.528***	-172.573***	-2050.121***	-519.793***	-158.172***	-1611.228***
	(-3.997)	(-2.928)	(-4.152)	(-3.811)	(-2.955)	(-2.743)
Year/Ind	Yes	Yes	Yes	Yes	Yes	Yes
Firm	Yes	Yes	Yes	Yes	Yes	Yes
N	34,368	34,368	34,368	34,368	34,368	34,368
Overall_R2	0.024	0.014	0.040	0.018	0.011	0.025

Note: *, **, and *** in the table indicate correlation at the 10%, 5%, and 1% significance levels, respectively. In parentheses is the value of the t- statistical.

5.5. Double Cluster Regression (Year and Firm)

To address the issue of standard error bias resulting from intra-group correlation, this study aims to employ double cluster regression analysis at both the firm and year levels.

Table 14 shows the results of the double clustering (year and firm) test, and column (4) shows that TMT's digitalization awareness (Dfmda) significantly positively affects Npat at the 1% level (coefficient 7.943, the t-value 3.241), supporting the hypothesis H1. The results of column (5) show that TMT's digitalization awareness (Dfmda) significantly positively affects Ninv at the 1% level (coefficient 3.679, t value 3.411), supporting the hypothesis H1a. Column (6) shows TMT digitalization awareness (Dfmda) significantly positively affects the number of Cited patents (Cited) at the 10% level (coefficient 19.820, t-value 1.680), supporting the hypothesis H1a.

6. Conclusions, Implications, Limitations and Future Research Suggestions

6.1. Conclusions

Using a sample of Chinese listed companies from 2007 to 2021, this paper conducts an empirical investigation into the impact of TMT's digitalization awareness on firm's (both substantive and strategic) innovation output. The findings indicate that TMT's digitalization awareness exerts a significant positive influence on firm's innovation output, particularly in terms of substantive innovation output. However, it does not significantly impact strategic innovation output. Furthermore, the empirical results of the influencing mechanism reveal that TMT's digitalization awareness enhances firm's (substantive) innovation output by increasing R&D investment and enhancing information transparency. The empirical results of the moderating effect show that when firm has a high asset-liability ratio and is state-owned, the positive impact of TMT's digitalization awareness on (substantive) innovation output is more obvious, and when largest shareholder holds a high proportion of shares, the positive impact of TMT's digitalization awareness on (substantive) innovation output is even less obvious.

6.2. Implications

The inspiration from this article is as follows: Firstly, the digital awareness of the executive team is a key influencing factor in enhancing substantive innovation in the company. Listed companies can enhance the digital awareness of the executive team through various means, such as recruiting CEOs with strong digital awareness and improving the degree of differentiation in the characteristics of the executive team. Secondly, it is observed that when the asset liability ratio of listed companies and state-owned enterprises is high, the positive impact of management's digital awareness on substantive innovation output becomes more evident. This suggests that in organizations with a higher level of financial risk, the management's digital awareness has a stronger driving effect on substantive innovation output. Therefore, listed companies can improve substantive innovation output by optimizing their asset liability ratio, improving their financing constraints, and reducing debt financing costs.

6.3. Limitations and Future Research Suggestions

The shortcomings of this article include: firstly, it only uses Chinese listed companies as samples for empirical testing; it does not include samples of non-listed companies, and it does not cover samples from other countries in the world. Secondly, this article only studied the impact of management's digital awareness on company output (patents), without studying its impact on company innovation investment, innovation efficiency, etc.

Future research recommendations: Firstly, the use of big data text analysis to construct a more scientific management digital awareness than questionnaire survey methods. In the future, the data on management digital awareness can be used to study its impact on company financing, investment, and other aspects. Secondly, further research can be conducted on whether management's digital awareness affects company performance, total factor productivity, green innovation, digital technology innovation, and so on.

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