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Research on Carbon Emission Reduction Mechanism Driven by Digital Economy: An Empirical Analysis of Northeast Asia with Sino-Korean Cooperative Enterprises as the Entry Point

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Abstract: Against the backdrop of the escalating global concern over climate change, digital transformation is emerging as a strategic tool for the industrial sector to reduce carbon emissions. This study explores the carbon emission reduction mechanisms facilitated by the digital economy, with a particular focus on Sino-Korean joint ventures operating in Northeast Asia. Based on a panel dataset of listed cooperative enterprises from China and South Korea from 2013 to 2022, we empirically examine how digital transformation (DT) affects carbon emission intensity (CEI) through green technological innovation (GTI), while considering environmental, social, and governance (ESG) practices as moderating factors. The results indicate that digital transformation significantly reduces carbon emission intensity by promoting green technological innovation, and strong ESG practices amplify this effect.

Keywords: Digital Transformation (DT); Carbon Emission Intensity (CEI); Green Technological Innovation (GTI); ESG Practices; Sino-Korean Joint Ventures

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1.Introduction

Facing increasingly severe climate change challenges, major carbon-emitting nations such as China and South Korea urgently need to achieve emission reductions while maintaining industrial growth. The digital economy (e.g., big data, AI) offers opportunities for low-carbon transition. Although its core driver, Digital Transformation (DT), has been proven to reduce Carbon Emission Intensity (CEI) through pathways like improving energy efficiency, its global emission reduction effect remains contentious. Moreover, research is particularly scarce on the impact mechanisms of Sino-South Korean digital cooperation on carbon emissions.

This study focuses on Sino-South Korean joint ventures and cooperative enterprises in Northeast Asia. Utilizing their panel data from 2013 to 2022, it empirically investigates:

1) How DT affects CEI;

2) The mediating role of Green Technological Innovation (GTI);

3) The moderating effect of ESG Performance and examines regional heterogeneity.

By constructing an enterprise-level DT-GTI-ESG interaction model, this research not only reveals the micro-level mechanisms of digital-driven emission reduction but also identifies the limitations of current digital technologies (at the current stage, prior to widespread AI adoption). It provides empirical evidence for deepening Sino-South Korean digital collaboration and coordinating regional development with carbon neutrality goals.

2.Literature Review

2.1 DT, Carbon Emissions, and the Cross-Border Gap

Digital transformation (DT), driven by AI, big data, and cloud computing, is recognized as a catalyst for industrial decarbonization. Studies indicate DT reduces carbon emission intensity (CEI) by optimizing resource allocation, improving energy efficiency, and enabling cleaner production [1][2], particularly in energy-intensive sector [3]. However, this effect remains contested due to potential "rebound effects" from increased production-driven energy demand [4]. Critically, extant research focuses predominantly on domestic contexts, leaving a gap in understanding cross-border applications—especially in Northeast Asia, where digital cooperation intersects with stringent carbon targets.

2.2 GTI: The Mediating Pathway

Green technological innovation (GTI) serves as a critical mechanism translating digital capabilities into environmental gains. DT enhances innovation capacity through improved information access, lower transaction costs, and accelerated R&D [5][6], thereby stimulating green patents and eco-product development that lower long-term emissions [7]. While GTI is established as a mediator between external drivers (e.g., policy) and carbon performance [8], the specific DT → GTI → CEI pathway lacks empirical validation, particularly in multinational settings where institutional diversity influences innovation diffusion.

2.3 ESG: Amplifying Digital Impact

ESG performance reflects corporate sustainability commitment and can potentiate DT's environmental efficacy. Firms with robust ESG practices are more likely to leverage digital solutions due to stakeholder engagement and long-term orientation [9]. Strong ESG governance further enhances DT's impact by fostering transparency, accountability, and cross-functional coordination [10]. Yet, research predominantly treats ESG as an outcome rather than a contextual moderator. Given varying ESG implementation across borders, its role in conditioning DT's CEI-reduction potential—especially in Sino-Korean joint ventures—remains unexplored.

2.4 Research Gaps and Contributions

While DT, GTI, and ESG independently influence environmental outcomes, no study integrates them into a unified framework for cross-border contexts. Northeast Asia—a critical region as both a top emitter and digital innovator—is notably underrepresented. This research addresses these gaps by:

1) Proposing and testing a DT–GTI–CEI mediation model within Sino-Korean joint ventures.
2) Examining ESG performance as a key moderator of the DT–CEI relationship.
3) Providing region-specific insights using firm-level panel data (2013–2022).

3.Theoretical Framework & Hypotheses

3.1 Conceptual Model

Building upon the existing literature, this study proposes a multi-level framework to analyze how digital transformation (DT) influences corporate carbon emission intensity (CEI), with green technological innovation (GTI) serving as a mediating mechanism and ESG performance as a moderating factor. This framework is particularly relevant for Sino-Korean joint ventures, where digital cooperation and sustainability goals intersect.

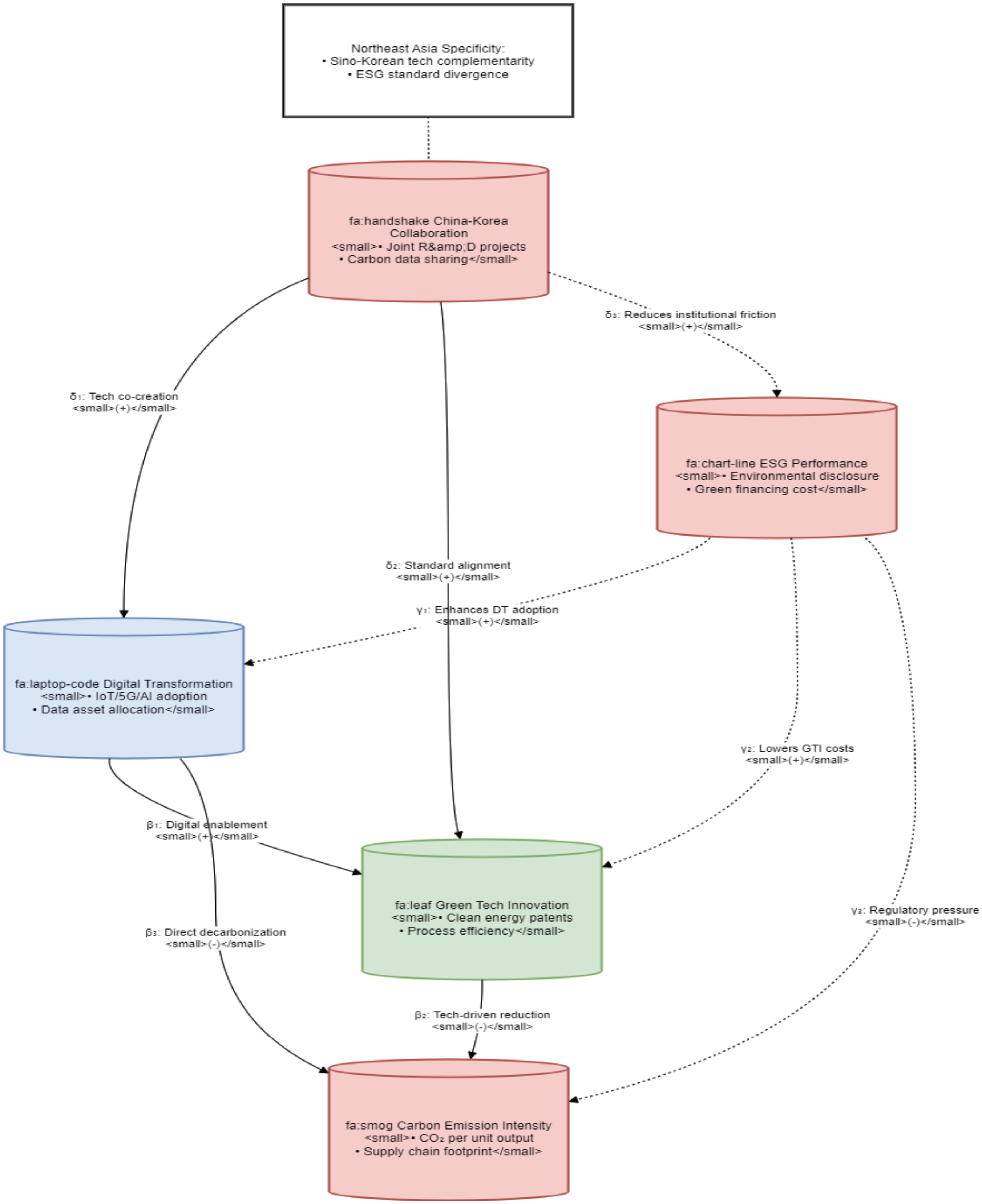
The theoretical foundation integrates resource-based theory [11], which posits that digital capabilities and green innovations are strategic assets that enhance environmental performance, and institutional theory [12], which emphasizes the role of ESG-driven norms in shaping corporate behavior.

3.2 Hypotheses Development

H1: Digital transformation significantly reduces firms' carbon emission intensity.

Digitally transformed firms are better positioned to optimize production processes, enhance energy efficiency, and implement smart carbon tracking tools [13] [14]. In the context of Northeast Asia, where digital infrastructure is relatively mature, these effects are expected to be more pronounced.

Figure.1 Conceptual model



H2: Green technological innovation mediates the relationship between digital transformation and carbon emission intensity. Digital tools not only enhance operational efficiency but also stimulate innovation capabilities, particularly in the domain of green technologies [15]. Firms undergoing digital transformation are more likely to invest in green R&D, leading to improved environmental outcomes through cleaner production and sustainable products [16].

H3: ESG performance positively moderates the relationship between digital transformation and carbon emission intensity.

Firms with higher ESG ratings tend to internalize environmental goals into their digital strategy, thereby enhancing the effectiveness of digital transformation in reducing carbon emissions [17]. ESG-oriented governance structures promote transparency, accountability, and stakeholder alignment, all of which are crucial for leveraging digital tools toward environmental sustainability.

H4: The impact of digital transformation on carbon emission intensity varies across regions and industries.

Given the heterogeneity in regional digital infrastructure and sectoral carbon intensity, the effectiveness of DT in reducing CEI is expected to differ. For example, manufacturing-intensive regions or energy-heavy sectors may exhibit a stronger DT–CEI linkage due to higher baseline emissions [18].

4.Data & Methodolog

4.1 Data and Sample

This study utilizes a balanced panel dataset comprising Sino-Korean joint ventures and cooperative enterprises listed in China and South Korea from 2013 to 2022. Firms are identified based on ownership structures and partnership disclosures in annual reports. Data are collected from multiple authoritative sources to ensure cross-national comparability and transparency:

1) Financial and firm-level data: CSMAR (China) and KISVALUE (Korea)

2) Digital transformation metrics: Textual analysis of annual reports via Python, using DART (Korea) and WIND (China)

3) Carbon emission intensity estimation: Calculated as industry-specific energy consumption* regional carbon emission factors / revenue, based on national energy statistics

4) Green innovation: Green patent counts from the CNIPA (China), KIPO (Korea), and PATSTAT database

5) ESG performance: ESG scores from third-party rating agencies (e.g., Huazheng ESG, Korea KCGS, Bloomberg ESG)

6) Macroeconomic and regional data: National statistical yearbooks and ICT infrastructure reports from the Korean Ministry of Science and ICT

Only firms with complete data across all variables for the observation period are retained, resulting in a final sample of N firms* T years.

Table.1Variable Definitions

Variable Type	Name	Symbol	Definition / Measurement	Source
Dependent Variable	Carbon Emission Intensity	CEI	Industry-level energy use* regional carbon coefficient / firm revenue	National energy statistics, CSMAR, KIS
Independent	Digital Transformation	DT	Frequency of digital-related keywords (AI, blockchain, IoT, etc.) in annual reports, log-transformed	WIND, DART, Python NLP
Mediator	Green Technological Innovation	GTI	Number of green patent applications (domestic and international)	CNIPA, KIPO, PATSTAT
Moderator	ESG Performance	ESG	ESG composite score from third-party ratings	Bloomberg ESG, KCGS, WIND ESG
Control	Firm Size	SIZE	Logarithm of total assets	WIND, KISVALUE
	Leverage	LR	Total liabilities / Total assets	WIND, KISVALUE
	Ownership Concentration	OC	Herfindahl index of top five shareholders	CSMAR, DART Korea
	Return on Assets	ROA	Net income / Total assets	WIND, KISVALUE
	Industry Carbon Intensity	ICI	Regional average CEI of firm's primary industry	Industrial yearbooks
	Regional Digital Infrastructure	DINFRA	Composite index of internet penetration, broadband coverage, digital investment per capita	NBS (China), MSIT (Korea)

4.2 Model Specification

To test the hypotheses outlined in Section 3, the following econometric models are estimated using fixed effects panel regression with firm and year fixed effects:

(1)Baseline Model – Direct Effect of Digital Transformation on Carbon Intensity:

$$CEI_{it} = \alpha + \beta DT_{it} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{1}$$

CEI*it*: Carbon emission intensity of firm i in year t

DT*it*: Digital transformation level of firm i in year t

X*it*: Vector of control variables for firm i in year t

μi: Firm fixed effect (controls for time-invariant firm heterogeneity)

λt: Year fixed effect (controls for time-specific macroeconomic shocks)

εit: Error term

(2) Mediation Test – Green Innovation Channel

Step 1 (DT → GTI):

$$GTI_{it} = \alpha + \beta 2DT_{it} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{2}$$

Step 2 (DT & GTI → CEI):

$$CEI_{it} = \alpha + \beta 3DT_{it} + \beta 4GTI_{it} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{3}$$

GTI*it*: Green technological innovation of firm i in year t

Mediation Assessment: A Sobel test and Bootstrap confidence intervals (5,000 repetitions) are used to validate the statistical significance of the indirect effect of DT on CEI via GTI2×β4).

(3)Moderation Test – ESG as Amplifier

$$CEI_{it} = \alpha + \beta 5DT_{it} + \beta 6ESG_{it} + \beta 7(DT_{it} * ESG_{it}) + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{4}$$

ESG*it*: ESG performance score of firm i in year t

DT*it*×ESG*it*: Interaction term between digital transformation and ESG performance.

Interpretation: A negative and statistically significant coefficient *β*7 implies that stronger ESG practices enhance (positively moderate) the carbon emission reduction effect of DT.

4.3 Identification Strategy

To mitigate endogeneity concerns (e.g., reverse causality between DT and CEI), several approaches are applied:

1) Lagged variables: Key independent variables are lagged one year to reduce simultaneity bias.

2) Instrumental Variable (IV) robustness (optional): Instruments such as regional AI infrastructure or digital subsidies can be introduced.

3) Placebo tests: Applying the model to industries with low carbon relevance to ensure the effect is not spurious.

4) Robustness checks:

Alternative DT proxies (e.g., digital investment intensity),

Subsample regressions by sector (e.g., manufacturing vs. service),

Winsorization of outliers at 1% and 99%.

5.Empirical Results and Discussion

Regression analyses confirm digital transformation (DT) significantly reduces carbon emission intensity (CEI) ($\beta_1 = -0.045$, $p < 0.05$), supporting H1. Robustness checks using alternative DT measures and lagged variables reinforce this core finding. Notably, green technological innovation (GTI) acts as a partial mediator: DT boosts GTI ($\beta_2 = 0.132$, $p < 0.01$), which subsequently lowers CEI ($\beta_4 = -0.031$, $p < 0.05$), with a statistically significant indirect effect (bootstrap 95% CI: -0.0065 to -0.0014), validating H2. Furthermore, ESG performance amplifies DT's impact, as evidenced by a negative and significant interaction term ($\beta_7 = -0.018$, $p < 0.05$). Marginal effect plots demonstrate firms with strong ESG governance achieve substantially greater CEI reduction from DT, confirming H3. Contextual heterogeneity exists, with stronger effects observed in manufacturing firms and regions with advanced digital infrastructure (DINFRA), underscoring H4.

Theoretically, this study advances sustainability research by establishing a multi-path decarbonization mechanism: DT directly reduces CEI while indirectly lowering emissions through GTI, with ESG governance potentiating DT's efficacy. Practically, policymakers should couple DT incentives (e.g., digital R&D subsidies) with ESG capacity-building (e.g., harmonized benchmarking) to maximize carbon reduction. Firms must integrate digital and ESG strategies, while China-Korea partnerships should prioritize cross-border digital infrastructure and aligned sustainability reporting to accelerate regional decarbonization.

Limitations and Future Research：

Several limitations warrant attention. First, findings may understate future DT potential as generative AI adoption in SMEs remains nascent; expanding samples to include AI-intensive firms would enhance generalizability. Second, measuring DT via keyword frequency introduces potential reporting bias; future studies should incorporate objective metrics like digital investment ratios. Third, inconsistent carbon/ESG reporting standards between China and Korea create measurement noise, necessitating research on standardized international sustainability data governance. Fourth, dynamic factors like carbon pricing and regional AI infrastructure indices should be integrated to model how market incentives and technology diffusion jointly shape the DT-CEI pathway. Finally, advanced causal modeling (e.g., Structural Equation Modeling) could unravel the complex interdependencies within the DT-GTI-ESG-CEI system. Addressing these gaps will refine our understanding of digital decarbonization as technologies evolve.

Conclusion

This study demonstrates that digital transformation (DT) significantly reduces carbon emission intensity (CEI) in Sino-Korean joint ventures through three interconnected mechanisms: directly by optimizing production efficiency and resource utilization, indirectly via stimulating green technological innovation (GTI) which subsequently lowers emissions, and conditionally through Environmental, Social, and Governance (ESG) performance which amplifies DT's decarbonization impact. To operationalize these findings, policymakers should establish cross-border digital collaboration platforms for shared smart manufacturing and carbon tracking solutions, strengthen green patent incentives through tax credits and accelerated examination to boost GTI, harmonize China-Korea ESG rating standards to reduce information asymmetry, and promote AI-enabled real-time carbon footprint reporting systems to enhance transparency. Implementing these measures will harness the synergistic potential of DT, GTI, and ESG governance to accelerate regional progress toward carbon neutrality goals.

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no

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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