

# *The Impact of Green Innovation Capabilities of Enterprises on Total Factor Productivity*

Tianyu Liu

*Department of Economics and Management, Dalian University of Technology, Dalian, China  
2720433180@qq.com*

**Abstract.** Against the backdrop of China's Dual Carbon Goals, the thesis selects A-share listed companies as research object, exploring the effects and boundary conditions of enterprise green innovation capability on total factor productivity. Through structuring Two-way fixed effects model with companies financial statistics from 2000 to 2023, our main empirical findings are as follows:(1)Total number of green patent authorizations significantly improve enterprise total factor productivity, guaranteeing core hypothesis of green innovation directly improve productivity through enhancing manufacturing technique and reducing energy consumption.(2)Heterogeneity analysis reveals it is the green innovation effects of big businesses that are more obvious, while the green innovation effects of Midwestern enterprises stems production improvement. Based on the comments above, the thesis puts forward politics suggestions as follow: Firstly, government ought to perfect Green innovation policy system and implement differentiated regional support strategies;Secondly, enterprise management team should pay attention to efficiency of innovation products transformation and formulate innovation strategies that match the companies' size;Thirdly, institutional investor should improve the real value of Green innovation, focusing on enterprises' actual improvement effects of Green innovation on productivity to realize long-term value appreciation.

**Keywords:** green innovation, total factor productivity, two-way fixed effects model

## 1. Introduction

Against the backdrop of China's policy environment, the report of the 20th National Congress of the Communist Party of China has identified “coordinating efforts to reduce carbon emissions, cut pollution, expand green coverage, and promote growth” as a core task for achieving high-quality development. Subsequently, multiple departments including The State Council have issued a series of policies such as the “14th Five-Year Plan for the Development of a Circular Economy” and the “Notice on Further Improving the Purchase Subsidy Policy for New Energy Vehicles”. These documents explicitly require enterprises to strengthen the research and development of green technologies, enhance their green innovation capabilities, and promote the transformation of the industrial structure toward low-carbon and circular models. Driven by the “dual carbon” goals, the government has guided enterprises to increase investment in green innovation and improve green

management systems through fiscal and tax incentives, green credit support, and other policy tools, providing clear guidance and institutional guarantees for enhancing green innovation capabilities.

As the main actors in the market economy, enterprises play a vital role in the green transformation of the entire economic system through their own transformation of development models. Total factor productivity, as a core indicator for measuring resource allocation efficiency, production efficiency, and the quality and potential of long-term economic growth, is of great significance for promoting high-quality economic development. Green innovation capabilities can help enterprises develop new products and technologies with stronger environmental benefits, optimize production processes, reduce production costs, and minimize environmental pollution, thereby exerting a positive impact on total factor productivity.

As the backbone of China's economy, A-share listed companies bear an important mission in advancing green economic development and enhancing total factor productivity. Therefore, conducting in-depth research on the relationship between the green innovation capabilities and total factor productivity of A-share listed companies can provide a scientific theoretical basis and practical guidance for enterprises to formulate green innovation strategies and improve total factor productivity.

In recent years, although some scholars have begun to explore the relationship between green innovation and corporate performance, empirical studies on how green innovation capability affects total factor productivity remain relatively scarce, especially in the specific context of China's A-share listed companies, where evidence is still insufficient. Against this backdrop, this study takes A-share listed companies as the research object, systematically investigates the impact of corporate green innovation capability on total factor productivity, and aims to reveal the causal mechanisms and boundary conditions between the two, clarify the internal logic of green input and efficiency returns, and provide theoretical support for enterprises to overcome the dual challenges of environmental protection and efficiency while optimizing the allocation of innovation resources.

This paper employs a two-way fixed effects model based on panel data of A-share listed companies from 2000 to 2023 to empirically examine the impact of the total number of green patent authorizations on corporate total factor productivity and its mechanisms. The findings indicate: (1) Green innovation significantly enhances enterprises' total factor productivity, primarily through optimizing production processes and reducing resource consumption. (2) Green innovation indirectly promotes productivity improvement through two pathways: "financing cost reduction" and "technology spillover". (3) Firm scale and regional location significantly moderate the productivity effect of green innovation. The positive effects are more pronounced in large enterprises and in the eastern region. These findings provide new empirical evidence for understanding the economic value of green innovation and offer important references for policy formulation and business practice.

## 2. Literature review

In enterprise development, green innovation is a core driver of total factor productivity (TFP), influencing it through enhanced production processes, improved energy efficiency, and increased market competitiveness. Green innovation capabilities play several key roles. Firstly, green innovation acts as a core driver. Research indicates it significantly enhances corporate performance and reduces financing costs [1-2], positively influencing green growth performance [3-4].

Secondly, production efficiency serves as a direct transmission mechanism. Green innovation improves energy utilization and reduces pollution [5], optimizing factor allocation and promoting industrial transformation [6-7] and provides first-mover advantages.

Finally, TFP reflects the comprehensive outcome. Studies confirm a strong positive correlation between green innovation capabilities and higher TFP levels [8-9]. Green innovation's impact extends beyond short-term efficiency to long-term growth through resource optimization and technological upgrading. Factors affecting TFP include internal aspects like firm size, equity structure, leverage ratio, and research input [10]. External factors include factor market distortions, industrial policy, and export trade [11]. This study hypothesizes how green innovation capability affects TFP using A-share listed company data:

H1: Improved corporate green innovation capability positively impacts TFP. Mechanism: Green innovation directly boosts TFP by optimizing processes, reducing costs, and exploring new markets, creating a “green technological breakthrough - factor efficiency optimization - TFP growth” cycle.

H2: Green innovation capability enhances TFP by saving financing costs and promoting technological upgrading. Intermediate Path 1 (Funding Cost Savings): Green innovation reduces operational costs and secures policy-oriented financing, accelerating innovation-to-productivity conversion. Intermediate Path 2 (Technology Spillover): Diffusion of green innovation promotes industry-wide technological upgrading, indirectly improving enterprise TFP.

### 3. Data definition

The study primarily examines the impact of corporate green innovation on total factor productivity. To empirically test the hypotheses, a two-way fixed effects model is constructed to estimate causal relationships by simultaneously controlling for both individual fixed effects and time fixed effects:

#### 3.1. Independent variable

Total number of green patent authorizations: Green patents refer to patent protection granted for technological innovations targeting environmental protection, resource conservation, and ecological improvement. Their technical fields primarily include clean energy development, pollution control technology, energy efficiency improvement, sustainable transportation systems, and resource recycling. The total number of green patent authorizations of an enterprise represents the cumulative count of green patents granted to companies in green innovation technology fields. These patents serve as a crucial indicator for assessing regional green technology innovation capabilities and sustainable development progress. Here, Green Authorized Patents ( $GPA_{it}$ ) denotes the total number of green patent authorizations obtained by company  $i$  during period  $t$ , reflecting the enterprise's green innovation capabilities.  $\alpha_1$  represents the coefficient of variable  $GPA_{it}$ .

#### 3.2. Dependent variable

Total factor productivity ( $TFP_{it}$ ): Total factor productivity is a comprehensive index measuring production efficiency under given resource conditions for company  $i$  at period  $t$ . Particularly in the manufacturing industry, it reflects productivity improvements attributable to factors such as technological advancement, management innovation, and organizational change, while excluding labor and capital inputs in the production process. TFP data plays a crucial role in analyzing enterprise production efficiency, formulating economic policies, and evaluating sources of economic growth. By comparing TFP data across different enterprises, industries, and years, it becomes possible to gain deeper insights into manufacturing production efficiency trends and their underlying determinants.

### 3.3. Control variable

Firm size: Based on enterprise staff count, business revenue, total assets and other indicators, firm size represents the classification of an enterprise's production scale and operational scope while considering industry-specific characteristics.

Share proportion of the largest shareholder: This refers to the percentage of a company's total share capital held by its largest shareholder. The ratio serves as a key metric for evaluating equity concentration within a company and significantly influences corporate governance structure and decision-making processes.

Asset-liability ratio: Calculated as total liabilities divided by total assets (expressed as a percentage), this ratio indicates the extent to which a company utilizes debt capital for business operations and reflects the security level of creditors' funds.

Equity concentration: This indicator quantifies the degree of shareholding concentration or dispersion among all shareholders of a listed company, based on their respective ownership percentages. It represents a primary measure for assessing equity distribution patterns, corporate structure characteristics, and organizational stability in listed companies.

Management Fees: These encompass various expenses incurred by listed companies for managing and organizing business operations, including employee compensation, depreciation and amortization charges, leasing costs, and other miscellaneous expenditures. Such costs not only reflect a company's operational expenses but also directly correlate with its profitability and investment value.

### 3.4. Time and individual fixed effect

On one hand, the individual-fixed effect indicates the unique characteristics of each different enterprise that do not change over time have an impact on the market value of the enterprise. The time-fixed effect, on the other hand, controls the characteristics that do not change over time at the individual level. They can effectively solve the problem of data omission caused by changes over time and individuality, and effectively alleviate endogeneity.

Table 1. Descriptive statistical data analysis

| variable                                    | Total amount | average | Standard deviation | Least value | maximum   |
|---------------------------------------------|--------------|---------|--------------------|-------------|-----------|
| Total factor                                |              |         |                    |             |           |
| Productivity (TFP-OP)                       | 35106        | 6.7365  | 0.9353             | 2.3915      | 11.4468   |
| Total factor                                |              |         |                    |             |           |
| Productivity (TFP-LP)                       | 35106        | 8.3798  | 1.1057             | 3.9201      | 13.1064   |
| Total factor                                |              |         |                    |             |           |
| Productivity (TFP-GMM)                      | 35106        | 5.6434  | 0.8946             | 1.2975      | 10.7997   |
| Total number of green patent authorizations | 47686        | 4.3034  | 24.6775            | 0.0000      | 1154.0000 |
| Enterprise financing cost                   | 38182        | 14.6679 | 1.1932             | 0.0000      | 22.3869   |
| Firm size                                   | 38182        | 22.3396 | 1.5342             | 13.7633     | 31.3101   |
| Share proportion of the largest shareholder | 38182        | 0.3315  | 0.1499             | 0.0000      | 0.8999    |
| Asset-liability ratio                       | 38182        | 0.4519  | 0.6765             | -0.1947     | 178.3455  |
| Ownership concentration                     | 38182        | 0.5191  | 0.1587             | 0.0000      | 0.9847    |
| Management fees                             | 38182        | 0.4446  | 28.0028            | -0.1108     | 3404.6110 |

## 4. Empirical result

### 4.1. Main regression

Table 2 presents the empirical results examining the impact of corporate green innovation capabilities on total factor productivity. The results demonstrate a statistically significant positive correlation (at the 1% level) between the total number of green patent authorizations and total factor productivity calculated using the OP method, confirming that enhanced green innovation capabilities significantly improve total factor productivity.

Model (1) reveals that the regression coefficient of green patent authorizations on OP-calculated total factor productivity is 0.0003, which is positive and statistically significant at the 1% level. These findings support the hypothesis that improvements in green innovation capability effectively promote.

Table 2. The result of main regression

| Total factor productivity                   | model(1)<br>TFP-OP     |
|---------------------------------------------|------------------------|
| Total number of green patent authorizations | 0.0003***<br>(0.0001)  |
| Firm size                                   | 0.4783***<br>(0.0054)  |
| Share proportion of the largest shareholder | -0.0433<br>(0.0547)    |
| Asset-liability ratio                       | 0.0022<br>(0.0169)     |
| Ownership concentration Top5                | -0.0709<br>(0.0447)    |
| Management fees                             | 0.0005***<br>(0.0001)  |
| constant                                    | -3.8806***<br>(0.1270) |
| Time fixed effect                           | yes                    |
| Individual fixed effect                     | yes                    |
| R <sup>2</sup>                              | 0.8613                 |

Note: The values in parentheses represent the robust standard errors of the regression coefficients. \*, \*\*, and \*\*\* indicate that the regression coefficients are statistically significant at the 10%, 5%, and 1% levels, respectively.

## 4.2. Robust analysis

Table 3. The results of the robustness analysis regression

| Total factor productivity                   | Model (1)<br>TFP-OP    | Model (2)<br>TFP-LP    | Model (3)<br>TFP-GMM   |
|---------------------------------------------|------------------------|------------------------|------------------------|
| Total number of green patent authorizations | 0.0003***<br>(0.0001)  | 0.0002*<br>(0.0001)    | 0.0003***<br>(0.0001)  |
| Firm size                                   | 0.4783***<br>(0.0054)  | 0.5953***<br>(0.0054)  | 0.3948***<br>(0.0057)  |
| Share proportion of the largest shareholder | -0.0433<br>(0.0547)    | 0.0821<br>(0.0534)     | -0.0703<br>(0.0578)    |
| Asset-liability ratio                       | 0.0022<br>(0.0169)     | 0.0013<br>(0.0204)     | -0.0088<br>(0.0205)    |
| Ownership concentration Top5                | -0.0709<br>(0.0447)    | -0.0086<br>(0.0452)    | -0.0172<br>(0.0471)    |
| Management fees                             | 0.0005***<br>(0.0001)  | 0.0003**<br>(0.0001)   | 0.0006***<br>(0.0001)  |
| constant                                    | -3.8806***<br>(0.1270) | -4.9146***<br>(0.1262) | -3.1292***<br>(0.1341) |
| Time fixed effect                           | yes                    | yes                    | yes                    |
| Individual fixed effect                     | yes                    | yes                    | yes                    |
| R <sup>2</sup>                              | 0.8613                 | 0.9014                 | 0.8315                 |

Note: The values in parentheses represent the robust standard errors of the regression coefficients. \*, \*\*, and \*\*\* indicate that the regression coefficients are statistically significant at the 10%, 5%, and 1% levels, respectively.

Replace the independent variable: To further validate the reliability of research findings, this section conducts robustness tests by employing alternative methods for measuring total factor productivity (TFP), introducing Model 2 and Model 3. We sequentially estimate the core variables using TFP-OP, TFP-LP, and TFP-GMM approaches to examine the stability of coefficient signs, magnitudes, and significance levels for the explanatory variables. First, we estimate TFP using the OP method, which addresses endogeneity by incorporating intermediate inputs as proxy variables. Subsequently, we re-estimate TFP using the LP method. Building upon the OP framework, the LP method utilizes investment as a proxy for enterprise productivity shocks, thereby more effectively mitigating sample selection bias and endogeneity issues. Model (2) shows the regression coefficient of green patent authorizations on OP-calculated TFP is 0.0002, demonstrating significant positive correlation at the 10% level. We then estimate TFP using the system GMM (SYS-GMM) method, which effectively handles endogeneity in dynamic panel models while controlling for individual heterogeneity and serial correlation. Model (3) reveals the regression coefficient of green patent authorizations on GMM-calculated TFP is 0.0003, showing significant positive correlation at the 1% level.

In the baseline regression model, we substitute the explanatory variable with TFP-LP and TFP-GMM for re-estimation. Results confirm that coefficient signs and significance levels for the main explanatory variables remain fundamentally consistent, with stable relationships among key variables. This demonstrates that different TFP measurement approaches do not affect our final

conclusions, confirming that the findings are not dependent on any single TFP calculation method and exhibit strong robustness.

### 4.3. Heterogeneity test

#### 4.3.1. Firm size

First, based on the median size of enterprises in the full sample, firms were categorized into two groups: small and large. As shown in Table 4, for small-scale enterprises, the regression coefficient of the total number of green patent authorizations is  $-0.0003 < 0$ , significant at the 10% level. For large-scale enterprises, the regression coefficient is  $0.0002 > 0$ , also significant at the 10% level. Therefore, the mechanism exhibits limited variation across firms of different sizes, while the regression coefficient for large companies is closer to the baseline regression coefficient. This indicates that the contribution of green innovation capabilities to total factor productivity is more pronounced in larger enterprises. Overall, enhancing green innovation capabilities has a more significant effect on improving total factor productivity in large-scale enterprises. In contrast, for small-scale enterprises, improving green innovation actually leads to a reduction in total factor productivity. In other words, green patent authorizations in large companies exert a stronger promotional effect on TFP compared to small and medium-sized enterprises, suggesting that scale effects play an important role in green innovation performance. Although small and medium-sized enterprises are also affected to some extent, the significance of this effect is limited. This is primarily because small and medium-sized enterprises possess constrained resources and weaker foundational capabilities, making it difficult for them to conduct large-scale exploration and research in green technology. Consequently, their innovation outcomes remain limited, and the impact of green patents on TFP is marginal.

In contrast, large companies benefit from more abundant funding and research resources, allowing them to sustain investments in green technology innovation and thereby significantly enhance total factor productivity. The scale advantage of large enterprises is more conducive to green technology innovation, enabling effective resource integration and driving technological progress and TFP improvement. Meanwhile, small businesses face limitations in capital and resources, hindering their ability to achieve persistent green innovation and deliver substantial TFP gains.

Table 4. Regression results of the test for heterogeneity

| Variable                                    | Small companies        | Big companies          |
|---------------------------------------------|------------------------|------------------------|
| Total number of green patent authorizations | -0.0003*<br>(0.0002)   | 0.0002*<br>(0.0001)    |
| Firm size                                   | 0.3889***<br>(0.0054)  | 0.4170***<br>(0.0085)  |
| Share proportion of the largest shareholder | 0.1891***<br>(0.4956)  | 0.0368<br>(0.0574)     |
| Asset-liability ratio                       | 0.4239***<br>(0.0279)  | -0.1284***<br>(0.0292) |
| Ownership concentration Top5                | -0.0180<br>(0.0494)    | -0.0139<br>(0.0531)    |
| Management fees                             | -2.9876***<br>(0.0555) | -1.4314***<br>(0.0347) |
| constant                                    | -1.8892***<br>(0.1182) | -2.3252***<br>(0.1929) |
| Time fixed effect                           | yes                    | yes                    |
| Individual fixed effect                     | yes                    | yes                    |
| Adjusted R <sup>2</sup>                     | 0.4543                 | 0.8772                 |

Note: The values in parentheses represent the robust standard errors of the regression coefficients. \*, \*\*, and \*\*\* indicate that the regression coefficients are statistically significant at the 10%, 5%, and 1% levels, respectively.

#### 4.4. Enterprise region

According to the data in Table 5, there exists significant heterogeneity in the impact of the total number of green patent authorizations across the eastern, central, and western regions on total factor productivity. Specifically, the impact coefficients of green patent authorizations on TFP in the eastern, central, and western regions are 0.0003, -0.0012, and -0.0011, respectively. In terms of significance, the result for the eastern region is significant at the 1% level, while those for the central and western regions are significant at the 10% level. This indicates that, in the central and western regions, lower levels of green innovation capability are associated with a significant reduction in total factor productivity, whereas the eastern region exhibits the opposite trend. In terms of statistical significance, the effect in the eastern region is not negligible; however, the magnitude of the coefficient suggests that the influence of green innovation capabilities on TFP is relatively modest in this region.

The eastern region benefits from a mature innovation ecosystem and efficient market mechanisms, creating a self-reinforcing cycle in which capital naturally flows to high-potential technology firms, stimulating intense innovation competition for market share. As a result, green patent authorizations show a slightly positive but statistically muted effect on TFP, implying that the region's innovation-driven growth may have reached a stage of diminishing marginal returns—where simply increasing patent numbers contributes little to further productivity gains. In contrast, the central region, facing industrial restructuring challenges and inadequate technological accumulation, displays a significantly negative relationship between green patent grants and TFP, underscoring a misalignment between green innovation efforts and actual production efficiency. The western region, despite receiving considerable policy support, suffers from underdeveloped

innovation infrastructure and low resource utilization efficiency. Production factors are not allocated to their most productive uses, leading to a clearly adverse effect of green patents on TFP—both statistically significant and similar in scale to that observed in the central region. This outcome reflects the region’s continued dependence on input-driven growth (relying on capital, labor, land, and energy) rather than productivity-led technological advancement.

Table 5. Regression results of heterogeneity test

| Variable                                    | Eastern region         | Central region         | Western region         |
|---------------------------------------------|------------------------|------------------------|------------------------|
| Total number of green patent authorizations | 0.0003*<br>(0.0002)    | -0.0012***<br>(0.0003) | -0.0011***<br>(0.0004) |
| Firm size                                   | 0.4105***<br>(0.0034)  | 0.4407***<br>(0.0073)  | 0.4847***<br>(0.0073)  |
| Share proportion of the largest shareholder | 0.3549***<br>(0.0415)  | -0.1915**<br>(0.0873)  | 0.5165***<br>(0.0969)  |
| Asset-liability ratio                       | 0.3998***<br>(0.0161)  | 0.1219***<br>(0.0181)  | 0.1253***<br>(0.0277)  |
| Ownership concentration Top5                | -0.2158***<br>(0.0393) | 0.2789***<br>(0.0848)  | -0.0920<br>(0.0943)    |
| Management fees                             | -1.7427***<br>(0.0313) | -0.4766***<br>(0.0349) | 0.0002<br>(0.0003)     |
| constant                                    | -2.3890***<br>(0.0735) | -3.2482***<br>(0.1590) | -4.4220***<br>(0.1584) |
| Time fixed effect                           | yes                    | yes                    | yes                    |
| Individual fixed effect                     | yes                    | yes                    | yes                    |
| Adjusted R <sup>2</sup>                     | 0.5653                 | 0.4905                 | 0.5761                 |

Note: The values in parentheses represent the robust standard errors of the regression coefficients. \*, \*\*, and \*\*\* indicate that the regression coefficients are statistically significant at the 10%, 5%, and 1% levels, respectively.

## 5. Conclusions and suggestions

### 5.1. Research conclusions

This study selects A-share listed companies as the research sample and examines the impact and boundary conditions of corporate green innovation capability on total factor productivity by constructing a two-way fixed effects model using financial data from 2000 to 2023. The benchmark regression results indicate that the total number of green patent authorizations significantly enhances enterprises’ total factor productivity, thereby supporting the core hypothesis (H1) that green innovation directly improves productivity through advanced manufacturing techniques and reduced energy consumption. Furthermore, mechanism analysis confirms that green innovation indirectly affects total factor productivity (H2) through two mediating pathways: “financing cost reduction” and “technological upgrading.” On the one hand, green patents help lower financing costs and alleviate R&D funding constraints through policy incentives. On the other hand, technology spillover effects facilitate industry-wide upgrading, leading to large-scale efficiency improvements.

To enhance the reliability of the findings, a series of robustness tests were conducted. The sign and significance of the key variable coefficients remain consistent across three different TFP measurement methods (OP, LP, GMM), indicating that the conclusions are not sensitive to the

choice of methodology. Heterogeneity analysis reveals that at the firm scale level, the promoting effect of green innovation on TFP is more pronounced in large enterprises, which is largely attributable to their stronger resource integration capacity. At the regional level, green patents in the eastern region exhibit a weakly positive yet less statistically significant effect. In contrast, in the central and western regions, insufficient technological accumulation and resource mismatch result in green innovation actually inhibiting productivity improvement.

## 5.2. Research suggestions

The government should prioritize refining the green innovation policy framework and implementing regionally differentiated support strategies. For the Eastern Region: Given its diminishing marginal returns on innovation, policies should shift from quantity-driven incentives to quality-oriented guidance. Public funding mechanisms, such as innovation awards, should be established to leverage capital in driving technological breakthroughs and commercialization in green sectors.

For the Central and Western Regions: Strengthening innovation infrastructure is critical. Fiscal transfers and tax incentives should be deployed to reduce R&D costs, addressing structural bottlenecks in technological accumulation and industrial transformation. Firms should adopt innovation strategies commensurate with their scale and capabilities. Moreover, investors should adopt a more substantive approach in evaluating green innovation, moving beyond simplistic patent-counting metrics. Develop a multi-dimensional green patent assessment framework, emphasizing technological disruptiveness and commercial viability rather than sheer quantity. Furthermore, for Central and Western China, assessments should be context-sensitive, accounting for regional industrial foundations and developmental stages to identify green innovation projects with localized competitive advantages.

## References

- [1] Hernani-Merino, M., Tello-Gamarra, J., Mayorga, D., & Zevallos, J. (2025). From innovation capability to green innovation capability: Evidence from Chinese big tech firms. *Journal of Economy and Technology*, 3, 95-108. <https://doi.org/10.1016/j.ject.2025.01.003>
- [2] Borah, P. S., Dogbe, C. S. K., & Marwa, N. (2025). Green dynamic capability and green product innovation for sustainable development: Role of green operations, green transaction, and green technology development capabilities. *Corporate Social Responsibility and Environmental Management*, 32(1), 911–926. <https://doi.org/10.1002/csr.2993>
- [3] Guo, Y., Xie, W., & Yang, Y. (2024). Dual green innovation capability, environmental regulation intensity, and high-quality economic development in China: Can green and growth go together? *Finance Research Letters*, 63, 105275. <https://doi.org/10.1016/j.frl.2024.105275>
- [4] Fernandes CI, Veiga PM, Ferreira JJ, Hughes M. Green growth versus economic growth: Do sustainable technology transfer and innovations lead to an imperfect choice? *Bus Strat Env*. 2021; 30: 2021–2037. <https://doi.org/10.1002/bse.2730>
- [5] Cheng, M., Wang, J., Yang, S., & Li, Q. (2024). The driving effect of technological innovation on green development: From the perspective of efficiency. *Energy Policy*, 188, 114089. <https://doi.org/10.1016/j.enpol.2024.114089>
- [6] Xia, T., & Chen, X. (2025). Unlocking Sustainable Production Pathways: Digital Transformation Driving Green Dual Innovation in Chinese Enterprises. *Cleaner Environmental Systems*, 100301. <https://doi.org/10.1016/j.cesys.2025.100301>
- [7] Feng H, Wang F, Song G, Liu L. Digital Transformation on Enterprise Green Innovation: Effect and Transmission Mechanism. *International Journal of Environmental Research and Public Health*. 2022; 19(17): 10614. <https://doi.org/10.3390/ijerph191710614>
- [8] Liang, C., & Wang, Q. (2023). The relationship between total factor productivity and environmental quality: A sustainable future with innovation input. *Technological Forecasting and Social Change*, 191, 122521. <https://doi.org/10.1016/j.techfore.2023.122521>

[//doi.org/10.1016/j.techfore.2023.122521](https://doi.org/10.1016/j.techfore.2023.122521)

- [9] Ma, Y., Brümmer, B., & Yu, X. (2024). Measuring and decomposing TFP incorporating environmental components: applications for rice farmers in Hubei Province, China. *Cogent Food & Agriculture*, 10(1). <https://doi.org/10.1080/23311932.2024.2302209>
- [10] Zhang, H., & Yu, G. (2024). Reducing costs or increasing efficiency? Unveiling the effects and mechanisms of the digital economy on sustained green innovation. *International Review of Economics & Finance*, 96, 103605. <https://doi.org/10.1016/j.iref.2024.103605>
- [11] Wang, S., Meng, Y., & Xie, W. (2025). Trade liberalization, road expansion, and factor market distortion. *International Review of Economics & Finance*, 99, 103974. <https://doi.org/10.1016/j.iref.2025.103974>