THE IMPACT OF MONETARY POLICY AND DIGITAL TRANSFORMATION ON GREEN INNOVATION PERFORMANCE IN ASIA: A QUANTILE REGRESSION ANALYSIS

TÁC ĐỘNG CỦA CHÍNH SÁCH TIỀN TỆ VÀ CHUYỂN ĐỔI SỐ ĐẾN HIỆU QUẢ ĐỔI MỚI XANH TẠI CHÂU Á: TIẾP CẬN HỒI QUY PHÂN VỊ

Nguyen Viet Hong Anh*, Phan Tran Huu Dat, Le Quang Vinh, Luong Thi Thao Vy

University of Finance – Marketing, Vietnam

*Corresponding author: nvhanh@ufm.edu.vn

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Abstract - This study investigates the impact of monetary policy and digital transformation on green innovation performance across 40 Asian countries using panel data from 2010 to 2023. Applying the method of moments quantile regression (MMQR), the results show that both tight monetary policy, reflected in rising interest rates, and expansionary monetary policy, reflected in money supply growth, negatively affect green innovation performance in Asian countries. However, digital transformation exerts a positive effect on countries with moderate and high levels of green innovation performance. Based on these findings, the paper proposes several policy implications and highlights the importance of monetary policy oriented toward green innovation in the context of digital transformation in Asia.

Key words - Monetary policy; Green innovation; digital transformation; MMQR.

Tóm tắt - Nghiên cứu này điều tra tác động của chính sách tiền tệ và chuyển đổi số đến hiệu quả đổi mới xanh trên 40 quốc gia châu Á bằng cách sử dụng dữ liệu bảng từ năm 2010 đến năm 2023. Bằng phương pháp hồi quy phân vị moment (MMQR), kết quả cho thấy chính sách tiền tệ thắt chặt với lãi suất tăng và chính sách tiền tệ mở rộng thông qua cung tiền đều có tác động nghịch chiều đến hiệu quả đổi mới xanh ở các nước Châu Á. Tuy nhiên, tác động của chuyển đổi số cho thấy động lực tích cực đối với các quốc gia có hiệu quả đổi mới xanh ở mức trung bình và cao. Từ đó, bài viết đề xuất một số hàm ý chính sách và làm nổi bật tầm quan trọng của chính sách tiền tệ hướng đến mục tiêu đổi mới xanh trong bối cảnh chuyển đổi số ở Châu Á.

Từ khóa - Chính sách tiền tệ; đổi mới xanh; chuyển đổi số; MMQR.

1. Introduction

In the context of globalization and intensifying climate change, Asian economies are facing an urgent need to transition toward a sustainable growth model, in which green innovation plays a central role. Green innovation refers to technological and process innovations aimed at reducing emissions, improving resource-use efficiency, and promoting cleaner production, thereby creating a driving force for high-quality growth in developing economies [1]. At the same time, the rapid development of the digital economy in many countries, reflected in the expansion of digital infrastructure and the adoption of big data and artificial intelligence, has created new favorable conditions for enhancing innovation capacity, facilitating knowledge diffusion, and improving the effectiveness of green technology implementation [2, 3].

Given two defining characteristics of green innovation- its substantial capital requirements and long-term technological risks-stable funding and an appropriate cost of capital are needed to compensate for the risks associated with research, development, and commercialization. Monetary policy instruments such as interest rates and the money supply therefore exert a direct influence [4]. Meanwhile, by increasing information transparency, reducing transaction costs, and improving risk-assessment capacity, digital transformation can promote a more efficient allocation of capital to green projects and enhance innovation performance [3, 5]. Accordingly, financial resources shaped by monetary policy and technological capacity strengthened by digital transformation should be examined within a common analytical framework to assess more fully the channels affecting green innovation performance [6].

The urgency of this issue is further emphasized by the degree of financial and trade interconnectedness in Asia. Studies on the spillover effects of China's monetary policy show that shocks from a major economy can strongly affect interest rates, inflation, and financial conditions in neighboring countries [7], thereby significantly altering the investment environment for green innovation. Moreover, heterogeneity in the level of digitalization, industrial structure, and governance quality across countries in the region increases the likelihood of divergent outcomes regarding the positive effects of "green" monetary policy [5, 8]. These differences highlight the need to examine the impacts of digital transformation and monetary policy on green innovation performance within the same analytical framework in Asia in order to provide a comprehensive multi-country perspective.

Although many previous studies have examined how digital transformation promotes green innovation through R&D, industrial upgrading, and green finance [2, 3], and how monetary policy affects green innovation through the cost-of-capital channel and climate-related monetary instruments [4, 6], these two drivers have generally been studied separately and in different contexts. Existing empirical evidence suggests that coordinating green monetary policy with digital transformation strategies may create complementary effects on green innovation performance, although the outcome depends substantially on an economy's technological readiness [1, 3, 5]. A clear gap therefore remains in the comparative assessment of both factors within a single analytical framework. This study has two objectives: (1) to clarify the channels through which two monetary policy instruments-interest rates and the money supply-affect green innovation performance; and (2) to estimate the effects of digital transformation and these monetary policy instruments in the same research setting, thereby comparing the two monetary policy transmission mechanisms. The integrated framework contributes to the literature and provides practical policy implications for Asian countries.

2. Theoretical background and review of empirical studies

Green innovation performance reflects the ability to transform input resources, including capital, knowledge-based labor, and technological capacity, into environmentally friendly technological innovation outcomes. Contemporary studies often measure green innovation performance through the quantity and quality of green patents, clean technology innovation capacity, or green R&D efficiency based on input–output efficiency evaluation models [5], [9], [2]. Alternative indicators such as emission intensity, energy-use efficiency, or green production efficiency are also used to assess green innovation outcomes at the firm and regional levels [3]. In addition, the level of digital transformation is commonly measured by indicators such as the digital economy development index, broadband Internet density, the rate of digital technology adoption in enterprises, the degree of digitalization in the service sector, or the level of investment in digital infrastructure ([8]; [5]).

The roles of monetary policy and digital transformation in promoting green innovation performance are confirmed not only by empirical research findings but also through theoretical foundations. First, Romer's endogenous growth model (1990) emphasizes that knowledge and technology are the decisive drivers of long-term growth, and that technological innovation depends on expenditure on research and development (R&D), knowledge accumulation, and the capacity for technological diffusion [10]. This explains why the development of the digital economy can improve the quality of green innovation, as demonstrated in previous empirical studies ([2]; [3]). Thus, digital transformation can be seen as affecting green innovation performance through three main channels. First, digital transformation enhances technological innovation capacity by improving information-processing capabilities and accelerating the discovery of knowledge, all of which improve innovation efficiency [2]. Second, digital transformation optimizes production processes, reduces fuel consumption, decreases waste, and improves supply chain management, thereby increasing green output efficiency [3]. Third, digital transformation improves the efficiency of financial markets and green finance by reducing information asymmetry, increasing transparency, and optimizing risk assessment, thereby enhancing the allocation of capital to green technologies [1, 11]. At the same time, studies show that this impact is heterogeneous, depending on the degree of marketization, institutional quality, and the level of development in the place where it is applied [8].

Meanwhile, the mechanism through which monetary policy exerts its effects can be explained by Keynes's theory on the role of interest rates in investment and aggregate demand [12]. According to Keynes, interest rates determine the cost of capital and therefore directly influence long-term investment decisions such as technological innovation. Since green innovation requires substantial capital, has a long payback period, and involves a high level of risk, it is particularly sensitive to interest rate fluctuations. Research conducted in East Asia–Pacific and Latin America, where firms rely heavily on borrowed capital for R&D, shows that real interest rates have a negative and statistically significant effect on green innovation [4]. According to Keynes, in addition to the interest rate channel, monetary policy also operates through the expansion of money supply, which improves system-wide liquidity and increases access to credit, thereby supporting innovation investment. Empirical findings from previous research indicate that money supply may have a negative impact on green innovation when capital flows are misallocated to carbon-intensive industries, whereas reserve money has a positive effect in economies with high governance quality, where credit can be directed toward green technologies [13]. This demonstrates the role of institutional factors in regulating the effectiveness of monetary policy in relation to green innovation. In addition, monetary policy instruments such as green refinancing or the screening of carbon assets in central bank portfolios can expand access to capital for green technology projects and improve innovation outcomes [6]. Furthermore, expansionary monetary policy, through an increase in money supply or a reduction in real interest rates, has been shown to have a positive and significant effect on green innovation activities in both the short and long term [14]. Conversely, tight monetary policy often reduces R&D expenditure, venture capital investment, and the number of patents, reflecting constraints in credit and market demand [15].

A synthesis of Keynes's and Romer's theories ([12]; [10]), together with previous empirical studies, clearly shows the transmission mechanism through which monetary policy and digital transformation affect green innovation performance. Specifically, monetary policy influences the cost of capital and liquidity, which are prerequisites for investment in technological innovation, while digital transformation enhances the capacity to generate green technologies through the mechanism of endogenous knowledge accumulation. Therefore, green innovation performance reaches its optimal level when these two factors are coordinated effectively: monetary policy supports capital flows, while digital transformation improves technological innovation productivity.

Overall, theory and empirical evidence confirm the important roles of monetary policy and digital transformation in green innovation performance. However, existing studies generally evaluate these factors separately and across different settings. Related evidence indicates that foreign ownership can promote corporate green innovation by facilitating access to capital, technology transfer, and improvements in corporate governance [19]. This finding supports the broader view that financial resources and technological absorptive capacity jointly shape green innovation outcomes. Building on this literature, the present study examines monetary policy and digital transformation within a common analytical framework and evaluates whether their effects vary across the conditional distribution of green innovation performance.

3. Research model and methodology

3.1. Research model

This study uses panel data from 40 Asian countries over the period 2010–2023, collected from official sources such as the World Bank, OECD, and IMF. The countries included in the research sample are Armenia, Azerbaijan, Bahrain, Brunei Darussalam, Cambodia, China, Cyprus, Egypt, Georgia, India, Indonesia, Iran, Iraq, Israel, Japan, Jordan, Kazakhstan, Korea, Kuwait, Kyrgyz Republic, Malaysia, Mongolia, Myanmar, Nepal, Oman, Pakistan, Philippines, Qatar, Russian Federation, Saudi Arabia, Singapore, Sri Lanka, Syria, Tajikistan, Thailand, Türkiye, Turkmenistan, United Arab Emirates, Uzbekistan, and Viet Nam.

The research model is grounded in Romer's endogenous growth theory (1990), Keynes's liquidity-preference theory and interest-rate transmission channel (1936), and empirical evidence on the effects of monetary policy and digital transformation on green innovation performance [4, 13, 16].

Table 1. *Details of the input-output factors when applying DEA to identify the dependent variable*

Group	Factors	Description
Inputs	Government R&D spending on environmental technology	% of GDP
	Annual energy consumption of each country	kWh
Outputs	Green patents	Quantity
	Share of renewable energy in total final energy consumption	% of total consumption
	Share of "green" products in total export value	% of total exports

(Source: Author group synthesis)

+ Dependent variable (DMX): This variable captures green innovation performance as the efficiency with which resources invested in green technologies are transformed into innovation outputs. It is measured using data envelopment analysis (DEA), an approach used in prior green innovation research [16]. Specifically, the study applies an output-oriented DEA model under variable returns to scale (VRS) to measure the ability to maximize green outputs from existing inputs, an assumption appropriate for economies operating at different scales. Country-year DEA scores form the DMX variable. Robustness is assessed through sensitivity checks using alternative input-output configurations; the substantive results remain unchanged. Table 1 presents the inputs and outputs used to construct DMX.

+ *Main independent variables:* These include monetary policy and digital transformation.

(i) Monetary policy: Monetary policy is measured through two separate instruments, each of which is included in a separate model to assess the different effects of each operating mechanism.

- **Short-term policy interest rate (LS):** This represents the cost-of-capital channel and reflects the Keynesian view of the sensitivity of R&D investment to interest rate fluctuations. Interest rates have been widely used in previous studies to analyze the impact of monetary policy on green innovation [4], [14].

- **Money supply (M2):** This represents the liquidity and credit channel, allowing the study to assess the impact of monetary expansion or tightening on green credit allocation and innovation performance. M2 is commonly used in empirical studies to evaluate the influence of liquidity on innovation capacity and technology investment [13], [14].

(ii) *Digital transformation (CDS):* This reflects the degree of digital technology adoption in the economy. Previous studies show that digital transformation has a positive impact on green innovation through mechanisms such as improving production efficiency, reducing transaction costs, and optimizing value chains [1–3]. In this study, the CDS variable is measured by the ICT Development Index (IDI) of the International Telecommunication Union (ITU) before 2023, which reflects the level of national digital development. IDI is a composite index consisting of three components: access infrastructure (40%), usage level (40%), and skills (20%), calculated using the entropy weighting method. A higher IDI value indicates a higher degree of digitalization and is expected to promote innovation performance.

+ *Control variables:* To ensure the completeness of the model, the study includes several control variables that have been shown in previous studies to affect green innovation, including economic growth (TTKT), foreign direct investment (DNN), government expenditure (CTC), trade openness (DMTM), urbanization rate (DTH), and institutional quality (CLTC).

To assess the impacts of monetary policy and digital transformation on green innovation performance, this paper establishes two research models corresponding to the two monetary policy instruments, namely interest rates and money supply. Specifically, the models are as follows:

Model (1): Monetary policy measured by interest rates (LS)

$$DMX_{it} = \alpha_0 + \alpha_1 LS_{it} + \alpha_2 CDS_{it} + \beta Z_{it} + \varepsilon_{it}$$

Model (2): Monetary policy measured by money supply (M2)

$$DMX_{it} = \alpha_0 + \alpha_1 M2_{it} + \alpha_2 CDS_{it} + \beta Z_{it} + \varepsilon_{it}$$

where subscript *i* denotes the countries in the research sample, and *t* represents the years in the period 2010–2023. Details of the variables and measurement methods are presented in Table 2.

Table 2. *Summary of variables in the research model*

No.	Variables	Symbol	Measurement	Previous studies	Data source
1	***Dependent variable:***				
	Green innovation performance	DMX	DEA method from input-output indicators	[16]; [4]	Data from the World Bank and OECD
2	***Main independent variables:***				
2.1	**Monetary policy**				
	+ Interest rate	LS	Short-term policy interest rates by year for each country	[4]; [14]	Data from the World Bank
	+ Money supply	M2	Money supply expansion as a percentage of GDP by country	[13]; [14]	Data from the World Bank
2.2	**Digital transformation**	CDS	Information and Communications Technology Development Index (IDI)	[1]–[3]	International Telecommunication Union (ITU)
3	***Control variables:***				
3.1	Economic growth	TTKT	Annual GDP growth rate of each country	[14]; [17]; [2]; [1]	Data from the World Bank
3.2	Foreign direct investment	DNN	Foreign direct investment flows into countries as a % of GDP		Data from the World Bank
3.3	Level of urbanization	DTH	Annual urbanization rates of countries		Data from the World Bank
3.4	Trade openness	DMTM	Calculated by total value of imported and exported goods as a percentage of GDP		Data from the World Bank
3.5	Government spending	CTC	Total government spending as a percentage of GDP		WDI–World Bank data
3.6	Institutional quality	CLTC	Method of calculating the PCA composite index from the set of 6 global public governance indices (World Governance Index – WGI)		WDI–World Bank data

(Source: Author group synthesis)

Drawing on previous empirical studies and the theoretical transmission mechanisms through which monetary policy and digital transformation affect green innovation performance, the following hypotheses are proposed:

H_1: Expansionary monetary policy, represented by a reduction in interest rates or an increase in money supply, has a positive (+) impact on green innovation performance in Asia.

H_2: Digital transformation has a positive (+) impact on green innovation performance in Asia.

3.2. Research methodology

This study employs panel quantile regression using the method of moments quantile regression (MMQR) approach [18]. Unlike conventional mean regression, MMQR estimates the effects of macroeconomic factors at different conditional quantiles of the dependent variable. This approach is appropriate because the effects of monetary policy and digital transformation may vary across the conditional distribution of green innovation performance in Asia, where countries differ substantially in development, institutional quality, and technological capacity.

MMQR accommodates unobserved country-specific heterogeneity and does not require normally distributed errors, making it useful for multi-country panel data with distributional heterogeneity. However, MMQR does not by itself eliminate endogeneity. The estimates are therefore interpreted as conditional associations, while potential reverse causality is acknowledged as a study limitation.

Slope-heterogeneity and cross-sectional-dependence tests for both models indicate significant coefficient heterogeneity and dependence across countries. The Westerlund panel cointegration test provides no evidence of a long-run cointegrating relationship among the variables. These results caution against relying solely on conventional homogeneous linear panel models.

In this context, MMQR is appropriate for identifying how the estimated associations vary across conditional quantiles of green innovation performance. The method is also relatively robust to outliers and can accommodate asymmetric conditional distributions.

4. Research results

4.1. Descriptive statistics

Table 3. *Descriptive statistics of variables in the period 2010-2023*

Variable	Obs	Mean	Std. dev.	Min	Max
DMX	560	0.2715	0.2980	0.0006	1
LS	560	0.0786	0.0676	0	0.2966
M2	560	0.7365	0.4951	0	2.84262
CDS	560	0.4790	0.2478	0	1
TTKT	560	0.0852	0.4944	-2.6534	5.8665
DNN	560	0.0101	0.4471	-2.9602	4.3180
DTH	560	2.4590	11.5226	0.1678	75.3311
DMTM	560	0.8815	0.5633	0.1187	3.7912
CTC	560	0.1561	0.0907	0.0272	1.0318
CLTC	560	-0.3034	0.7870	-1.93	1.91

(Source: Calculation from Stata 16.0 software)

The data in Table 3 show that the mean values of the DMX and CDS variables are 0.2715 and 0.479, respectively, compared with the maximum value of 1. This indicates that both green innovation performance and the level of digital transformation remained limited and varied considerably across Asian countries during the research period from 2010 to 2023.

4.2. Research results on the impacts of monetary policy and digital transformation on green innovation performance

The effective estimation samples differ between Models (1) and (2), reflecting model-specific data availability and estimation requirements for the interest-rate and money-supply specifications. This difference should be considered when comparing coefficient magnitudes across the two models; the within-model patterns and significance levels remain stable across the reported quantiles.

The MMQR estimates for Models (1) and (2) reveal heterogeneous associations between monetary policy, digital transformation, and green innovation performance over 2010–2023. The 0.25, 0.50, and 0.75 quantiles refer to points in the conditional distribution of green innovation performance; they should not be interpreted as fixed groups of countries. Coefficients at these quantiles indicate whether the estimated associations differ between lower-, median-, and upper-performance conditions after accounting for the covariates. This distributional interpretation is consistent with the premise that monetary and digital effects depend on an economy's underlying conditions.

Table 4. *MMQR regression results of Model (1)*

Variable	Quantiles 0.25	0.5	0.75
LS	-1.160***	-0.970***	-0.623***
	(0.002)	(0.009)	(0.019)
CDS	-0.020***	0.002*	0.041***
	(0.000)	(0.001)	(0.002)
TTKT	-0.040***	-0.058***	-0.090***
	(0.000)	(0.001)	(0.002)
DNN	0.006***	0.017***	0.037***
	(0.000)	(0.001)	(0.001)
DTH	0.332***	0.285***	0.198***
	(0.000)	(0.002)	(0.005)
DMTM	0.250***	0.265***	0.293***
	(0.000)	(0.001)	(0.002)
CTC	0.337***	0.503***	0.806***
	(0.002)	(0.008)	(0.017)
CLTC	0.057***	0.239***	0.572***
	(0.002)	(0.008)	(0.018)
Constant	0.070***	0.155***	0.310***
	(0.001)	(0.004)	(0.009)
Observations	480	480	480

*Note: *** p < 0.01; ** p < 0.05; * p < 0.1.*

(Source: Calculation from Stata 16.0 software)

For Model (1), Table 4 shows that the coefficient on LS is negative at all reported quantiles, indicating a consistently adverse association between interest rates and green innovation performance. The cost of capital therefore appears to be an important barrier to green innovation in Asia. Under the Keynesian mechanism, investment in high-risk projects with long payback periods, such as green R&D, is particularly sensitive to interest-rate changes. In many Asian economies, where firms rely heavily on bank financing, higher borrowing costs can constrain investment in green technologies and cleaner innovation. The absolute magnitude of the negative LS coefficient declines toward the upper quantile, suggesting lower interest-rate sensitivity under higher-performance conditions. This result supports H1 for the interest-rate specification and is consistent with previous evidence for East Asia–Pacific and Latin America [4].

The coefficient on CDS is negative and statistically significant at the 0.25 quantile, but positive and statistically significant at the 0.50 and 0.75 quantiles. Digital transformation therefore does not appear to produce immediate green innovation benefits under lower-performance conditions, possibly because of limited technological absorptive capacity, weak digital infrastructure, or insufficient integration of digital technologies into green R&D. At the median and upper quantiles, however, digital transformation becomes a positive driver of innovation productivity and R&D efficiency. This pattern is consistent with Romer's endogenous growth mechanism [10] and prior empirical evidence [2]. Accordingly, H2 is supported at the 0.50 and 0.75 quantiles, but not at the 0.25 quantile.

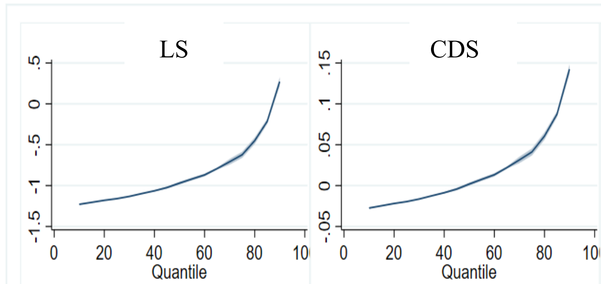

Figure 1. *Quantile regression coefficient plot of LS and CDS in Model (1)*

(Source: Calculated using Stata 16.0)

Table 5. *MMQR regression results of Model (2)*

Variable	Quantiles 0.25	0.5	0.75
M2	-0.044***	-0.060***	-0.087***
	(0.000)	(0.000)	(0.001)
CDS	-0.020***	-0.007***	0.017***
	(0.000)	(0.000)	(0.001)
TTKT	-0.032***	-0.049***	-0.079***
	(0.000)	(0.001)	(0.001)
DNN	0.006***	0.016***	0.034***
	(0.000)	(0.000)	(0.001)
DTH	0.298***	0.296***	0.294***
	(0.000)	(0.000)	(0.000)
DMTM	0.189***	0.213***	0.254***
	(0.000)	(0.001)	(0.002)
CTC	0.399***	0.591***	0.926***
	(0.000)	(0.006)	(0.015)
CLTC	0.115***	0.311***	0.654***
	(0.000)	(0.006)	(0.016)
Constant	0.069***	0.158***	0.314***
	(0.000)	(0.003)	(0.007)
Observations	520	520	520

*Note: *** p < 0.01; ** p < 0.05; * p < 0.1.*

(Source: Calculation from Stata 16.0 software)

For Model (2), Table 5 shows that the coefficient on M2 is negative and statistically significant at all three quantiles. Unlike the interest-rate effect, the negative association becomes stronger toward the upper quantile, where the coefficient has the largest absolute value. One possible explanation is that a broad expansion of liquidity does not necessarily prioritize green activities; without effective credit allocation mechanisms, additional funding may flow to carbon-intensive sectors rather than green technological innovation. This result is consistent with previous evidence [13] but does not support H1 for the money-supply specification.

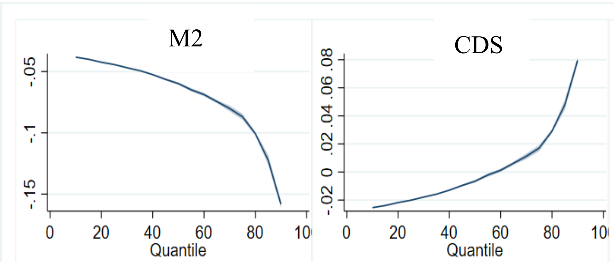

***Figure 2.** Quantile regression coefficient plot of M2 and CDS in Model (2)*

(Source: Calculated using Stata 16.0)

The coefficient on CDS is statistically significant at all three quantiles: negative at the 0.25 and 0.50 quantiles and positive at the 0.75 quantile. Thus, in Model (2), digital transformation becomes a positive driver only under upper-performance conditions. Under lower- and median-performance conditions, the estimated association remains negative.

This pattern suggests that, in an environment of credit expansion and high liquidity, only economies with strong green innovation capacity may be able to translate digital transformation into higher green innovation performance. Under weaker performance conditions, benefits from digitalization may be offset by undirected capital allocation, implementation risks, or insufficient institutional support for technology adoption. H2 is therefore supported only at the 0.75 quantile in Model (2).

5. Conclusions and policy implications

5.1. Conclusions

Comparison of Models (1) and (2) shows that the estimated associations of monetary policy and digital transformation with green innovation performance depend on the monetary policy instrument. Although both short-term interest rates and the money supply have negative coefficients at all reported quantiles, the magnitude and distributional pattern of these associations differ.

The effect of digital transformation also differs across the two specifications. In the interest-rate model, its positive association appears at the median and upper quantiles. In the money-supply model, the positive association appears only at the upper quantile. Monetary policy and digital transformation should therefore not be treated as entirely independent influences: different monetary conditions may shape an economy's capacity to absorb digital technologies and convert them into green innovation outcomes.

5.2. Policy implications

The results show meaningful differences across the conditional distribution of green innovation performance. Policy design should therefore account for heterogeneous economic, technological, and institutional conditions rather than apply a uniform approach across Asian countries.

First, Asian countries should consider prioritizing the use of interest rate instruments in monetary policy implementation when pursuing green innovation objectives in the context of rapid digitalization. This is because digital transformation produces positive effects earlier in countries seeking to accelerate green innovation performance under an interest-rate-based operating mechanism. Specifically, monetary policy should maintain a stable interest rate level and avoid excessive tightening, as interest rates have been shown to have a negative relationship with green innovation performance. In addition, implementing preferential interest rates for green credit activities is necessary to direct capital flows effectively toward green innovation objectives.

Second, Asian countries need to exercise caution in expanding money supply (M2) if effective "green-oriented" instruments are lacking. Since money supply (M2) has been shown to exert a negative effect on green innovation performance across all groups of Asian countries, this means that money supply expansion does not support green innovation and may risk channeling capital into high-emission industries. Therefore, monetary expansion through money supply (M2) should be accompanied by "green-oriented" instruments such as credit quotas and refinancing for "green" projects.

Another important implication is that digital transformation does not always generate immediate effectiveness but depends greatly on each country's absorptive capacity and level of green innovation development. Economies in the lower quantile group may face high transition costs, insufficient technological infrastructure, or human resource constraints, leading to negative effects in the short term. Therefore, digital transformation strategies should be placed within a roadmap that takes technological readiness into account, including investment in digital infrastructure, improvement of labor skills, and the development of open databases to support green innovation. For countries with stronger green innovation foundations, combining digital transformation with appropriate monetary policy can create synergistic momentum, thereby promoting green innovation performance in a sustainable manner.

Finally, the differences in responses across quantiles show that the green innovation foundation of countries is a decisive factor for monetary policy and digital transformation strategies to maximize their effectiveness. Countries with the highest levels of green innovation performance are those where digital transformation has a positive impact regardless of the monetary policy instrument used. Therefore, institutional reform and the enhancement of the green innovation ecosystem should be regarded as fundamental conditions for monetary policy and digital transformation to be harmoniously combined, thereby promoting the development of green innovation in the Asian region.

5.3. Limitations of the study

This study has several limitations. First, although MMQR accommodates unobserved heterogeneity and non-normal distributions, it does not establish causality or fully address endogeneity arising from possible bidirectional relationships between monetary policy and green innovation performance. Second, digital transformation measured by the IDI may not capture newer dimensions of the digital economy. Third, DEA scores remain sensitive to the selection of inputs and outputs, although alternative specifications were examined. Finally, the study does not estimate interaction effects directly; the proposed coordination mechanisms should therefore be tested in future research.

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