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-RESEARCH ARTICLE-

DIGITALIZATION, GREEN INNOVATION AND INDUSTRIAL UPGRADING: THE MODERATING ROLE OF ENVIRONMENTAL REGULATION IN CHINESE MANUFACTURING

Dandan Fu

PhD candidate, School of Business and Economics, Universiti Putra Malaysia, Selangor, Malaysia
ORCID: https://orcid.org/0009-0009-1328-7390
Email: fdd345311@126.com

***Suryati Ishak (Corresponding Author)**

Assistant Professor, School of Business and Economics, Universiti Putra Malaysia, Selangor, Malaysia
ORCID: https://orcid.org/0000-0001-5561-6505
Email: suryatiis@upm.edu.my

Yasmin Bani

Assistant Professor, School of Business and Economics, Universiti Putra Malaysia, Selangor, Malaysia
ORCID: https://orcid.org/0000-0002-1950-7771
Email: nor_yasmin@upm.edu.my

Olohunlana Somod Dapo

PhD candidate, School of Business and Economics, Universiti Putra Malaysia, Selangor, Malaysia
ORCID: https://orcid.org/0000-0002-5477-6520
Email: gs65052@upm.edu.my

─Abstract─

This study examines whether firm-level digitalization promotes green innovation and whether this relationship becomes stronger in the presence of environmental regulation.

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Using an unbalanced panel comprising 2,356 Chinese manufacturing A-share firms and 16,787 firm-year observations covering 2014–2023, the study employs the System GMM estimator to capture the dynamic relationships between the variables. The results indicate a positive relationship between digitalization and green patent applications, with the finding remaining robust when alternative patent measures and winsorised specifications are employed. Furthermore, the interaction between digitalization and environmental regulation demonstrates a complementary effect, indicating that regulatory intervention strengthens the economic benefits associated with digitalization by directing information, capital, and managerial resources towards cleaner forms of innovation. These findings offer relevant implications for industrial upgrading and green-transition policies in emerging economies.

Keywords: Digitalization; Green Innovation; Environmental Regulation; Manufacturing; Industrial Upgrading.

INTRODUCTION

Manufacturing occupies a central position in structural transformation because it contributes substantially to capital accumulation, employment generation, productivity growth, technological learning, and export competitiveness. China provides a particularly clear illustration of this role. Its manufacturing sector has evolved from an economy primarily receiving industrial relocation into one capable of sustaining extensive production networks both domestically and internationally. At the same time, the country's development priorities have increasingly moved towards higher value-added activities, innovation-led development, and more sustainable economic growth (Li, 2012; Yihsing Yang et al., 2013). Consequently, innovation has become increasingly important to firm-level economic development, requiring enterprises to strengthen productivity and competitive performance while simultaneously reducing the resource consumption and environmental burdens associated with production.

Within this context, green innovation extends beyond the pursuit of environmental improvement alone. It encompasses the development or enhancement of products, processes, and technologies capable of reducing energy use, material consumption, emissions, and waste. It may also generate productivity and competitive benefits when environmental considerations are embedded within production systems and product-development activities (Chen et al., 2006; Eiadat et al., 2008; Fussler, 1996). However, firms face an important economic dilemma when undertaking green innovation because the returns from such investments can be uncertain and may materialise only over an extended period. Moreover, part of the environmental benefit generated by cleaner technologies accrues to society rather than exclusively to the investing firm. Thus, technologies capable of producing positive social returns may remain under adopted when private incentives are insufficient. This tension represents an important challenge

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for innovation economics, industrial upgrading, sustainable development, and managerial decision-making.

Digitalization changes the conditions under which firms undertake such investments. Technologies including industrial internet applications, enterprise systems, artificial intelligence, data analytics, and intelligent production equipment strengthen firms' capacity to acquire, integrate, and analyse information. Through these capabilities, firms can reduce information-search and coordination costs, improve production monitoring, support predictive maintenance, identify inefficiencies in material and energy use, and shorten the feedback cycle connecting research, production, and customers. Such capabilities can increase the efficiency of green R&D while also supporting the identification and development of innovative products with commercial potential. Evidence from China broadly indicates a positive association between digitalization and green innovation, productivity, or green productivity (Gao et al., 2022; Lee et al., 2023; Luo et al., 2023).

Nevertheless, digitalization should not be regarded as inherently green. Its implementation requires financial investment, managerial resources, and energy, while ineffective coordination can produce duplicated systems, fragmented information environments, and temporary diversion of resources away from R&D. Furthermore, the expansion of digital infrastructure itself can increase electricity consumption and associated emissions. Accordingly, the economic value generated by digitalization depends partly on how firms deploy their digital capabilities, particularly whether these capabilities are directed towards productive and innovation-enhancing activities or adopted primarily as an end in themselves (Ardito et al., 2021; Avom et al., 2020). This makes the institutional environment particularly consequential. Environmental regulation can alter the relative economic costs associated with pollution-generating inputs and outputs, reduce uncertainty concerning future environmental standards, and encourage firms to redirect resources towards cleaner technologies. Although appropriately designed regulation can impose short-run costs, it may simultaneously stimulate innovation that improves productivity, consistent with the Porter and van der Linde hypothesis (Gollop Frank & Roberts Mark, 1983; Porter & van der Linde, 1995).

The central issue, therefore, extends beyond determining whether digitalization is associated with green innovation. It is also necessary to establish the conditions under which digital capabilities are translated into green innovation and to determine how this relationship changes within different economic and institutional settings. To address this issue, the study examines an unbalanced panel of Chinese manufacturing firms listed on the Chinese A-share market over the 2014–2023 period. Green innovation is measured as the logarithm of green patent applications, whereas digitalization is captured through the number of digital-technology keywords appearing in firms' annual reports. Environmental regulation is measured using the ratio of regional expenditure on air- and water-pollution control to total industrial output. The empirical investigation

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adopts a dynamic panel framework and applies System GMM to examine the relationship between digitalization and green innovation and to assess whether environmental regulation moderates this relationship.

The study makes four contributions. First, it conceptualises digitalization as an economic capability that can improve the efficiency and effectiveness of innovation investment while strengthening firm productivity and competitiveness, rather than treating it solely as an instrument of environmental management. Second, it integrates Information Processing Theory with innovation economics, institutional economics, and the dynamic-capabilities perspective to explain how digital capability can be converted into green innovation outcomes. Third, it clarifies the role of environmental regulation in reshaping firm incentives, directing resource allocation, and influencing the returns associated with digital investment. Fourth, the Chinese manufacturing setting provides evidence from a large emerging economy undergoing simultaneous digital and green transformations. The findings consequently offer useful insights for other economies seeking industrial transformation while facing resource limitations and environmental pressures. The remainder of the article develops the theoretical framework and hypotheses, describes the research design, reports the empirical findings, discusses their economic implications, and concludes by outlining policy implications and study limitations.

THEORETICAL FRAMEWORK AND HYPOTHESES

Information Processing Theory

Information Processing Theory rests on the premise that organisations operate under conditions of uncertainty while facing inherent limitations in their capacity to acquire, process, and utilise information and knowledge (Simon, 1947). Galbraith (1974) conceptualises the organisation as an information-processing system in which organisational structures and technologies should correspond to the volume of information required for effective decision-making. Increasing uncertainty consequently creates a greater need for firms to strengthen their mechanisms for collecting, interpreting, communicating, and receiving feedback from information. Digitalization can enhance this organisational capacity by integrating information across functional areas, reducing delays in reporting, and providing managers with greater visibility of operational and environmental conditions.

For manufacturing firms, this theoretical perspective provides a basis for explaining the direct association between digitalization and green innovation. Digital simulation can allow alternative production processes or product designs to be assessed before firms commit resources to physical implementation. At the same time, integrated databases can facilitate coordination among R&D, production, procurement, and suppliers by reducing informational barriers between these activities. The availability of real-time

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production information can further assist firms in detecting energy inefficiencies and identifying sources of emissions. More effective information management can also connect environmental outcomes with financial and operational performance, allowing firms to evaluate green projects more systematically. Consequently, improved information-processing capabilities may strengthen the selection of promising environmental projects and facilitate the reallocation of resources towards practical innovations that generate both environmental and business benefits (Cegielski et al., 2012; Wei & Sun, 2021). This theoretical reasoning provides support for the baseline proposition that greater digitalization can contribute to higher levels of green innovation.

Innovation Economics and Sustainable Productivity

From the perspective of innovation economics, economic development is driven by the continual introduction of new combinations of technologies, knowledge, and production processes (Schumpeter, 1934). Endogenous growth theory similarly emphasises that technological progress and the accumulation of knowledge contribute directly to sustained productivity growth rather than functioning merely as exogenous determinants (Romer Paul, 1990). Green innovation is consistent with this theoretical perspective because it can produce new products and production methods while reducing environmental externalities. Digitalization can expand the knowledge resources available to firms while lowering the costs associated with experimentation, information search, and coordination. It can also improve the effectiveness of existing research teams by automating routine information-processing activities and creating stronger links between design decisions and production-related information.

This perspective also provides an alternative interpretation of green patenting. Although patent applications represent an imperfect proxy for innovation, they provide a measurable indication of a firm's commitment of knowledge, financial resources, and managerial effort towards developing technically viable and protectable solutions. By reducing information and coordination costs, digitalization can increase the expected productivity of innovation-related investments that depend on information integration and coordination. At the industry level, these firm-level improvements may contribute to industrial upgrading by encouraging production to move towards higher-value capabilities and technologies with greater resource efficiency. The resulting economic benefits may therefore operate through two complementary channels: lower environmental pressure and stronger competitiveness based on innovation. This mechanism is consistent with existing evidence at both the firm and city levels (Chen et al., 2024; Jia et al., 2022; Wang et al., 2023).

Institutional Economics and Environmental Regulation

Institutional economics emphasises how formal rules, enforcement arrangements, and

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incentive structures shape the behaviour and decisions of economic actors (North, 2012). From this perspective, environmental regulation constitutes an institutional mechanism capable of changing the relative returns associated with polluting activities and cleaner technologies. Command-and-control standards can increase the financial consequences of non-compliance, whereas price-based instruments can alter the economic cost of pollution. Similarly, environmental disclosure and monitoring requirements may influence corporate reputation, access to finance, and pressure from stakeholders. Through these channels, regulatory institutions affect not only environmental outcomes but also firms' decisions concerning capital allocation, including the balance between compliance expenditure, conventional growth-oriented investment, and innovation.

From a conventional cost-effectiveness perspective, environmental regulation may also divert resources away from other productive activities. The burden of compliance can be particularly significant for firms with limited financial slack or weaker technological capabilities (Gollop Frank & Roberts Mark, 1983; Tang et al., 2020). The Porter perspective, however, considers regulation in dynamic rather than purely cost-based terms. Well-designed and forward-looking regulatory measures can expose existing inefficiencies, stimulate technology-oriented problem solving, and generate demand for environmentally cleaner products. Regulation may consequently increase the private value of digital systems capable of monitoring environmental performance, detecting process inefficiencies, and facilitating compliance at lower cost. Evidence from China indicates that environmental regulation can contribute positively to green innovation, intelligent upgrading, and industrial restructuring, although the magnitude and direction of these effects depend on regulatory intensity and the effectiveness of implementation (Cui et al., 2022; Meng et al., 2020; Yin et al., 2024).

Accordingly, this study conceptualises environmental regulation not only as a direct determinant of green innovation but also as a moderating condition affecting the value of digitalization. Under relatively weak regulatory pressure, firms may direct digital investments primarily towards production speed, operational scale, or conventional cost reduction. As environmental pressure increases and remains sufficiently predictable, the opportunity cost associated with neglecting environmental performance also becomes greater. Digital capabilities may then acquire additional value because they facilitate emissions monitoring, compliance documentation, resource-efficiency improvements, and the identification of opportunities for green R&D. Environmental regulation can therefore complement digitalization by directing information, managerial attention, and financial resources towards green innovation. Nevertheless, the empirical specification tests a linear interaction effect and does not imply that an intermediate level of regulation is necessarily optimal, nor does it rule out potentially adverse effects arising from excessively stringent regulation.

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Firm Capabilities and Hypotheses Development

The dynamic-capabilities perspective helps explain why identical technologies or regulatory conditions may produce different outcomes across firms. Dynamic capabilities refer to an organisation's ability to recognise opportunities and threats, respond through appropriate investment decisions, and reconfigure its resources as circumstances evolve (Teece, 2007; Teece et al., 1997). In this study, digitalization is therefore conceptualised as a capability rather than as a simple possession of hardware or software. Its economic value does not arise automatically from acquiring digital technologies. Instead, value emerges when firms embed these technologies within organisational workflows to detect production problems, integrate and coordinate knowledge, adjust production configurations, and derive learning from performance data.

The four theoretical perspectives provide complementary explanations of the proposed relationship. Information Processing Theory explains the informational mechanism through which digitalization can improve the acquisition, integration, and use of information. Innovation economics clarifies why improved information-processing capabilities can increase the productivity and commercial potential of green R&D. Institutional economics explains how environmental regulation reshapes the incentives and constraints confronting firms. The dynamic-capabilities perspective, in turn, explains how firms can transform digital resources into innovation outcomes by adapting, integrating, and reconfiguring those resources in response to changing conditions. Taken together, these perspectives imply that greater digitalization should be associated with stronger green innovation. They further suggest that this association can become more pronounced under environmental regulation because regulatory pressure can increase the economic value of using digital information to improve cleaner production and develop environmentally oriented technologies.

H1: *The positive correlation between digitalization and green innovation performance of manufacturing firms is confirmed.*
H2: *The link between digitalization and green innovation can be strengthened by an increase in environmental regulatory intensity.*

RESEARCH DESIGN

Data and Sample

The empirical analysis focuses on Chinese manufacturing firms listed on the A-share market during 2014–2023. Following the screening procedures and the availability of the required variables in the source study, the resulting unbalanced panel comprises 2,356 firms and 16,787 firm-year observations. Firm-level information concerning digitalization is manually identified and extracted from corporate annual reports, while green patent data are obtained from the China National Intellectual Property

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Administration. Regional data on pollution-control expenditure and industrial output are collected from provincial statistical yearbooks, and firm-level control variables are sourced from CSMAR. This multi-source data structure integrates information on firm-level innovation and financial characteristics with the regional institutional environment in which individual firms operate.

Variable Measurement

Green Innovation

Green innovation (GI) is measured as the natural logarithm of one plus the number of green patent applications. This measure captures the flow of firms' innovative efforts through patent applications and is suitable for the dynamic analysis because innovation-related decisions may generate effects that persist over time. Applying the logarithmic transformation reduces the influence of unusually large patent counts while also accommodating observations with zero applications. As a robustness measure, the study additionally uses the natural logarithm of one plus the number of granted green patents (GIgrants). Granted patents have undergone an additional examination stage and therefore provide a more stringent representation of realised green-innovation output (Fan et al., 2023; Hao & He, 2022).

Digitalization

Digitalization (Digital) is operationalised through text mining of firms' annual reports. The source study first identifies keywords associated with modern information systems, artificial intelligence, internet-based business models, and digital-technology applications. Statements containing negative terms are subsequently excluded, after which the number of relevant digital terms appearing in each firm-year report is calculated. This measure captures the extent to which digital transformation is reflected in a firm's strategic and operational disclosures. Rather than representing the adoption of any single technology, the indicator is intended to reflect the broader degree of digital orientation and deployment evident from corporate reporting (Dong & Netten, 2017; Li et al., 2023).

Environmental Regulation

Environmental regulation (ER) is operationalised as the proportion of regional expenditure on air- and water-pollution control relative to total industrial output for the corresponding region and year. A larger value of this ratio represents greater regulatory and compliance pressure. The regional nature of this indicator makes it appropriate for analysing listed firms within a panel framework because firms operating in different regions are exposed to variations in regulatory conditions. At the same time, the measure may not fully capture forms of informal environmental supervision that influence firms without being reflected in recorded expenditure. The indicator follows

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the expenditure-based approach adopted in previous research examining environmental regulation and green technological innovation (Ren et al., 2024; Shao & Chen, 2023).

Control Variables

The empirical models incorporate several firm-level control variables, namely firm age, firm size, profitability, ownership concentration, fixed-asset intensity, cash ratio, and state ownership. Firm age is measured as the natural logarithm of establishment age plus one, whereas firm size is represented by the natural logarithm of total assets. Profitability is captured through return on assets, calculated as net income divided by total assets. Ownership concentration is measured by the proportion of shares held by the ten largest shareholders. Fixed-asset intensity is calculated as net fixed assets relative to total assets, while the cash ratio is defined as operating cash flow divided by total assets. State ownership is represented by a binary variable that takes a value of 1 for state-owned firms and 0 otherwise. These control variables account for differences in firms' resource endowments, organisational maturity, ownership structures, and financial capacity, all of which may influence both digitalization and green innovation.

Empirical Models

Baseline Model

Green innovation may exhibit path dependence because firms with established R&D practices or accumulated knowledge relating to patents and cleaner production are better positioned to undertake subsequent innovation. At the same time, digitalization may be endogenous if firms that are already more innovative or economically successful are more likely to allocate resources towards digital systems. These issues create potential concerns regarding dynamic persistence, unobserved firm-specific effects, and reverse causality. To address these econometric concerns, the study specifies a dynamic panel model and estimates it using the System GMM approach (Arellano, 1991; Blundell & Bond, 1998). The baseline specification is:

$$GI_{it} = \alpha + \rho GI_{i,t-1} + \beta Digital_{it} + \gamma' X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

GI_it denotes green innovation for firm i in time t, GI_i,t−1 denotes its one-period lag, Digital_it denotes the level of digitalization, X_it denotes the vector of the firm's other controls, μ_i denotes the time-invariant firm specific effects, and ε_it denotes the idiosyncratic errors. The coefficient β provides the basis for testing H1. Incorporating the lagged dependent variable as an endogenous regressor captures the persistence of green innovation over time and thereby helps reduce potential bias arising from pre-existing innovation trends.

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Moderation Model

To determine whether environmental regulation conditions the effect of digitalization on green innovation in China's manufacturing sector, the baseline specification is extended to incorporate environmental regulation and its interaction with digitalization. The resulting model is specified as follows.

$$GI_{it} = \alpha + \rho GI_{i,t-1} + \beta_1 Digital_{it} + \beta_2 ER_{it} + \beta_3 (Digital_{it} * ER_{it}) + \gamma' X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

In Equation (2), ER_{it} represents the intensity of environmental regulation, while the interaction term $Digital_{it} * ER_{it}$ captures its moderating effect on the relationship between digitalization and green innovation. The statistically significant coefficient β_3 would indicate that environmental regulation changes the strength or direction of the relationship between digitalization and green innovation.

Estimation and Diagnostic Strategy

System GMM combines equations specified in levels with equations expressed in first differences and relies on internal instruments constructed from appropriately lagged variables under the relevant moment conditions. This makes the estimator suitable for firm-level panel data in which digitalization, green innovation, and financial controls may need to be modelled simultaneously. Nevertheless, System GMM should not be regarded as an alternative to a natural experiment, as its validity depends on credible instrument construction, appropriate lag selection, and the absence of second-order serial correlation in the differenced residuals. To assess these conditions, the analysis reports the Arellano–Bond AR (1) and AR (2) serial-correlation tests together with the Hansen test of over identifying restrictions. Some first-order serial correlation is generally expected after first differencing, making the AR (1) result less informative on its own. By contrast, the absence of statistically significant AR (2) provides evidence against second-order serial correlation and therefore supports the specification. A non-small Hansen test p-value indicates that the null hypothesis concerning the validity of the instruments cannot be rejected. OLS and fixed-effects estimates are additionally reported as benchmark specifications; however, they are presented for comparison rather than as substitutes for the dynamic System GMM estimator.

EMPIRICAL RESULTS

Descriptive Statistics

Table 1 reports the descriptive statistics for the variables included in the analysis. The number of green patent applications, used as the original measure of green innovation (GI), ranges from 0 to 1,486 with a standard deviation of 41.128. After logarithmic transformation, the values range from 0 to 7.305, with a standard deviation of 1.194.

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The substantial dispersion indicates considerable variation in green innovation activity across firms.

The original frequency of digitalization-related keywords ranges from 0 to 1,162, with a standard deviation of 61.436. Its logarithmic transformation ranges from 0 to 7.059, with a standard deviation of 1.067, likewise indicating substantial variation in firms' levels of digitalization. ER has a mean of 0.132 and reaches a maximum of 2.451. The control variables likewise exhibit meaningful dispersion in firm age, size, profitability, ownership concentration, fixed-asset intensity, liquidity, and state ownership. This variation provides the within-firm and between-firm differences required for the subsequent estimation.

Table 1: Descriptive Statistics

Variables		Unit	Obs	Mean	Std. Dev.	Min	Max
GI	Number of patent applications	Count	16787	7.628	41.128	0	1486
	Ln (1 + number of patent applications)	Log value	16787	0.943	1.194	0	7.305
Digital	Digital word frequency	Count	16787	41.596	61.436	0	1162
	Ln (1 + digital word frequency)	Log value	16787	3.186	1.067	0	7.059
ER		Percentage	16787	0.132	0.131	0.0001	2.451
Age	Firm age	Year	16787	7.586	6.819	0	31
	Ln (1+firm age)	Log value	16787	1.780	0.899	0	3.466
Size	Firm assets	Billion CNY	16787	9.493	34.173	0.238	1007
	Ln (total firm assets)	Log value	16787	21.986	1.134	19.288	27.638
ROA		Ratio	16787	0.046	0.068	-1.199	0.759
Share		Ratio	16787	0.597	0.146	0.088	0.960
Fixed		Ratio	16787	0.211	0.124	0.001	0.808
Cash		Ratio	16787	0.224	0.149	0.027	0.698
SOE		Dummy	16787	0.182	0.386	0	1

Note: GI is the logarithm of one plus green-patent applications; Digital is the annual-report digital-keyword frequency; ER is regional pollution-control expenditure divided by total industrial output. Source: Authors' calculations from the study sample.

Panel Unit-Root Tests

Given the unbalanced structure of the panel, the Fisher–ADF panel unit-root test is employed, following Maddala and Wu (1999) and Choi (2001). The findings reported in Table 2 indicate that the variables are stationary at conventional levels of statistical significance. The Fisher–ADF statistics for GI, Digital, ER, Age, Size, ROA, Share, Fixed, Cash, and SOE are statistically significant either in levels or after first differencing, with the first difference of SOE achieving significance at the 5 per cent level. These findings reduce concerns regarding common non-stationary trends across the panel and support the application of the subsequent dynamic-panel estimation.

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Table 2: Fisher–ADF Panel Unit-Root Tests

Variable	Level Statistic	First-Difference Statistic
GI	−68.832***	−51.142***
Digital	−62.973***	−48.975***
ER	−60.737***	−42.467***
Age	−14.417***	−10.171***
Size	−40.789***	−36.994***
ROA	−58.498***	−49.694***
Share	−40.756***	−33.596***
Fixed	−55.238***	−49.687***
Cash	−77.146***	−58.974***
SOE	−3.350***	−2.252**

Note: ** $p < 0.05$; *** $p < 0.01$. The Fisher–ADF test is reported for the unbalanced panel. Source: Authors' calculations from the study sample.

Baseline Estimates

Table 3 presents the estimates obtained from the OLS, fixed effects, and System GMM models. Across all four specifications, Digital has a positive and statistically significant coefficient, providing consistent evidence in support of H1.

Table 3: Baseline and Moderation Estimates

Variables	OLS	FE	System GMM	System GMM+ Moderation
L. GI	—	—	0.156*** (0.042)	0.164*** (0.042)
Digital	0.174*** (0.016)	0.066*** (0.015)	1.616*** (0.221)	1.231*** (0.197)
ER	—	—	—	0.044 (0.075)
Digital*ER	—	—	—	0.656*** (0.170)
Age	-0.009** (0.004)	-0.070 (0.053)	-0.494*** (0.066)	-0.511*** (0.065)
Size	0.503*** (0.023)	0.384*** (0.030)	0.366*** (0.120)	0.526*** (0.114)
ROA	-0.006 (0.015)	-0.001 (0.009)	-0.274* (0.163)	-0.244 (0.153)
Share	-0.006*** (0.001)	0.003* (0.002)	-0.159*** (0.029)	-0.189*** (0.030)
Fixed	-0.758*** (0.149)	0.050 (0.120)	-0.523 (2.301)	2.321 (1.895)
Cash	-0.206*** (0.028)	-0.002 (0.017)	2.690*** (0.902)	2.815*** (0.858)
SOE	0.184*** (0.060)	0.263 (0.188)	0.101** (0.048)	0.120*** (0.046)
Constant	-10.035*** (0.472)	-7.906*** (0.706)	-1.459 (2.417)	-2.252 (2.167)
Observations	16787	16787	14431	14431
R^2	0.302	0.134	—	—

Note: Entries are coefficients, with standard errors in parentheses. For the baseline System GMM column, statistics are calculated from the reported coefficient/standard-error pairs in the source output; the other reported statistics are retained. *, ** and *** denote $p < 0.10$, $p < 0.05$ and $p < 0.01$, respectively. Source: Authors' calculations from the study sample.

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In the specifications without the interaction term, the System GMM coefficient is 1.616, compared with 1.231 in the moderation specification, while the corresponding coefficients from OLS and the fixed-effects model are 0.174 and 0.066, respectively. These estimates are not expected to be numerically identical because the models exploit different sources of identifying variation and account differently for dynamic persistence. Nevertheless, the consistent positive sign across specifications supports H1. The lagged dependent variable is positive and statistically significant in both System GMM specifications, indicating persistence in firms' knowledge outputs and green-innovation activities. This persistence is economically plausible because knowledge stocks, R&D capabilities, production routines, and supplier relationships accumulate progressively and can subsequently be translated into patentable innovations. Digitalization may therefore contribute to green innovation not only through changes in technology adoption but also by strengthening firms' capacity to maintain innovation over time. Beyond the principal explanatory variables, the control estimates indicate that firm age, ownership concentration, liquidity, and state ownership are relevant correlates of green-patent performance in the dynamic specifications.

The Moderating Role of Environmental Regulation

Within the moderation specification, the interaction term Digital × ER has a coefficient of 0.656 and is statistically significant at the 1 per cent level. Its positive coefficient provides support for H2, indicating that the relationship between digitalization and green innovation becomes stronger as measured environmental-regulatory intensity increases across regions. By contrast, the coefficient of ER itself is positive but statistically insignificant. This result is consistent with treating ER primarily as a conditioning factor rather than as an independent direct determinant of green innovation, thereby highlighting its role in shaping the returns generated by firms' digital capabilities.

The finding provides empirical support for the economic logic underlying the Porter mechanism. As regulatory pressure increases, the opportunity cost associated with retaining inefficient or pollution-intensive production processes also rises, while digital systems can reduce the information and coordination costs involved in adapting to these pressures. Through monitoring and analytical capabilities, digitalization can reveal production inefficiencies, integrate environmental considerations into product and process development, and direct R&D efforts towards technologies that reduce compliance costs while improving productivity. In this setting, environmental regulation and digitalization therefore operate as complementary forces in promoting green innovation. However, the results should not be interpreted as evidence that every form or intensity of environmental regulation produces a positive moderating effect on innovation. In particular, the present analysis does not examine non-linear moderation patterns, such as Inverted-U or U-shaped relationships.

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Table 4: System GMM Specification Diagnostics

Diagnostic	Baseline System GMM	System GMM + Moderation
Observations	14,431	14,431
AR(1) P-Value	0.003	0.002
AR(2) P-Value	0.733	0.955
Hansen Test P-Value	0.211	0.308

Note: A significant AR(1) and an insignificant AR(2) are consistent with the expected serial-correlation pattern for difference residuals. Hansen p-values do not reject the reported instrument sets. Source: Authors' calculations from the study sample.

Robustness Tests

Accordingly, two robustness checks are reported in Table 5.

Table 5: Robustness Tests

Variable	(1) Granted Green Patents	(2) Winsorized Specification
L.GIgrants	0.094***(0.035)	—
L.GI	—	0.169*** (0.043)
Digital	0.441*** (0.130)	1.581*** (0.209)
Age	-0.266*** (0.038)	-0.476*** (0.062)
Size	1.378*** (0.209)	0.359*** (0.109)
ROA	-0.169** (0.083)	-0.306** (0.141)
Share	-0.079*** (0.017)	-0.148*** (0.028)
Fixed	0.488 (1.134)	-0.006 (1.940)
Cash	0.990** (0.436)	3.076*** (0.848)
SOE	0.077* (0.042)	0.106** (0.046)
Constant	-24.930*** (4.392)	-2.170 (2.266)
Observations	14431	14431
AR (1) p-value	0.000	0.000
AR (2) p-value	0.257	0.887
Hansen test p-value	0.117	0.471

Note: Entries are coefficients, with reported standard errors in parentheses. *, ** and *** denote $p < 0.10$, $p < 0.05$ and $p < 0.01$, respectively. Source: Authors' calculations from the study sample.

The first replaces the dependent variable based on green-patent applications with the natural logarithm of one plus the number of granted green patents. Under this alternative measure, Digital retains a positive and statistically significant coefficient of 0.441, while the lagged dependent variable is likewise positive and significant. This result strengthens the baseline conclusion by indicating that the observed relationship is not driven exclusively by patent applications that ultimately fail to receive grants. The second robustness test winsorises all variables at the 1st and 99th percentiles to reduce the influence of extreme observations. Digital remains positively and significantly associated with green innovation, with a coefficient of 1.581, while lagged GI continues to exhibit a positive and statistically significant coefficient. Across both robustness specifications, the AR(1) tests are statistically significant, whereas the AR(2) tests

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remain insignificant and the Hansen p-values are not small. Taken together, these results are consistent with the direction and statistical stability of the baseline findings. Nevertheless, the robustness checks cannot eliminate the possibility of measurement error or bias arising from omitted variables.

DISCUSSION

Economic Meaning of the Findings

The empirical evidence indicates that digitalization can function as a productivity-enhancing input to green innovation. This has important implications for economics and finance because green innovation is often viewed either as a compliance-related expenditure or as an environmental outcome, requiring firms to determine whether the prospective benefits of current investment will justify its immediate costs. Digital capabilities can improve this investment assessment by reducing uncertainty surrounding production processes, narrowing information asymmetries across organisational units, and making environmentally related resource losses more visible in financial terms. With better information, firms can consequently allocate R&D resources towards projects capable of generating both environmental and economic returns, including lower emissions and operating costs, product differentiation, or entry into environmentally sensitive markets.

The institutional role of environmental regulation further reinforces the view that regulatory conditions can affect the productivity of private investment. The positive interaction between digitalization and ER indicates that digital resources contribute more strongly to green innovation when the regulatory environment provides clear incentives to deploy those resources towards environmental improvement. Regulation therefore need not operate solely as an additional cost; it can also redirect managerial attention and financial resources towards technological upgrading. This interpretation is consistent with the proposition that environmental policy can strengthen competitiveness when regulation is predictable, technologically neutral, and sufficiently difficult to circumvent to prevent inefficient responses (Porter & van der Linde, 1995). It also helps explain why digitalization, when pursued without an appropriate institutional and regulatory context, does not necessarily translate into green innovation.

Theoretical Contributions

The first contribution concerns theoretical integration. Information Processing Theory explains how digital technologies improve the operational use of information by increasing the speed, availability, and quality of information processing. Innovation Economics then clarifies how greater productivity in innovation investment can contribute to structural transformation. Institutional Economics explains how regulatory rules alter the expected returns, incentives, and constraints associated with

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investments in digital and green technologies. Dynamic-capabilities theory extends this framework by emphasising that digital technologies generate economic value when firms possess the organisational capacity to develop routines for sensing opportunities, seizing them, and reconfiguring resources. The empirically observed direct relationship and interaction effect are consistent with the predictions of this integrated theoretical framework.

The second contribution concerns the economic dimension of the green transition in an emerging economy. Existing discussions of digitalization often focus on advanced economies or treat technology adoption primarily as an instrument for achieving predetermined objectives. This study instead demonstrates how digital transformation and environmental regulation interact within an industrial-upgrading process, using the Chinese manufacturing sector as the empirical context. Firms must simultaneously develop digital capabilities, respond to environmental objectives, and maintain competitiveness in manufacturing markets. This setting also offers relevant implications for other developing economies characterised by constrained capital availability, heterogeneous regulatory environments, and the need to strengthen environmental performance without sacrificing productivity.

Implications for Firms and Investors

The findings suggest that managerial decisions concerning digital investment should be aligned with clearly measurable operational and innovation objectives. Priority should be given to integrated data architectures, digital monitoring of energy and material use, traceable green R&D pipelines, predictive maintenance, and cross-functional decision-making routines. Evaluation of digital projects should combine conventional financial measures with assessments of resource-productivity effects, compliance risk, and the quality of green patents generated. Such an approach can support the expansion of technology investment without weakening innovation efficiency or environmental performance, thereby reducing the risk of a digital paradox. Digital and environmental capabilities may also become relevant to assessments of future competitiveness and transition risk by investors and financial institutions. Firms with strong environmental information systems, effective digital process controls, and a credible pipeline of green innovation may be better positioned to obtain green credit, meet disclosure requirements, and maintain access to environmentally sensitive markets. However, the data used in this study do not establish a direct effect of these capabilities on firm value or financing costs. Accordingly, these implications should be regarded as recommendations for managerial practice and directions for investment research rather than as empirically tested causal effects.

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CONCLUSION AND POLICY IMPLICATIONS

Conclusion

This study examines the relationship between digitalization and green innovation among Chinese A-share manufacturing firms and evaluates whether environmental regulation conditions this relationship. The empirical analysis covers 2,356 firms and 16,787 firm-year observations over the 2014–2023 period, with System GMM employed to estimate the dynamic panel model. The results demonstrate a positive association between digitalization and green-patent activity. This relationship remains positive when extreme observations of the dependent variable are winsorised and when granted green patents are used as an alternative measure of green innovation. Moreover, the positive and statistically significant interaction between digitalization and environmental regulation indicates that the contribution of digital capabilities to green innovation becomes stronger under greater regulatory intensity. The central economic implication is that digitalization can support sustainable industrial upgrading when firms possess the necessary capabilities and operate within a credible environmental-incentive framework. Environmental regulation increases the value of information in innovation and production decisions, while digital systems expand the availability and usability of such information. The findings therefore favour a complementarity perspective, in which digital capabilities and environmental regulation jointly contribute to green innovation, rather than an explanation based solely on technological adoption or regulatory pressure.

Policy Implications

First, industrial policy should support the development of digital infrastructure and its integration into production activities. Public investment should facilitate reliable connectivity, common standards for industrial data, interoperability across digital systems, and access to digital services, particularly for firms that lack the financial capacity to undertake transformation independently. Such support should be tied to measurable outcomes, including energy productivity, material efficiency, green R&D, and technology diffusion, rather than simply subsidising the acquisition of digital equipment. This approach can encourage productivity-enhancing digital investment while reducing the risk that smaller or less technologically capable firms are excluded from industrial upgrading.

Second, environmental regulation should be predictable, enforceable, and coordinated with innovation policy. Clear standards and credible monitoring can provide firms with a more stable investment horizon, while tax incentives, green credit, accelerated depreciation, and competitive grants can reduce the financing burden associated with cleaner technologies. Digital monitoring, environmental data reporting, and intelligent production systems should not be treated as separate compliance and innovation activities. Instead, policy packages should encourage their integration so that firms can

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meet environmental requirements at the lowest feasible long-run cost. Although the positive interaction observed in this study indicates complementarity, the evidence does not justify increasing regulatory stringency on its own. Regulators should therefore monitor compliance costs alongside firms' productivity and innovation responses. Third, policy frameworks should be strengthened in relation to green-information disclosure and data governance. Environmental data can simultaneously support regulatory oversight, reduce information asymmetry, and increase the demand among lenders and investors for credible green innovation. At the same time, data-governance frameworks should protect commercially sensitive information while promoting interoperability across reporting standards. Greater transparency can enable financial markets to distinguish between symbolic environmental disclosure and genuine digital and green capabilities.

Fourth, this policy framework can be adapted to the institutional and resource constraints of emerging economies. Basic monitoring infrastructure, technical assistance, and regional experimentation may generate greater benefits than highly complex regulatory systems that exceed local enforcement capacity. Digital industrial policy should therefore be coordinated with environmental policy and workforce development so that firms possess both the incentives and the capabilities required for green technological investment. This consideration is particularly important for smaller organisations and regions where the fixed costs associated with digital transformation may constitute a substantial barrier to adoption.

LIMITATIONS AND FUTURE RESEARCH

Several limitations should be acknowledged. First, the frequency of digitalization-related keywords in annual reports provides an observable proxy for digitalization, but the measure may capture both firms' disclosure strategies and their actual implementation of digital technologies. Future research could strengthen measurement by combining text-based indicators with digital-investment expenditure, records of intelligent-manufacturing technology adoption, or external assessments of intelligent-manufacturing capabilities. Second, although green patents provide an indicator of innovative output, they do not fully capture patent quality, commercialisation, or the realised environmental benefits of the underlying innovations. Subsequent studies could therefore distinguish among patent quality, green-product sales, energy productivity, and emissions outcomes. Third, the regional ER measure may not fully reflect differences in local enforcement, informal regulatory supervision, or the distinct effects of command-and-control and market-based regulatory instruments. Where more granular regulatory information becomes available, future research could examine these channels separately.

Finally, although System GMM addresses important dynamic and indigeneity concerns, it does not provide the same degree of causal confidence as a well-identified policy

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shock. Future research could therefore employ quasi-natural experiments, staggered policy implementation, external instruments, or matched-firm research designs to strengthen causal identification. It would also be useful to examine whether very weak and highly stringent regulatory conditions produce different effects, including potential non-linear moderation. Cross-country studies could further assess whether the complementarity identified in China extends to other emerging economies with different financial systems, industrial structures, and regulatory capacities.

DECLARATIONS

CONFLICT OF INTEREST:

The authors declare no conflict of interest.

FUNDING:

No external funding was reported for this study.

DATA AVAILABILITY:

The study uses firm-level and regional secondary data described in the Research Design section. Access conditions for proprietary databases are governed by their respective providers.

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