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Article

Intellectual property protection, digital economy development, and corporate green innovation: threshold effects and regulatory mechanisms

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ABSTRACT

This study examines the complex interactions among intellectual property protection (IPP), digital economy development, and corporate green innovation using panel data from Chinese listed firms (2014-2022). Employing threshold regression models and moderated regression analysis, we identify significant nonlinear relationships and regulatory mechanisms. Results reveal a U-shaped relationship between IPP and the quantity of green innovation, with identifiable threshold effects across multiple protection regimes. However, IPP exhibits predominantly negative effects on innovation quality across protection levels, with varying intensities observed in different regimes (zones 1-4). Digital economy development demonstrates dimension-specific moderating effects, significantly amplifying the promotional effect on innovation quantity (coefficient 0.711**) but showing minimal impact on innovation quality (-0.085, insignificant), functioning as an "efficiency amplifier" rather than a "quality enhancer." Green agency costs exhibit complex regulatory mechanisms that vary across institutional regimes, resulting in compensatory effects in weak protection environments and triggering institutional overload in strong protection contexts. These findings challenge the linear "more protection equals more innovation" assumption and highlight fundamental distinctions in how technological and institutional drivers affect different dimensions of green innovation. The results have crucial implications for policymakers in designing differentiated IPP regimes and targeted digital economy policies optimized for specific development stages.

1. Introduction

Climate warming and ecological pollution have worsened, and the concept of carbon peak and carbon neutrality has gained worldwide consensus, whereas green development is the most strategic objective for all nations, particularly China, to achieve sustainable development [1]. Here, green technology innovation, as a key driving force for the realization of a symbiotic development between economic growth and ecological environment protection, is extremely important for firms to reduce pollution emissions and accelerate their green transformation [2,3]. Yet, green innovation is often faced with "double externalities" [4] - the intersection point of innovation spillovers and environmental externalities, which can deter the market mechanism from adequately stimulating firms to invest in green innovation [5,6]. Intellectual property rights (IPR) protection is a crucial institutional tool for encouraging green innovation and marketization [7,8]. Theoretically speaking, good intellectual property protection can internalize the positive spillovers of innovation by granting innovators exclusive rights, thereby increasing the value that green R&D outcomes can capture, and hence inducing enthusiasm among enterprises to conduct green innovation. However, the impact of IPR protection on green innovation is not a simple linear relationship; overly strong protection may inhibit knowledge flow and technology diffusion through the 'tragedy of the anticommons' effect [9], where fragmented IP rights create barriers to cumulative innovation, while protection that is too weak may fail to provide sufficient incentives for innovation. Meanwhile, the booming development of the digital economy is profoundly changing the economic and social landscape. It is regarded as a new type of productivity that promotes green transformation and enhances innovation capacity [10,11]. The digital economy can significantly reduce the search cost and coordination cost of green innovation, optimize the allocation of innovation resources, and promote green innovation through the spillover effect of data knowledge, enhancing information transparency, and reducing transaction costs [11,12]. Above all, the evolution of the digital economy can revolutionize the external environment upon which IPR protection is embedded, altering or adding to the mode of institutional policy impact. Though the role of intellectual property protection and the digital economy in promoting green innovation has drawn extensive academic attention, there are some obvious shortcomings in previous research. First, intellectual property protection or the digital economy itself is usually considered in most research, excluding its interactive mechanism. Second, most research is linear in type, failing to fully display policy effects under varying protection levels. Third, the multi-dimensional characteristics of green innovation are often overlooked, with a limited distinction between innovation quantity and quality. Fourth, the internal corporate governance elements that act as moderators are not explored well, particularly the role of agency costs in influencing how firms respond to external institutional incentives. According to these research gaps, this paper meticulously examines the dynamic regulatory effect mechanism of digital economy growth between intellectual property protection and green innovation, highlighting particular attention to threshold effects and nonlinearity. Using threshold regression models and moderated regression analysis with panel data from Chinese listed companies spanning 2014-2022, this study aims to: identify the nonlinear features and critical values of IPR protection's impact; analyze the moderating role of digital economy development; distinguish between quantitative and qualitative dimensions of green innovation; and examine the moderating effect of agency costs. This study makes three key contributions: (1) Theoretical innovation - we enrich green innovation theory by identifying threshold effects and distinguishing quantity-quality dimensions, challenging the linear 'more protection equals more innovation' assumption; (2) Methodological advancement - we provide a novel analytical framework integrating threshold regression with triple and quadruple moderated regression analysis to capture complex interaction effects; (3) Policy implications - we offer empirical evidence for implementing regime-specific IPR strategies and targeted digital economy policies across different development stages, recognizing that optimal policy configurations vary with institutional maturity.

2. Literature review

2.1 Intellectual property protection and green innovation

As a core institutional arrangement of the modern innovation system, the mechanism through which intellectual property protection impacts green innovation has received increasing attention from academics. From a theoretical perspective, intellectual property protection can effectively internalize the positive externalities of innovation activities by granting exclusive rights to innovators and providing incentives for enterprises to increase R&D investment [13]. Such incentives are particularly important in the case of green innovation, which often faces the challenge of "double externalities" - the knowledge spillovers of general technological innovation and the social benefits of environmental protection - making it difficult for the market mechanism to incentivize firms to invest on their own adequately [5]. Empirical studies generally support the positive effect of IPR protection on green innovation [14]. Strengthening IPR protection can significantly increase the commercial value of environmental R&D results, reduce the risk of imitation by competitors, and thereby enhance the endogenous motivation of enterprises to undertake green innovation [2,13]. However, a growing number of studies have revealed the complexity and non-linear nature of the impact of IPR protection on green innovation. Excessive IPR protection may create an "innovation lock-in" effect, inhibiting the flow of knowledge and the diffusion of technology [6,15]. Meanwhile, different strengths of IPR protection may have differentiated impacts on the quantity and quality of innovations, as an increase in patent applications does not always equate to high-quality technological breakthroughs [3]. Based on the above literature, this study proposes hypothesis H1. Initial enforcement costs may deter innovation at lower protection levels, but accumulated benefits emerge as protection strengthens, creating threshold turning points [2].

H1a: IPR protection exhibits a non-linear U-shaped relationship with green innovation quantity, with identifiable threshold effects. Strong protection may create "patent thickets" that fragment knowledge and incentivize incremental over breakthrough innovations [3,6].

H1b: IPR protection negatively affects green innovation quality in regimes 1-4, with varying intensities.

2.2 Digital economy and green innovation

The digital economy, as the core driving force of the new round of technological revolution, is profoundly reshaping enterprise innovation patterns and resource allocation mechanisms. Existing studies generally agree that the development of the digital economy has a significant role in promoting green innovation [16,17]. In terms of the mechanism of action, digital technology can significantly improve information transparency, optimize the efficiency of resource allocation, and promote knowledge sharing and data overflow through big data analysis, artificial intelligence algorithms, and cloud computing platforms, thus reducing the search cost, coordination cost, and trial-and-error cost of green innovation [11]. Particularly, enterprise digital transformation can support green innovation through various channels, including realizing actual environmental observation and resource management, integrating innovation organizations to facilitate industry-university-research collaboration, and offering financial and policy incentives [18]. Empirical evidence suggests that enterprise digital transformation will substantially promote the degree of green innovation, particularly substance-based green innovation [12]. However, the impact of the digital economy on green innovation is characterized by pervasive heterogeneity among variables such as enterprise size, industry, and technology platform type. For instance, Xu et al. [18] found that larger firms benefit more from digital economy development through enhanced resource allocation efficiency and stronger innovation network effects, while smaller enterprises face greater implementation barriers. Different dimensions of green innovation may respond differently to digital tools, as the advantages of digital technologies in facilitating innovation scale-up may not be fully applicable to quality innovations that require long-term accumulation and deep insights [19].

2.3 Regulatory mechanisms and threshold effects in the digital economy

Although relatively few studies have directly explored the moderating role of the digital economy in the relationship between intellectual property protection and green innovation, the existing literature provides important theoretical foundations and empirical clues for understanding this complex interaction mechanism. Theoretically, the development of the digital economy may have a moderating influence on the incentive effect of green innovation by altering the implementation environment and the transmission mechanism of IPR protection. The digital economy can significantly enhance the actual effectiveness of IPR protection by improving information transparency and regulatory efficiency. In a highly digitalized environment, IPR infringements can be more easily identified, tracked, and punished, thereby better protecting the exclusivity rights of IPRs and allowing the incentive effect to be fully realized [7]. This "technology-enabling" effect enables more digitized enterprises to obtain better IPR protection even at relatively low levels of institutional protection. The digital economy facilitates the flow of knowledge and the formation of innovation networks, which may have a differentiated impact on the effectiveness of IP protection at different stages of development. At the stage of low digitization, IPR protection primarily serves as an incentive; whereas in a highly digitized environment, overly strong IPR protection may conflict with the digital economy's features of open innovation and knowledge sharing, creating institutional friction [20]. This dynamic feature implies that the level of digital economy development may constitute an important threshold variable for the effect of IPR protection.

Recent studies have begun to directly test the interaction effect of digital technology and IPR protection. Huang and Lau [11] explicitly incorporate the interaction term between digital transformation and IPR protection (DT × IPP) in their analysis of the quality of firms' green innovations, providing direct empirical evidence of the moderating effect of the digital economy. This suggests that the level of digital economy development may indeed change the intensity or direction of the impact of IPR protection on green innovation, and this moderating effect may be characterized by heterogeneity across different dimensions of innovation. Based on the above literature, this study proposes hypothesis H2:

H2a: The level of digital economy development can significantly modulate the promotion effect of intellectual property protection on the number of green innovations.

H2b: There are dimensional differences in the moderating effect of the level of digital economy development on the relationship between intellectual property protection and the quality of green innovation.

2.4 The moderating role of corporate governance factors

In the research on the relationship between intellectual property protection and green innovation, the internal governance factors of enterprises, especially the issue of agency cost, have gradually received attention from scholars. Agency cost reflects the degree of conflict of interest between owners and managers of enterprises, which directly affects the investment decision and resource allocation efficiency of enterprises. In green innovation decision-making, as green projects are typically characterized by long investment cycles and high uncertainty of returns, the agency problem may be more pronounced, and managers may reduce green innovation investments due to risk aversion or short-term performance considerations [21]. Existing research suggests that agency costs not only directly affect the level of firms' investment in innovation, but may also have a complex impact on the incentive effects of IP protection through interaction with the external institutional environment. In firms with high agency costs, managers may fail to respond adequately to institutional incentives due to internal governance problems, even if the level of external IP protection is strong. In contrast, the incentive effects of IP protection can be better realized in well-governed firms. This interaction between internal and external institutions offers a new perspective on understanding firm heterogeneity in the effects of IP protection. Based on the above literature, this study proposes hypotheses H3 and H4:

H3: Green agency costs play a complex regulatory role in the relationship between intellectual property protection and green innovation.

H3a: Green agency costs weaken the promotion effect of IP protection on green innovation.

H3b: The moderating effect of green agency costs is significantly different under different levels of IP protection.

H4: There is a triple interaction effect among digital economy, intellectual property protection, and green agency costs.

H4a: The triple interaction of the development level of the digital economy, the intensity of intellectual property protection, and green agency costs has a significant effect on the number of green innovations.

H4b: The triple interaction effect exhibits different modes of action and regime characteristics in the dimension of green innovation quality.

3. Research methodology

3.1 Data

This study employs five main variables to test the research hypotheses. Green innovation is measured from two dimensions: quantity (GreenInnN) using the natural logarithm of green patent applications plus one, and quality (GreenInnQ) using the natural logarithm of green patent citations plus one, with self-citations excluded. Intellectual property protection level (IPProtect) is calculated based on the ratio of intellectual property cases in a city to its GDP, normalized by the national average [22]. The digital economy level (dig_level) is a comprehensive index constructed using the entropy weight method, incorporating digitization-related vocabulary frequency from annual reports, including keywords such as big data, artificial intelligence, and cloud computing. Green agency cost (GreenAgCst) is measured by the ratio of environmental management expenses to operating revenue [23]. Detailed variable definitions are presented in Table 1. The choice of control variables was based on past literature. The specific settings are shown in Table 2. Descriptive statistics of the data are shown in Table 3. The main variables are characterized as follows. The mean values of green innovation quantity (GreenInnN) and quality (GreenInnQ) are 1.129 and 0.915, respectively, with large standard deviations, indicating significant differences in the level of green innovation among enterprises. The mean value of intellectual property protection level (IPProtect) is 0.661, and the mean value of digital economy development level (dig_level) is 0.226. The mean value of green agency cost (GreenAgCst) is close to 0, and the maximum value is only 0.083, which indicates that the cost is relatively low. The control variables are characterized as follows. The average ROA of the sample enterprises is 5.9%, with moderate profitability; the mean value of sales growth rate is 22.5%, but the variation is extremely large (standard deviation of 3.369), reflecting the disparity of enterprise growth; the mean value of TobinQ is 2.139, and the maximum value reaches 56.664, showing that the market valuation is obviously differentiated.

The distribution of financial indicators such as enterprise size and leverage ratio is relatively stable.

Table 1. Main variables

Variable name	Interpretation
GreenInnN	ln(green patent applications + 1)
GreenInnQ	ln(green patent citations + 1), excl. self-citations
IPProtect	(City IP cases/GDP) / (National IP cases/GDP), nationally normalized
dig_level	Entropy-weighted digitalization index (keywords: big data, AI, cloud computing)
GreenAgCst	Environmental management expenses / Operating revenue

Note: ln(x+1) transformation handles zero values following standard patent study practices. GreenInnQ excludes self-citations for quality validity. dig_level uses frequency of digitalization terms from annual reports. IPProtect is normalized for cross-region comparability.

Table 2. Control variables

Variable name	Interpretation
Size	Company size
Lev	Ratio of liability and asset, expressed as gearing
ROA	Net interest rate on total assets
Liquid	Current ratio
Growth	Sales growth rate
Invest	Company investment level
Board	Number of Board of Directors
Indep	Proportion of independent directors
Top5	Shareholding ratio of top five shareholders
TobinQ	Tobin's Q
FirmAge	Company age
ATO	Total asset turnover
CEOHoldR	Number of shares held by CEO
KZIndex	Financing constraints KZ index
PollEmis	Company Pollution Levels
EconDevLvl	Level of urban economic development, log of urban GDP per capita
SecInd	Logarithm of urban secondary sector output
OpenDegree	Degree of openness of the city's economy, total city imports and exports/city GDP
FinDevLvl	Level of urban financial development, total urban savings and loans/urban GDP
HumanCapLv	Level of urban human resources, number of urban university students/total urban population
GovRevenue	Logarithm of municipal revenues
UrbanLvl	Urbanization rate of cities

Note: Variables are measured as ratios (Lev, ROA, Liquid, etc.), frequency-normalized indices (dig_level), or logarithmic transformations (Size, SecInd, GovRevenue) to ensure comparability and normalize distributions.

Figures 1-3 reveal the distributional characteristics of the key variables. Both the quantity of green innovation and the quality of green innovation show typical right-skewed long-tailed distributions, with a large number of firms (about 3,000-3,400 samples) concentrating their green innovation values around 0, indicating that the majority of firms have fewer or missing green innovation activities, while a few firms have a high level of green innovation, which reflects a significant differentiation in green innovation capability among firms. In contrast, the distribution of intellectual property protection level is relatively uniform, showing an approximate normal distribution, with the peak value concentrated in the 0.5-0.8 range, indicating that the differences in intellectual property protection level among enterprises in the samples are relatively small, and the overall level is in the middle of the range. Figure 4 shows the trajectory of the three key variables over the 2014-2022 period: the quantity of green innovation shows a stable linear growth trend, more than doubling from 0.7 to 1.5, reflecting the continued activity of green innovation activities by firms.

Table 3. Descriptive statistics for variables

	Obs	Mean	SD	Min	Max
GreenInnN	6032	1.129	1.448	0.000	7.439
GreenInnQ	6032	0.915	1.328	0.000	7.322
IPProtect	6032	0.661	0.536	0.000	3.751
dig_level	6032	0.226	0.097	0.061	0.566
GreenAgCst	6032	0.000	0.002	0.000	0.083
Size	6032	22.790	1.322	18.370	28.636
Lev	6032	0.412	0.190	0.028	0.943
ROA	6032	0.059	0.047	0.000	0.466
Liquid	6032	2.289	2.097	0.079	38.253
Growth	6032	0.225	3.369	-0.940	251.211
Invest4	6032	0.126	0.186	-0.791	6.443
Board	6032	2.146	0.192	1.099	2.890
Indep	6032	0.374	0.057	0.222	0.800
Top5	6032	0.528	0.147	0.164	0.985
TobinQ	6032	2.139	1.866	0.641	56.664
FirmAge	6032	2.998	0.282	1.609	3.714
ATO	6032	0.655	0.441	0.011	5.116
CEOHoldR	6032	0.029	0.085	0.000	0.667
KZIndex	6032	0.701	1.925	-9.417	7.196
PollEmis	6032	0.145	0.003	0.138	0.152
EconDevLvl	6032	11.441	0.467	9.671	12.293
SecInd	6032	26.409	0.909	22.780	27.766
OpenDegree	6032	0.452	0.352	0.001	1.697
FinDevLvl	6032	3.960	1.692	0.802	13.530
HumanCapLv	6032	0.042	0.030	0.001	0.140
GovRevenue	6032	25.129	1.365	21.159	27.379
UrbanLvl	6032	0.730	0.131	0.257	0.971

Note: This table reports descriptive statistical information for all main and control variables in the study. GreenInnQ is constructed from patent citation data (natural logarithm of citations plus one), with self-citations excluded to ensure quality measurement validity. Patent data are sourced from the China National Intellectual Property Administration (CNIPA) database.

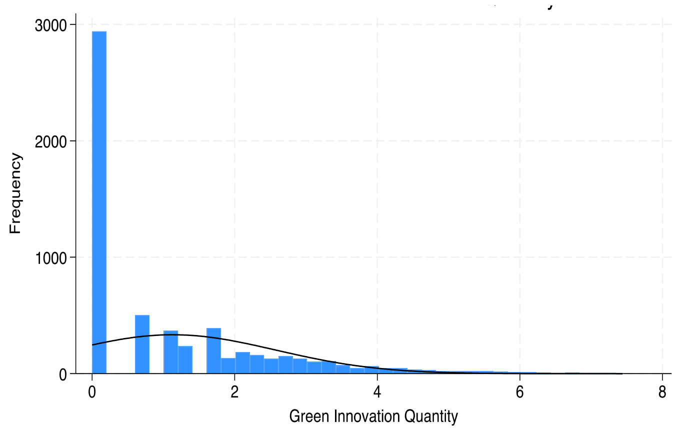

Figure 1. Distribution of green innovation quantity (Note: Data source: EPS database, CSMAR database, and wind database)

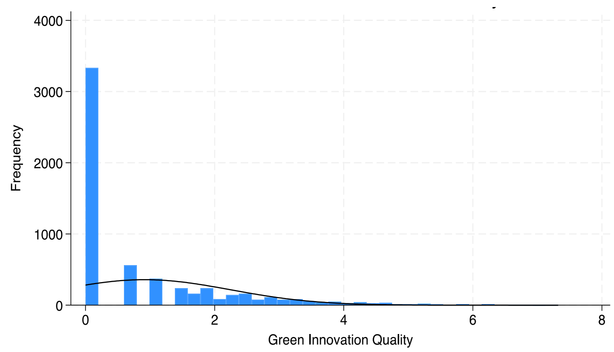

Figure 2. Distribution of green innovation quality (Note: Data source: EPS database, CSMAR database, and wind database)

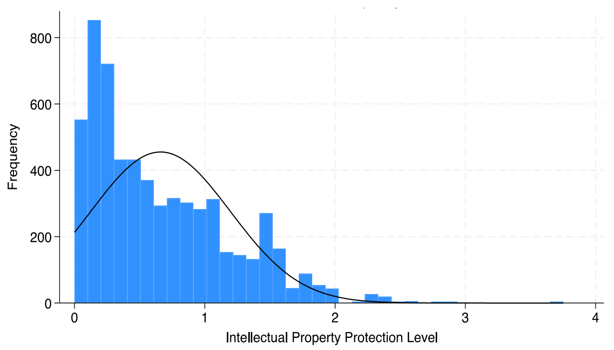

Figure 3. Distribution of intellectual property protection level (Note: Data source: EPS database, CSMAR database, and wind database)

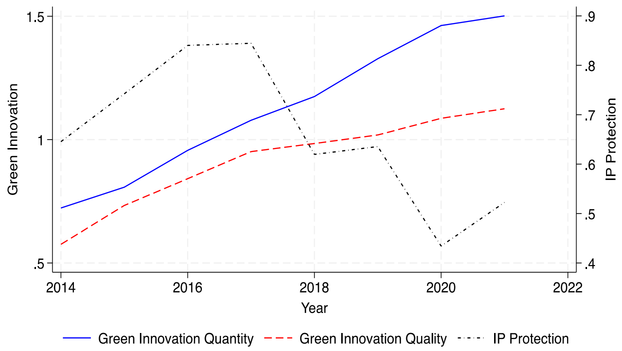

Figure 4. Annual trends of main variables (Note: Data source: EPS database, CSMAR database, and wind database)

The quality of green innovation maintains the same upward trend but with a relatively moderate growth rate from 0.6 to 1.1; and the level of intellectual property rights (IPRs) protection shows an " The level of intellectual property protection, on the other hand, is characterized by an "inverted U-shaped" change, with a significant decline after reaching a peak in 2017 (about 0.85), and then dropping to a low point in 2019-2020 (about 0.45), followed by a slight rebound. This trend suggests that, despite fluctuations in the intellectual property protection environment over the study period, firms' green innovation inputs and outputs have continued to grow, possibly reflecting the roles of other factors, such as policy-driven initiatives, market demand, or technological advances, in driving green innovation.

Figure 5 shows that the level of IP protection is negatively correlated with the number of green innovations (solid line decreasing) in a low digital economy environment (blue dots), while the relationship is relatively flat (dashed level) in a high digital economy environment (pink triangles), implying that the level of digital economy development may modulate the effect of IP protection on green innovation.

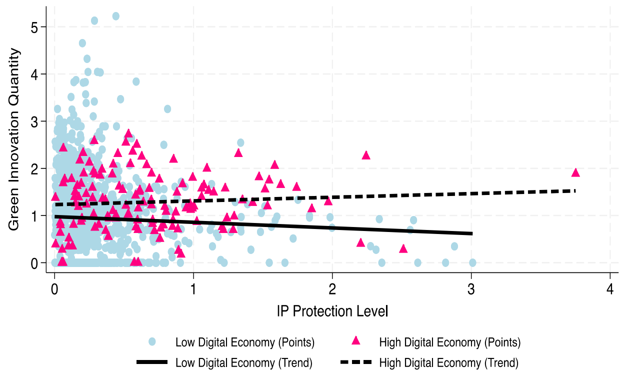

Figure 5. Moderating Effect of Digital Economy Level (Note: Data source: EPS database, CSMAR database, and wind database)

3.2 Model specification

Based on the research hypotheses and theoretical analysis, this study develops a series of progressive econometric models to test the complex relationships among intellectual property protection, digital economy development, and green innovation. To assess the fundamental impact of intellectual property protection on green innovation, this study first develops the following benchmark regression model.

$$GreenInnovation_{i,t} = \alpha_0 + \alpha_1 IPProtect_{i,t} + \alpha_2 Controls_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (1)$$

where $GreenInnovation_{i,t}$ represents the level of green innovation of firm i in year t, which is measured by the quantity of green innovation and the quality of green innovation, respectively; $IPProtect_{i,t}$ denotes the level of intellectual property protection of the region where firm i is located in year t; $Controls_{i,t}$ is the set of control variables; μ_i and λ_t represent firm fixed effects and time fixed effects, respectively; $\varepsilon_{i,t}$ is a randomized disturbance term.

In order to test the moderating effect of the level of digital economy development and green agency costs, this study constructs a moderating effect model with interaction terms. Firstly, the moderating effect of the digital economy is tested:

$$GreenInnovation_{i,t} = \beta_0 + \beta_1 IPProtect_{i,t} + \beta_2 digevel_{i,t} + \beta_3 IPProtect_{i,t} \times digevel_{i,t} + \beta_4 Controls_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (2)$$

Further incorporate green agent costs to construct a triple interaction model:

$$GreenInnovation_{i,t} = \gamma_0 + \gamma_1 IPProtect_{i,t} + \gamma_2 digevel_{i,t} + \gamma_3 GreenAgCt_{i,t} + \gamma_4 IPProtect_{i,t} \times digevel_{i,t} + \gamma_5 IPProtect_{i,t} \times GreenAgCt_{i,t} + \gamma_6 digevel_{i,t} \times GreenAgCt_{i,t} + \gamma_7 IPProtect_{i,t} \times digevel_{i,t} \times GreenAgCt_{i,t} + \gamma_8 Controls_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (3)$$

where $dig_l evel_{i,t}$ denotes the digitization development level of firm i in year t, and $GreenAgCt_{i,t}$ denotes the level of green agency costs of firm *i* in year *t*.

In order to identify the nonlinear characteristics and threshold effects of the impact of intellectual property protection on green innovation, this study adopts the threshold regression model proposed by Hansen [24]. Taking the level of intellectual property protection as the threshold variable, the following model is constructed. When $IPProtect_{i,t} \leq \tau$ (regime 1):

$$GreenInnovation_{i,t} = \delta_0^{(1)} + \delta_1^{(1)} IPProtect_{i,t} + \delta_2^{(1)} digevel_{i,t} + \delta_3^{(1)} GreenAgCt_{i,t} + \delta_4^{(1)} IPProtect_{i,t} \times digevel_{i,t} + \delta_5^{(1)} IPProtect_{i,t} \times GreenAgCt_{i,t} + \delta_6^{(1)} IPProtect_{i,t} \times digevel_{i,t} \times GreenAgCt_{i,t} + \delta_7^{(1)} Controls_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (4)$$

In practical application, this study identifies five IPR protection zone systems (Regime 1-5), corresponding to different thresholds, to form a more refined segmented regression model.

In order to deeply explore the differential moderating effects of the digital economy and green agency costs under different IPR protection regimes, this study constructs an extended model containing a fourfold interaction term:

$$GreenInnovation_{i,t} = \theta_0 + \theta_1 IPProtect_{i,t} + \theta_2 digevel_{i,t} + \theta_3 GreenAgCt_{i,t} + \theta_4 IPProtect_{i,t} \times digevel_{i,t} + \theta_5 IPProtect_{i,t} \times GreenAgCt_{i,t} + \theta_6 IPProtect_{i,t} \times digevel_{i,t} \times GreenAgCt_{i,t} + \sum_{j=1}^{5} \delta_{0+j}\, IPProtect_{i,t} \times digevel_{i,t} \times GreenAgCt_{i,t} \times regime_j + \theta_{12} Controls_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (5)$$

where $regime_j$ is a dummy variable that takes the value of 1 when the level of IPR protection in the region where the firm is located in i^{th} t^{th} year is in the jth zone system, and 0 otherwise.

4. Analysis of empirical results

4.1 Basic regression

The baseline regression results (Table 4) show that the direct effect of intellectual property protection on green innovation is not statistically significant. Neither the linear term (IPProtect) nor the squared term (IPProtect_sq), whose coefficients do not reach the level of statistical significance, indicates that there is no significant direct relationship between intellectual property protection and the quantity and quality of green innovation. Among the control variables, enterprise size (Size) has a significant positive effect on green innovation, leverage (Lev) has a significant negative effect, the financing constraint index (KZIndex) is significantly positive, and the urbanization level (UrbanLvl) has a significant promotion effect on the quantity of green innovation. The adjusted R^2 of the model reaches 0.801 and 0.882, respectively, indicating strong explanatory power. This result implies that there may be a more complex mechanism for the effect of intellectual property protection on green innovation, and other nonlinear models need to be used to find the causal relationship between them.

Table 4. Results of basic regression

	(1)	(2)	(3)	(4)
	Green innovations Number	Green innovations Number	Green Innovation Quality	Green Innovation Quality
IPProtect	0.002	0.023	-0.011	-0.080
	(0.036)	(0.084)	(0.026)	(0.061)
IPProtect_sq		-0.009		0.030
		(0.032)		(0.022)
Size	0.464***	0.464***	0.232***	0.232***
	(0.063)	(0.063)	(0.051)	(0.051)
Lev	-0.385*	-0.385*	-0.366**	-0.368**
	(0.200)	(0.200)	(0.147)	(0.147)
ROA	-0.479	-0.480	-0.213	-0.208
	(0.395)	(0.395)	(0.311)	(0.311)
Liquid	0.004	0.004	-0.010*	-0.010*
	(0.008)	(0.008)	(0.005)	(0.005)
Growth	-0.001	-0.001	0.002*	0.002*
	(0.001)	(0.001)	(0.001)	(0.001)
Invest4	0.126**	0.126**	-0.059	-0.059
	(0.058)	(0.058)	(0.044)	(0.044)
Board	-0.156	-0.155	-0.069	-0.071
	(0.141)	(0.141)	(0.109)	(0.109)
Indep	-0.159	-0.156	-0.448	-0.455*
	(0.374)	(0.374)	(0.274)	(0.273)
Top5	0.140	0.139	-0.280	-0.278
	(0.245)	(0.245)	(0.188)	(0.188)
TobinQ	0.012	0.012	0.007	0.008
	(0.009)	(0.009)	(0.008)	(0.008)
FirmAge	0.207	0.208	0.361	0.360
	(0.392)	(0.392)	(0.276)	(0.276)
ATO	0.127*	0.127*	0.013	0.012
	(0.070)	(0.070)	(0.049)	(0.049)
CEOHoldR	0.304	0.305	0.180	0.177
	(0.269)	(0.268)	(0.197)	(0.196)
KZIndex	0.031***	0.031***	0.032***	0.032***
	(0.008)	(0.008)	(0.008)	(0.008)
PollEmis	-13.825	-13.815	-7.462	-7.496
	(8.597)	(8.598)	(5.931)	(5.943)
EconDevLvl	-0.136	-0.140	0.152	0.164
	(0.168)	(0.168)	(0.119)	(0.119)
SecInd	-0.091	-0.087	-0.093	-0.104
	(0.130)	(0.130)	(0.105)	(0.106)
OpenDegree	0.048	0.046	-0.017	-0.010
	(0.173)	(0.173)	(0.156)	(0.156)
FinDevLvl	0.004	0.004	0.039	0.039
	(0.039)	(0.039)	(0.030)	(0.030)
HumanCapLv	0.391	0.448	-0.847	-1.028
	(2.477)	(2.487)	(2.390)	(2.388)
GovRevenue	-0.045	-0.042	0.141	0.131
	(0.132)	(0.132)	(0.098)	(0.098)
UrbanLvl	1.108**	1.115**	0.025	0.003
	(0.526)	(0.529)	(0.372)	(0.373)
Constant	-3.515	-3.652	-6.711**	-6.270*
	(4.465)	(4.500)	(3.258)	(3.316)
Observations	6031	6031	6031	6031
Adj. R-squared	0.801	0.801	0.882	0.882

Note: ***, **, and * indicate significant at the 1%, 5%, and 10% levels, respectively; standard errors in parentheses; all regressions control for firm, province, region, and year fixed effects and adjust for clustered standard errors at the firm level.

4.2 Threshold regression

The threshold regression results (Table 5) reveal significant nonlinear characteristics in the impact of IPR protection on green innovation, with F-statistics of 16.94 and 11.88, respectively, indicating that the threshold effect is highly significant and verifying the hypothesis of the existence of multiple thresholds for IPR protection. The impact is still positive but decreases significantly in the second zone (0.373**), suggesting a diminishing marginal effect; the third zone turns negative but insignificant (-0.214), suggesting that overprotection may inhibit the diffusion of innovation; and the fourth zone (the highest level of protection) turns positive again but with a weak impact (0.116), reflecting a complex equilibrium in a high protection environment. In contrast, the impact of IPR protection on the quality of green innovation is consistently negative and increasing: the coefficients are negative and mostly significant in all zones, ranging from -0.414 in the first zone to -1.431* in the second zone, showing a strong dampening effect. This counterintuitive result may reflect the phenomenon of the quantity-quality trade-off. Firms are more inclined to pursue a large number of patents than breakthrough innovations under a strong protection environment, or the high cost of protection forces firms to reduce the quality of individual innovations.

Table 5. Threshold regression results

	(1) Green innovations Number	(2) Green Innovation Quality
IPProtect_sq	-0.038	0.070***
IPProtect @ regime1	3.862***	-0.414**
	(1.190)	(0.204)
IPProtect @ regime2	0.373**	-1.431***
	(0.178)	(0.367)
IPProtect @ regime3	-0.214	-0.113*
	(0.179)	(0.061)
IPProtect @ regime4	0.116	-0.174***
	(0.090)	(0.062)
Observations	6032	6032
Adj. R-squared	0.198	0.168
F-statistic	16.94	11.88

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors in parentheses; control variables are included but not reported; all regressions control for firm, province, region, and year fixed effects and adjust for clustered standard errors at the firm level.

4.3 Results of moderated effects regression

The results reveal an important effect reversal: the direct effect of IPR protection is negative (-0.096), but the interaction term with digital economy is significantly positive (0.711**), suggesting that digital economy fundamentally changes the direction of IPR protection's impact. When the digitization level is low, IPR protection may inhibit green innovation; when digitization increases, this negative effect is significantly offset or reversed. The value of 0.711 denotes that by a one-unit increase in digitization, the marginal effect of protection of IPR to green innovation increases by around 0.71 units, which determines the causal importance of the digital economy as an "institutional enhancer" (Table 6). Triple interaction analysis produces nonlinear relations of regulation between regimes. The reinforcing regime with a coefficient of 6.854 is the first regime, and the digital economy is "compensatory" in environments of poor protection for IPRs. The middle regimes (2-3) are stable with coefficients of 0.000. The high protection regimes (4-5) produce differentiation effects with coefficients of -0.024 and 1.111 and have complex dynamics between institutional excess and technological empowerment (Table 7).

In contrast with innovation quantity outcomes, the digital economy's moderating effect on innovation quality is significantly ineffective. The value of the interaction term's coefficient (IPProtect × dig_level) is -0.085 and is not significantly effective, essentially the opposite of the significantly positive 0.711 for innovation quantity. This finding indicates dimension-specificity: digital technologies excel best in supporting innovation scale extension but are less effective in stimulating innovation depth and breakthrough quality. The information economy is more of an "efficiency amplifier" and not a "quality enhancer." The regime triple interaction terms also confirm this trend. The initial regime coefficient is 2.551, but has a very high standard error of 3.537, i.e., exceedingly uncertain. The fourth regime coefficient is -0.882 and suggests that the digital economy may even negatively regulate innovation quality in high protection settings, possibly an indication of built-in competition among digital standardization tools and innovation peculiarity.

Table 6. Moderating effects of the digital economy (number of green innovations)

Variables	(1) Basic model	(2) Regime 1	(3) Regime 2	(4) Regime 3	(5) Regime 4	(6) Regime 5
IPProtect	-0.096	-0.140	-0.096	-0.096	-0.116	-0.064
	(0.100)	(0.101)	(0.100)	(0.100)	(0.113)	(0.155)
IPProtect×dig_level	0.711**	0.772**	0.711**	0.711**	0.766	0.454
	(0.295)	(0.268)	(0.295)	(0.295)	(0.465)	(0.462)
Triple interaction by regime:						
IPProtect×dig_level ×regime1	-	6.854	-	-	-	-
IPProtect×dig_level ×regime2	-	-	0.000	-	-	-
IPProtect×dig_level ×regime3	-	-	-	0.000	-	-
IPProtect×dig_level ×regime4	-	-	-	-	-0.024	-
IPProtect×dig_level ×regime5	-	-	-	-	-	1.111
Standard errors	-	(3.907)	(.)	(.)	(0.525)	(0.627)
Model statistics:						
Observations	6028	6028	6028	6028	6028	6028
Adj. R-squared	0.803	0.803	0.803	0.803	0.803	0.803

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors in parentheses; control variables are included but not reported; all regressions control for firm, year, industry, province, and region fixed effects.

Table 7. Moderating effects of the digital economy (green innovation quality)

Variables	(1) Basic model	(2) Regime 1	(3) Regime 2	(4) Regime 3	(5) Regime 4	(6) Regime 5
Main effects:						
IPProtect	-0.066	-0.076	-0.066	-0.066	-0.170*	-0.041
	(0.072)	(0.085)	(0.072)	(0.072)	(0.091)	(0.117)
IPProtect×dig_level	-0.085	-0.249	-0.085	-0.085	0.432	0.142
	(0.173)	(0.145)	(0.173)	(0.173)	(0.281)	(0.496)
Regime-specific interactions:						
IPProtect×dig_level×regime	-	2.551	0.000	0.000	-0.882	0.027
	-	(3.537)	(.)	(.)	(0.480)	(0.612)
Model statistics:						
Observations	6028	6028	6028	6028	6028	6028
Adj. R-squared	0.883	0.883	0.883	0.883	0.883	0.883

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors in parentheses; control variables are included but not reported; all regressions control for firm, year, industry, province, and region fixed effects.

Figure 6 clearly shows the divergence pattern between the level of IPR protection and the quantity and quality of green innovations: the quantity of green innovations shows a "U-shaped" trajectory, dropping from 1.25 at the low level of protection to a low of 1.00 at the medium level, and then rebounding to 1.06 at the medium-high level of protection; whereas the quality of green innovations shows a continuous monotonically decreasing trend, dropping from 1.09 at the low level to 0.47 at the medium-high level, a drop of more than 50%. to 0.47 at medium-high protection, a decrease of more than 50%. This comparison validates the core finding of the threshold regression. IPR protection has distinct impacts on the "quantity" and "quality" of innovation - moderate protection is conducive to quantitative growth, but a strong protection environment may incentivize firms to pursue easily accessible incremental innovations at the expense of breakthrough quality innovations, resulting in structural changes in innovation that "compensate for quantity and dilute quality".

The results reveal a complex multilevel moderating mechanism (Table 8). The moderating effect of digital economy remains significant (0.763**), but the addition of green agency costs produces a "moderating the moderator" effect: the triple interaction term IPProtect×dig_level×GreenAgCt coefficient is -217.524, implying that green agency costs may systematically weaken the positive moderating effect of digital economy. Being a mirror of governance problems within, green agency fees act as a "friction brake" on the synergies of intellectual property rights and the digital economy.

The quadrupled interaction term discloses regime heterogeneity at the extremes. For regime 1 (lowest protection), the coefficient is 4726.206*, indicating a "compensatory explosion" effect—where there is a lack of external institutional protection, internal agency conflicts push firms to implement more robust internal control mechanisms, and digital technology offers useful coordination tools, which leads to unexpected synergistic improvement. By way of comparison, regime 4 (medium-high protection) has a highly negative coefficient (-1266.740**), resonating with "institutional overload"—where IPR protection is highly developed externally, the interaction between high green agency costs and digitization may create negative synergies via excessive institutional intricacy.

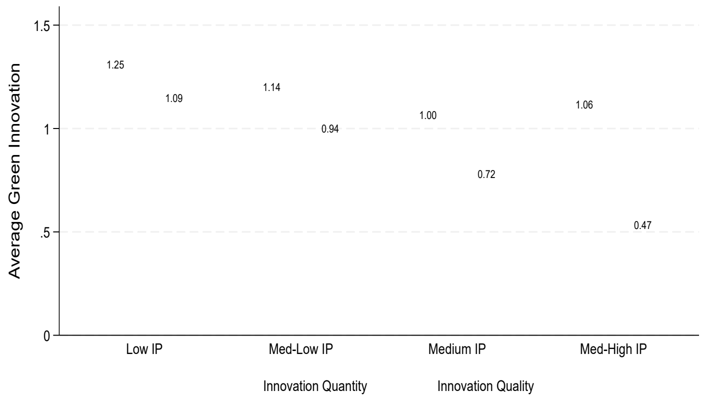

Figure 6. The moderating effect of the digital economy level (Note: Data source: EPS database, CSMAR database, and wind database)

As for innovation quality results, green agency costs have entirely dissimilar moderating processes in regard to quality (Table 9). The net moderating effect of electronic economy (IPProtect × dig_level) is -0.084 and not significant, merely different from the highly significant positive 0.763 in quantity. The IPProtect×dig_level×GreenAgCt three-way interaction term is -86.955, indicating that agency costs can work through a "quality dilution effect"—the management is likely to seek short-term tangible outputs instead of long-term quality breakthroughs. The quadruple interaction term is extremely polarized. In regime 1, the coefficient stands at -583.668, and this indicates a "quality trap" in that, under weak institutional contexts, companies are subject to greater uncertainty, and agency costs impose short-termism, rendering quality innovation problematic in spite of digital facilitation. On the other hand, with regime 5 (greatest protection), the coefficient strongly becomes positive (1302.802*), depicting a "quality burst" effect—at the greatest level of institutional protection, safe property rights ensure long-term investment in quality, and agency costs no longer deter innovation but potentially create quality breakthroughs under competitive pressure. The substantial negative direct effect of IPR protection (-0.178*) in regime 4 and the substantial positive quadruple interaction in regime 5 imply a high institutional threshold effect on quality innovation.

Table 8. Moderating effects of green agency costs (green innovation numbers)

Variables	(1) Basic	(2) Regime 1	(3) Regime 2	(4) Regime 3	(5) Regime 4	(6) Regime 5
Main and interaction effects:						
IPProtect	-0.106	-0.165	-0.106	-0.106	-0.120	-0.078
	(0.092)	(0.099)	(0.092)	(0.092)	(0.102)	(0.159)
IPProtect×dig_level	0.763**	0.859**	0.763**	0.763**	0.793	0.482
	(0.281)	(0.295)	(0.281)	(0.281)	(0.446)	(0.563)
IPProtect×GreenAgCt	30.718	73.740	30.718	30.718	16.247	-4.582
	(48.099)	(40.508)	(48.099)	(48.099)	(49.173)	(118.256)
IPProtect×dig_level×GreenAgCt	-217.524	-499.035*	-217.524	-217.524	-118.789	-144.291
	(255.891)	(240.717)	(255.891)	(255.891)	(265.735)	(435.164)
Quadruple interactions:						
Regime-specific coefficient	-	4726.206*	0.000	0.000	-1266.740**	323.989
Standard error	-	(2323.924)	(.)	(.)	(476.706)	(483.216)
Model statistics:						
Observations	6028	6028	6028	6028	6028	6028
Adj. R-squared	0.803	0.803	0.803	0.803	0.803	0.802

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors in parentheses; control variables are included but not reported; all regressions control for firm, year, industry, province, and region fixed effects.

Table 9. Moderating effects of green agency costs (green innovation quality)

Variables	(1) Basic	(2) Regime 1	(3) Regime 2	(4) Regime 3	(5) Regime 4	(6) Regime 5
Main and interaction effects:						
IPProtect	-0.063	-0.063	-0.063	-0.063	-0.178*	-0.041
	(0.072)	(0.087)	(0.072)	(0.072)	(0.093)	(0.117)
IPProtect×dig_level	-0.084	-0.272	-0.084	-0.084	0.498	0.142
	(0.170)	(0.146)	(0.170)	(0.170)	(0.280)	(0.496)
IPProtect×GreenAgCt	7.916	-0.198	7.916	7.916	26.102	76.102
	(8.973)	(18.269)	(8.973)	(8.973)	(20.973)	(45.401)
IPProtect×dig_level×GreenAgCt	-86.955	-67.974	-86.955	-86.955	-192.288	-295.110*
	(50.729)	(136.337)	(50.729)	(50.729)	(134.370)	(135.367)
Quadruple interactions:						
Regime-specific coefficient	-	-583.668	0.000	0.000	209.071	1302.802*
Standard error	-	(1309.582)	(.)	(.)	(296.253)	(588.810)
Model statistics:						
Observations	6028	6028	6028	6028	6028	6028
Adj. R-squared	0.883	0.884	0.883	0.883	0.883	0.883

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors in parentheses; control variables are included but not reported; all regressions control for firm, year, industry, province, and region fixed effects.

The gigantic coefficient 1302.802 in regime 5 implies a high sensitivity of quality innovation choices, displaying a characteristic "quality leverage effect"—quality innovation is more susceptible to steep fluctuations from institutional, governance, and technological situations than the relative stability of quantitative innovation.

5. Discussion and policy recommendations

This research illustrates the non-linear, intricate effect of intellectual property protection on green innovation, refuting the conventional linear hypothesis of 'more protection equals more innovation'.

Threshold regression estimates confirm a "U-shaped" relationship between intellectual property protection and the number of green innovations, yet the quality of innovation remains negatively impacted. This quantitative-qualitative asymmetry is representative of the structural asymmetry of the current system of patents to overweight measurable outputs of innovation and not to establish strong incentives for innovative breakthroughs. The policymakers have to create a differentiated protection system for intellectual property, with standard protection for progressive green innovations and shorter protection terms and weaker protection for breakthrough innovations, and a mechanism for assessing the quality of innovations, synthesizing technological advancement and ecological merits into a unified consideration, so as not to miss the problem of quality dilution due to sheer quantitative focus [25]. The digital economy's moderating role is typically dimension-specific: it operates very effectively to energize the amount of innovation but ineffectively to moderate the quality of innovation. Digital technologies primarily enhance substantive green innovation rather than serving as universal quality enhancers [12], as their advantages in facilitating innovation scale-up do not fully translate to breakthrough innovations requiring deep insights and long-term experimentation. Future research should explore AI-specific digital tools designed to support quality innovation through enhanced R&D analytics and knowledge integration [26]. From this consciousness, the Government needs to adopt a clear policy to promote digitalization [27]: on the one hand, for green innovation for quantitative growth, it shall emphasize building strong digital infrastructure construction and cultivating digital platform development; on the other hand, for quality breakthrough-type innovation, it shall depend more on conventional R&D factors, human resource cultivation and foreign cooperation, and shun the tendency of short-termism most likely brought about by overdependence on digitalization tools.

The green agency cost moderating effect highlights the central role of internal corporate governance and its intricate interaction with the institutional environment in the external environment. When there is poor IPR protection, agency costs can induce firms to create more efficient internal controlling systems, and new information and communication technologies offer effective coordinating mechanisms that yield synergistic benefits [28]. In a well-protected environment, high agency costs and the complexity of the external institutional environment may result in institutional overload and increase the burden of decision-making [29]. This dynamic game relationship between internal and external systems requires enterprises to establish governance mechanisms that are compatible with the external environment: weak systems need to strengthen internal control systems and digital applications, while perfect systems should focus on governance streamlining and long-term incentives. Threshold regression and moderating effect analysis together reveal the significant differences in policy effects under different institutional environments, providing a scientific basis for the implementation of district-oriented and precise policies. Regions with a low level of IPR protection should focus on the construction of basic systems and digital empowerment by strengthening laws and regulations, improving enforcement mechanisms, and promoting the construction of digital infrastructure [30]. Regions with moderate levels of protection should turn to system optimization and quality enhancement, establish classified protection mechanisms, and develop high-end R&D services and technology transfer [31,32]. Regions with a high level of protection need to prevent over-protection by improving patent examination standards, compulsory licensing systems, and other measures, and at the same time strongly support basic research and original innovation [33].

The construction of a systemic green innovation policy framework needs to be coordinated across multiple dimensions, including intellectual property protection, digital economy development, and improved corporate governance. Such a framework should be differentiated and dynamic, taking into account the differences in the stages of development of different regions, as well as the different needs for the quantity and quality of innovation. In the long term, a dynamic adjustment mechanism for the level of intellectual property protection should be established [34], the deep integration of the digital economy and green innovation should be promoted [35], a new model of digital technology supporting quality innovation should be explored, and the long-term mechanism of corporate governance for green innovation should be improved, so as to promote the sustainable enhancement of the green innovation capacity of corporations through legal improvement, incentive optimization and monitoring and evaluation measures [36].

6. Conclusion

This study systematically investigates the complex relationship between intellectual property protection, digital economy development, and corporate green innovation through threshold regression and moderated regression analysis of Chinese listed companies from 2014-2022. Our findings fundamentally challenge the conventional linear assumption that stronger IPR protection uniformly promotes innovation. The empirical evidence reveals a U-shaped relationship between IPR protection and green innovation quantity, with five distinct threshold regimes demonstrating varying policy effectiveness across different institutional maturity levels. Critically, IPR protection exhibits persistent negative effects on innovation quality across all regimes, suggesting a troubling quantity-quality trade-off in which enterprises strategically prioritize patent volume over breakthrough innovations in strong protection environments. The research makes three substantive contributions to innovation theory and policy design. Theoretically, we advance green innovation literature by identifying threshold effects and dimensional asymmetries between innovation quantity and quality, demonstrating that institutional impacts are regime-dependent rather than uniform across development stages. Methodologically, our integrated analytical framework combining threshold regression with triple and quadruple interaction analysis successfully captures the complex interplay among institutional protection, technological infrastructure, and corporate governance mechanisms. In practice, we provide robust empirical evidence for policymakers to design regime-specific strategies: low-protection regions should prioritize strengthening institutional foundations and digital infrastructure; moderate-protection regions should optimize quality-oriented mechanisms and knowledge diffusion channels; while high-protection regions must prevent over-protection that stifles knowledge flow and quality breakthroughs. Future research should extend this framework across different national contexts to test generalizability beyond the Chinese setting, examine the dynamic mechanisms underlying threshold transitions over longer time horizons, and explore industry-specific heterogeneities in how firms respond to institutional and technological changes. Additionally, investigating the role of emerging digital technologies, such as artificial intelligence and blockchain, in supporting quality innovation is a promising avenue for advancing our understanding of the effectiveness of innovation policy in the rapidly evolving digital era.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically regarding authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with research ethics policies. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the authors.

Conflict of interest

The authors declare no potential conflict of interest.

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