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FOREIGN DIRECT INVESTMENT, FINANCIAL DEVELOPMENT, AND TECHNOLOGICAL INNOVATION: A NEW PERSPECTIVE ON SPATIAL SPILLOVERS

Wei JIANG[1], Xiang MA[2], Lingli QING[3,4]✉

[1]*School of Business, Zhejiang Industry Polytechnic College, Shaoxing, China*
[2]*School of Management, Guangdong University of Science and Technology, Dongguan, China*
[3]*School of Accounting, Guangzhou College of Commerce, Guangzhou, China*
[4]*E-Commerce Research Center of Guangdong-Hong Kong-Macao Greater Bay Area, Guangzhou College of Commerce, Guangzhou, China*

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Abstract. This study used data from cities in the Yangtze River Delta (YRD) in China between 2012 and 2022 to analyze how foreign direct investment (FDI) and financial development impact technological innovation and how these effects spread to nearby areas. We found that (1) FDI significantly boosted technological innovation, and financial development effectively strengthened this effect. (2) The YRD urban agglomeration exhibited clear spatial spillovers in technological innovation, in that geographically adjacent regions showed technological siphoning effects, whereas regions with similar economic development levels demonstrated positive spillovers. (3) The synergistic effects of FDI and financial development varied by region, with positive spillovers in economically linked regions but insignificant effects in geographically adjacent regions. The findings also suggested that late-developing regions exhibited stronger absorptive capacity for FDI technology spillovers. The YRD and Pearl River Delta regions exhibited significantly superior synergistic effects compared to the Beijing-Tianjin-Hebei and Chengdu-Chongqing regions. This study enriches the understanding of the relationship among FDI, financial development, and technological innovation along with their spatial heterogeneity. It also provides valuable innovative insights for formulating regionally differentiated innovation policies, thereby offering practical guidance for fostering coordinated technological innovation across regions.

Keywords: FDI, financial development, technological innovation, Yangtze River Delta.

JEL Classification: F23, O16, O33.

✉Corresponding author. E-mail: ***cleverqing@pukyong.ac.kr***

1. Introduction

Regional collaborative innovation is the key to promoting the integrated and high-quality development of the Yangtze River Delta (YRD). Since the 1990s, the YRD region has taken the lead in opening up to the outside world. With a large inflow of Foreign Direct Investment (FDI), this region has earlier introduced and absorbed advanced technology and management experience from abroad, fostering technological progress and structural upgrading. The YRD urban agglomeration is the region with the strongest innovation capacity in China. Figure 1 illustrates the spatial distribution of patent grants in the cities of the YRD urban agglomeration in 2012 and 2022. However, regardless of the year, highly economically developed cities such as Shanghai, Suzhou, Hangzhou, Ningbo, and Nanjing have maintained a core position in technological innovation. Wuxi, Nantong, Changzhou, Jinhua, Wenzhou, and Hefei, as well as relatively developed cities adjacent to Shanghai, have also maintained high levels of technological innovation capacity. Other cities in Jiangsu and Zhejiang Provinces are ranked at the third level in terms of technological innovation. Most cities in Anhui Province show low-value agglomeration. This phenomenon suggests that patents granted in the YRD urban agglomeration exhibit significant spatial spillover characteristics. In addition, the surrounding regions of cities with high technological innovation levels, such as Hefei, Nanjing, and Hangzhou, typically have lower technological innovation levels. This indicates that technological innovation agglomerations have been formed in economically developed regions to attract innovation resources from regions with relatively less developed technological levels, which in turn produces a spatial polarization effect.

However, no consensus has been reached in the literature regarding the impact of FDI on technological innovation. Researchers such as Cheung and Lin (2004), Liu and Buck (2007), Erdal and Göçer (2015), Sugiharti et al. (2022), Ali et al. (2023), and Yue (2022) found a significant positive impact of FDI on technological innovation. In contrast, researchers such as Aitken and Harrison (1999), Konings (2001), Blalock and Gerlter (2008), Fu and Gong (2011), and García et al. (2013) have argued that the impact of FDI is significantly negative. Furthermore, some other researchers such as Cohen and Levinthal (1989), Fosfuri et al. (2001), Huang et al. (2012), Lin and Kwan (2016), Brenner and Broiekel (2011), Liu and Buck (2007), and Fu (2008) suggested that certain conditions need to be met for FDI to promote technological innovation. They also argued that because of the differences in various absorptive capacity factors, the effects of FDI on technological innovation vary in different countries or regions. Thus, FDI may not necessarily be able to promote technological innovation in the host country. Alfaro et al. (2004), Girma et al. (2008), and Tang et al. (2023) posited that the development level of finance, as the core of the modern economy, has become an important factor influencing the technological progress effect of FDI by alleviating the financing constraints and enhancing the

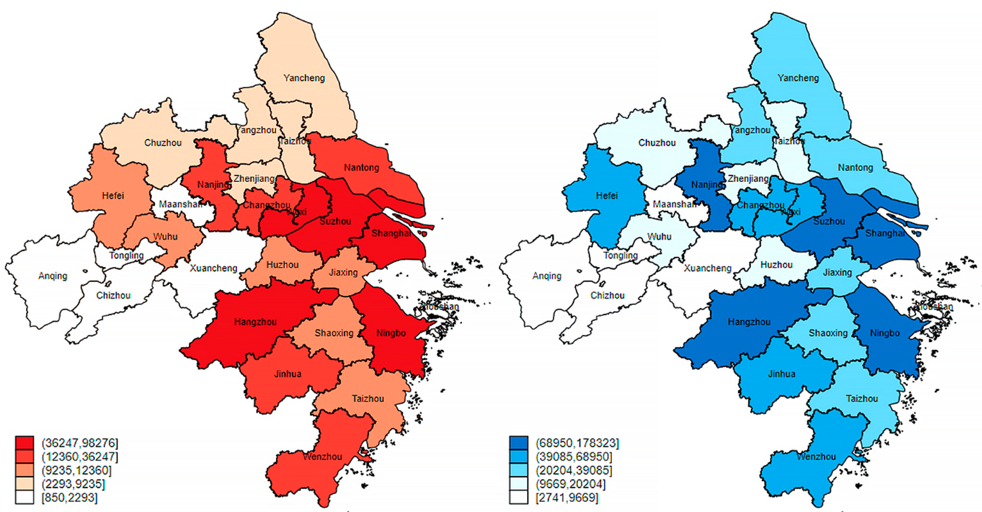

Figure 1. Spatial distribution of patent grants in the YRD urban agglomeration during 2012–2022

capital allocation efficiency. However, prior studies have predominantly relied on conventional econometric analyses and have rarely considered spatial spillovers. In particular, the synergies between FDI and financial development remain underexplored.

Therefore, this study constructed baseline regression and spatial econometric models based on panel data from the YRD urban agglomeration from 2012 to 2022 to address three questions. First, how do FDI and financial development jointly influence technological innovation? An interaction term was introduced to explore whether financial development can strengthen FDI technology spillovers. Second, do FDI and financial development generate spatial spillover effects? Multiple spatial weight matrices (e.g., geographic adjacency and economic distance matrices) were employed to analyze spillover patterns at different spatial scales. Third, how does regional heterogeneity influence the synergic effects of FDI and financial development on technological innovation? Absorption capacity for FDI technology spillovers were compared between developed and late-developing regions.

This study can make three marginal contributions to the literature. First, this study is the first to include the interaction term of FDI and financial development in the analytical framework and reveals their synergic effects on technological innovation. Second, an innovative perspective on spatial spillovers was adopted by transcending traditional non-spatial analyses to systematically examine the cross-regional technology diffusion effects of FDI and financial development. Third, the research methodology was improved, in that multi-dimensional spatial weight matrices (e.g., geographic adjacency and economic distance matrices) were employed to enhance the robustness of the empirical results and reveal heterogeneous spillover effects under different spatial correlation patterns. The findings of this study can serve as a reference for formulating spatially differentiated innovation policies in the YRD urban agglomeration. Specifically, the findings suggest promoting high-quality coordinated development by strengthening financial systems to enhance the FDI absorption capacity and optimizing the cross-regional innovation collaboration network.

The remainder of this paper is structured as follows. Section 2 presents the theoretical analysis and research hypotheses. Section 3 describes the regression model, variables, samples, and data sources. Section 4 introduces the spatial correlation analysis and selection of the spatial econometric model. Section 5 analyzes the empirical results, robustness, endogeneity, and heterogeneity. Section 6 provides the conclusions, theoretical contributions, policy implications, limitations, and future research directions.

2. Theoretical analysis and research hypotheses

2.1. FDI and regional technological innovation

Technological innovation is a complex and systematic process that involves not only the progress of technology itself but also multiple dimensions such as new product development, process innovation, market development, and organizational change (Schumpeter, 1912). For emerging economies such as China, acquiring global innovation resources through international technology spillover channels such as FDI and subsequently developing localized innovations based on these resources is an important pathway for enhancing technological innovation capacities. International investment theory (Dunning, 1977) suggests that multinational enterprises make FDI decisions based on their technological advantages and management capabilities, as well as the conditions of the host country. The inflow of FDI not only brings financial support but also introduces advanced technology, production experience, and management patterns, thereby exerting multiple effects on technological innovation in the host country. Furthermore, endogenous growth theory (Lucas, 1988; Romer, 1990) reveals that FDI fosters technological innovation through knowledge spillovers and human capital accumulation. Thus, multinational enterprises facilitate knowledge diffusion via technology demonstration and personnel mobility, while local enterprises enhance their technological absorptive capacity through learning-by-doing processes. Specifically, FDI fosters technological innovation through three primary mechanisms: 1) capital supply effects (i.e., alleviating R&D financing constraints for local enterprises), 2) technology spillover effects (i.e., driving technological upgrading through demonstration, imitation, and competition), and 3) industrial synergy effects (i.e., promoting the cooperation between multinational enterprises and local enterprises to optimize industrial structures) (Osabuohien-Irabor & Drapkin, 2024). Recent studies have shown that effective organizational management (e.g., paradoxical leadership) promotes knowledge sharing and further strengthens the innovation effect of FDI (Deng et al., 2023). These theories provide a multidimensional perspective for understanding the relationship between FDI and technological innovation and a theoretical foundation for this study to analyze the technological innovation mechanism in the YRD urban agglomeration. Based on the above theoretical analysis, this study proposes the following hypothesis:

H1: *FDI has a significant positive effect on technological innovation in the YRD urban agglomeration.*

2.2. FDI, financial development, and technological innovation

Prior studies have found that a well-developed financial system provides key support for technological innovation. Ozsahin and Uysal (2017) argued that a developed financial market can substantially enhance national innovation capacity and productivity, whereas financial underdevelopment hinders the technological innovation process. Furthermore, an empirical study by Levine (2002) revealed the dual role of financial development in moderating the relationship between FDI and technological innovation. At the macro level, financial development strengthens the technological innovation effects of FDI through three primary channels: 1) optimizing the capital allocation to direct FDI toward high-return innovation projects, 2) pooling social capital to support capital-intensive technological innovation, and 3) expanding technological diffusion channels to facilitate the dissemination and absorption of advanced technologies. At the micro level, the financial system supports technological innovation through three channels: 1) providing R&D financing to mitigate corporate underinvestment in innovation, 2) diversifying innovation risks and encouraging enterprises to take on high-risk R&D activities, and 3) reducing information asymmetry to improve the financing efficiency of innovation projects. Based on the above theoretical analysis, this study proposes the following hypothesis:

H2: *Financial development significantly and positively moderates the promoting effect of FDI on technological innovation.*

2.3. Spillover effects of technological innovation

Spatial economics research shows that geographic factors play a key role in regional innovation activities. The new economic geography, represented by Krugman, emphasizes that technological innovation has clear spatial agglomeration characteristics. Balland et al. (2019) found that innovative activities are unevenly distributed spatially, showing significant agglomeration effects and regional heterogeneity. Capello and Lenzi (2013) empirically demonstrated that economic agglomeration not only promotes local innovation but also has a positive effect on adjacent regions through knowledge spillovers and technology diffusion. Further research Crescenzi et al. (2007) confirmed the spatial correlation of science and technology innovation activities across regions, and this positive externality has been verified in both Europe and the US. However, Pan et al. (2023) found that in industrial synergy networks, core enterprises tend to proactively diffuse digital innovations, while complementary enterprises actively absorb them, thus facilitating the spatial diffusion of innovations. Based on these findings, this study proposes the following hypothesis:

H3: *Technological innovation in the YRD urban agglomeration demonstrates significant spatial spillover effects, which are manifested in cross-regional diffusion and innovation exchange.*

2.4. Spillover effects of financial development and FDI on technological innovation

Recent studies have shown that spatial econometric approaches offer novel research perspectives for analyzing the complex relationships among FDI, absorptive capacity, and regional innovation. Miguélez and Moreno (2015) innovatively incorporated the interaction term of absorptive capacity and FDI into a Spatial Durbin model (SDM) and validated the important facilitating effect of regional absorptive capacity on knowledge flows. Feng et al. (2019) further extended this research paradigm by constructing multiple spatial weight matrices (neighborhood distance, geographic inverse distance, and economic distance matrices) to systematically examine the synergistic innovation effect of environmental regulation and FDI, finding a significant positive effect of the interaction term on urban innovation. Duan et al. (2021) used the entropy method to measure absorptive capacity and revealed the mechanism through which transnational knowledge spillovers influence the innovation quality of high-tech industries in the host country. Based on the above research foundations and developmental characteristics of the YRD region, this study focuses on the moderating role of financial development as a key variable affecting absorptive capacity. Extant theories posit that well-developed financial systems can substantially improve the regional absorption efficiency of FDI technology spillovers through channels such as resource allocation optimization and financing cost minimization. Therefore, this study proposes the following hypothesis:

H4: *Under spatial interactions, the synergy between FDI and financial development generates significant positive spatial spillover effects on technological innovation in the YRD urban agglomeration. These effects may be realized through cross-regional financial connectivity, industrial synergy, and technology diffusion.*

The theoretical framework is illustrated in Figure 2.

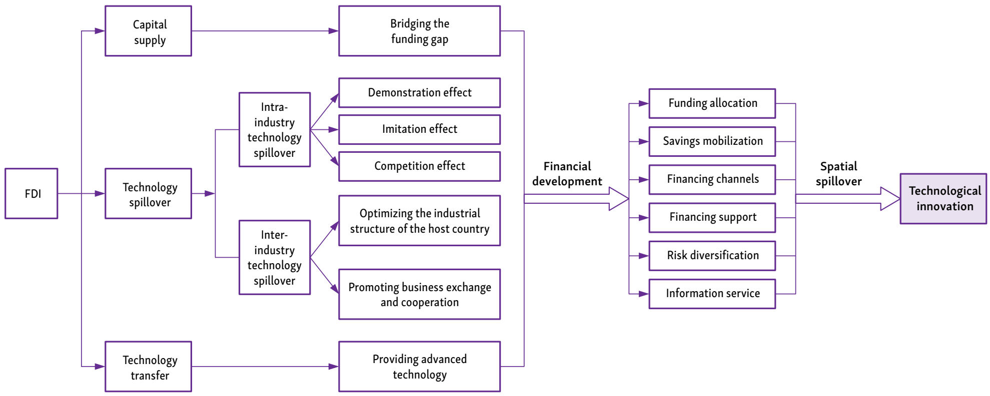

Figure 2. Theoretical framework

3. Methodology

3.1. Settings for the baseline regression model

To investigate the direct effects of FDI on the technological innovation level of the YRD urban agglomeration, we regarded technological innovation as a new technological output based on the theoretical analysis of the impact of FDI on regional technological innovation. According to $Y = A \times FDI^{\alpha 1} \times X_i^{\alpha_p}$ (i.e., the Cobb–Douglas production function of the new technological output), we took the logarithm on both sides of the equation and constructed the following baseline regression model:

$$\ln Y_{it} = \alpha_0 + \alpha_1 \ln FDI_{it} + \sum_{p=2}^{3} \alpha_p \ln X_{it} + \mu_i + \lambda_t + \varepsilon_{it}, \tag{1}$$

where Y_{it} is a technological innovation variable vector, FDI_{it} denotes the actual FDI, X_{it} denotes control variables including labor inputs and capital inputs, α_0 represents the intercept term, α_1 represents the regression coefficient for the effect of FDI on technological innovation, α_p represents the regression coefficients of the control variables (i.e., capital and labor inputs), λ_t represents the time fixed effect, ε_{it} represents the error term, i represents the sample of cities, and t represents the year.

3.2. Settings for the moderating effect model

Based on the moderating mechanism of financial development in the relationship between FDI and technological innovation, we used financial development level as a moderator to explore its critical moderating effect. The following moderating effect model was constructed:

$$\ln Y_{it} = \beta_0 + \beta_1 \ln FDI_{it} + \beta_2 FIN_{it} + \beta_3 \ln FDI_{it} \text{x}\, FIN_{it} + \sum_{p=2}^{3} \beta_p \ln X_{it} + \mu_i + \lambda_t + \varepsilon_{it}, \tag{2}$$

where FIN_{it} denotes the financial development level, $FDI_{it} \text{x}\, FIN_{it}$ is a variable describing the interactive effect of FDI and financial development, β_2 is the regression coefficient for the effect of financial development on technological innovation, and β_3 is the regression coefficient for the interactive effect of FDI and financial development. The remaining variables have the same meanings as in the baseline model. Special attention should be provided to the economic interpretation of β_3.

3.3. Variable selection

(1) Explained variable

Technological output (Y_{it}). Referring to Sun et al. (2020), we used the number of patent applications granted as an alternative indicator of technological innovation output. Patent applications filed by inventors or creators in a region with the patent examining authority can often be regarded as an indicator of regional innovation capacity.

(2) Core explanatory variables

FDI (FDI_{it}). Drawing on the methods of Qing et al. (2024), we measured this variable using the actual amount of FDI attracted by a certain city. Since the original data were denominated in US dollars (USD), we converted the data to be expressed in Chinese yuan (CNY) according to the annual average exchange rate of CNY to USD.

Financial development (FIN_{it}). Referring to Tang et al. (2023), we measured the regional financial development level by the ratio of the deposit/loan balance of financial institutions in domestic and foreign currencies to the regional GDP. The higher the ratio, the larger the size of the region's financial market relative to the economy as a whole, and the more adequate its allocation of resources and supply of funds.

Interaction term of FDI and financial development $\left(FDI_{it} \times FIN_{it}\right)$. The role of financial development in the effects of FDI on technological innovation can be considered to moderate this effect. To avoid the problem of multicollinearity, we referenced Asamoah and Alagidede (2023) and mean-centered the interaction term of FDI and financial development.

(3) Control variables

Socioeconomic development level (ED_{it}). This variable was measured based on GDP per capita, reflecting capital absorption capacity.

Human capital (PC_{it}). Drawing on the method proposed by Wang et al. (2023), we used the number of university students per 10,000 people in a city as a proxy variable to depict the capacity for absorbing human capital. Table 1 summarizes the definitions of the variables.

Table 1. Variable definitions

Variables	Measurement	Symbol	Definitions
Explained variable	Technological output	lnY	Logarithm of the number of patent applications granted
Core explanatory variables	FDI	lnFDI	Logarithm of the actual FDI amount
	Financial development	FIN	Ratio of the deposit/loan balance of financial institutions in domestic and foreign currencies to the GDP
	Interaction term of FDI and financial development	lnFDI x FIN	Mean-centered value of the product of FDI and financial development
Control variable	Economic development level	lnED	Logarithm of GDP per capita
	Human capital	lnPC	Logarithm of the number of university students per 10,000 people

3.4. Samples and data sources

We used panel data from 27 cities in the YRD urban agglomeration from 2012 to 2022 as the research sample, obtaining a total of 297 valid city-year observations. The data were mainly collected from the provincial or municipal statistical yearbooks of three provinces (Jiangsu, Zhejiang, and Anhui) and one municipality (Shanghai), as well as the statistical yearbooks and bulletins for each city. For missing data, linear interpolation was performed to fill in reasonably to ensure data completeness. Table 2 presents the descriptive statistics of each variable, laying the data foundation for subsequent empirical analysis.

Additionally, to enhance the generalizability of the research findings, we selected three major urban agglomerations (i.e., Beijing-Tianjin-Hebei [BTH], PRD, and Chengdu-Chongqing [CC]), as comparative samples. These data were also sourced from the respective city-level statistical yearbooks of the regions. Through cross-regional comparative analysis, we thoroughly explored 1) the commonalities and characteristics of the spatial spillover effects of technological innovation across different urban agglomerations and 2) the regional heterogeneity in the synergistic effects of FDI and financial development. This type of multi-regional comparison helped us provide more targeted policy recommendations for China's coordinated regional development.

Table 2. Descriptive statistics of the study variables

Variable	Obs	Mean	Std. Dev.	Min	Max.
lnY	297	9.609	1.203	6.745	12.129
lnFDI	297	4.529	1.128	1.581	7.385
FIN	297	3.028	1.115	.226	7.033
lnED	297	2.146	.414	1.082	2.988
lnPC	297	2.277	1.18	–.562	5.412

4. Spatial correlation analysis and spatial econometric model selection

4.1. Construction of spatial weight matrices

Spatial weight matrices should be determined to measure the geographic or economic distance between cities. When the spatial linkages between cities are measured only with the distance criterion, errors may occur. Therefore, we used various criteria for the measurement.

(1) Geographic adjacency matrix. This matrix was constructed based on the geographic location information of the cities. When city i is adjacent to city j, W_{ij} is equal to 1; otherwise, W_{ij} is equal to 0.

$$W_{ij} = \begin{cases} 0 & \text{Cities } i \text{ and } j \text{ are not adjacent} \\ 1 & \text{Cities } i \text{ and } j \text{ are adjacent} \end{cases}. \quad (3)$$

(2) Geographic inverse distance matrix. Based on the latitude and longitude data of the cities, the actual geographic distance d_{ij} between city i and city j was calculated. Subsequently, the inverse of this calculated distance was used as a spatial weight matrix to reveal the spatial relationship between cities.

$$W_{ij} = 1/d_{ij}. \tag{4}$$

(3) Distance square matrix. First, the actual geographic distance d_{ij} between city i and city j was calculated. Then, the inverse square of this distance was used as the element of the spatial weight matrix to better depict the spatial relationship between cities.

$$W_{ij} = 1/d_{ij}^2. \tag{5}$$

(4) Economic inverse distance matrix. First, the difference in GDP between city i and city j was calculated based on the current GDP of each city. Then, the absolute inverse of the difference was used as the element of the economic distance matrix to represent the spatial correlation between cities.

$$W_{ij} = 1/\left|\mathrm{GDP}_i - \mathrm{GDP}_j\right|. \tag{6}$$

4.2. Spatial correlation analysis

The correlation test of spatial variables is the core of regression analysis using spatial econometric models. This study calculated the global Moran's I index (a traditional method) to demonstrate the average spatial correlation of different variables among cities. The calculation process of Moran's I is as follows:

$$\text{Moran's } I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})w_{ij}\left(x_j - \bar{x}\right)}{S^2\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}}, \tag{7}$$

where S^2 is the sample variance, $\bar{x}$ represents the sample mean, and w_{ij} is the element of the spatial weight matrix W_{ij}, which measures the spatial distance between city i and city j. Typically, Moran's I range from –1 to 1. If it is greater than zero, it implies a positive correlation between a high value and its neighboring high value or between a low value and its neighboring low value. Conversely, if it is less than zero, a negative correlation exists between the high and low values.

The analysis results in Table 3 show a significant positive correlation in the number of patents granted between the cities in the YRD urban agglomeration under different spatial weight matrices. Thus, cities with higher innovative technological achievements tended to be concentrated together, while those with lower innovation capacities also showed a relative concentration trend. This phenomenon suggests that the cities in the YRD region have strong scientific and technological innovation capacities, and these capacities have a certain spatial aggregation effect. These findings also imply that neighboring cities, especially those with similar economic levels, may experience a certain degree of competition, imitation, and cooperation in terms of scientific and technological innovation.

The local correlation of the technological innovation output in different cities was analyzed by drawing Moran scatterplots. Owing to space constraints, we only focused on the data from 2022, and explored the correlations based on the spatial weights of spatial inverse distance matrix W2 and economic inverse distance matrix W4, as shown in Figures 3–4.

Table 3. Spatial correlation analysis of the patent grants based on global Moran's I in 2012–2022

Year	Adjacency matrix W1 I Z	Inverse distance matrix W2 I Z	Inverse distance square matrix W3 I Z	Economic inverse distance matrix W4 I Z
2012	0.236** 2.145	0.081*** 4.020	0.196*** 3.541	0.557*** 5.267
2013	0.230** 2.100	0.081*** 4.042	0.199*** 3.577	0.555*** 5.244
2014	0.262** 2.352	0.090*** 4.348	0.219*** 3.881	0.599*** 5.628
2015	0.282** 2.505	0.099*** 4.626	0.234*** 4.104	0.635*** 5.938
2016	0.232** 2.120	0.080*** 4.023	0.202*** 3.636	0.641*** 6.026
2017	0.203* 1.896	0.077*** 3.895	0.195*** 3.523	0.627*** 5.893
2018	0.224** 2.056	0.080*** 4.006	0.204*** 3.670	0.635*** 5.965
2019	0.190* 1.786	0.068*** 3.599	0.181*** 3.311	0.617*** 5.794
2020	0.177* 1.690	0.068*** 3.590	0.185*** 3.383	0.616*** 5.806
2021	0.142 1.419	0.058*** 3.279	0.168*** 3.123	0.600*** 5.670
2022	0.088 0.989	0.043*** 2.748	0.135*** 2.619	0.573*** 5.424

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

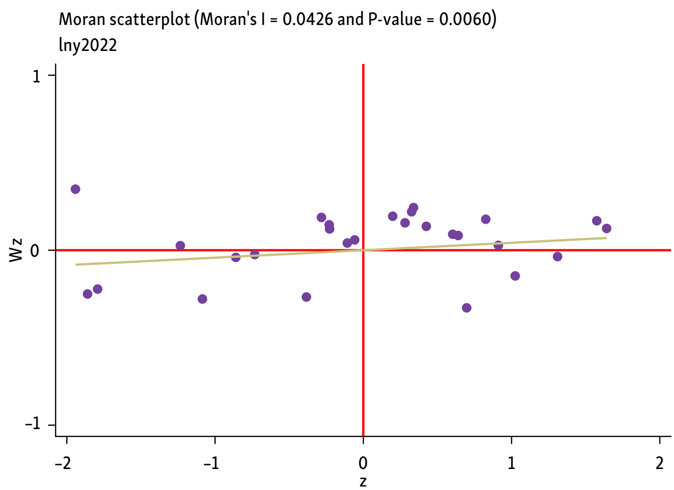

Figure 3. Moran scatterplot under spatial distance matrix W2 in 2022

Based on Moran's I and the accompanying probability (p-value) in the Moran scatterplots, the number of patents granted in the YRD urban agglomeration in 2022 was significantly positive at the 1% level, indicating that the number of patents granted showed a significant positive correlation. Furthermore, the connections between each city and their neighboring cities were identified based on the four quadrants of each Moran scatterplot. Most of the points in the scatter plots were located in the first and third quadrants under each spatial weight matrix. These findings indicated that the cities with more patent grants tended to be surrounded by a large number of cities at the same level, and vice versa. This phenomenon confirms that cities in the YRD region exhibit similar degrees of agglomeration in scientific and technological innovation.

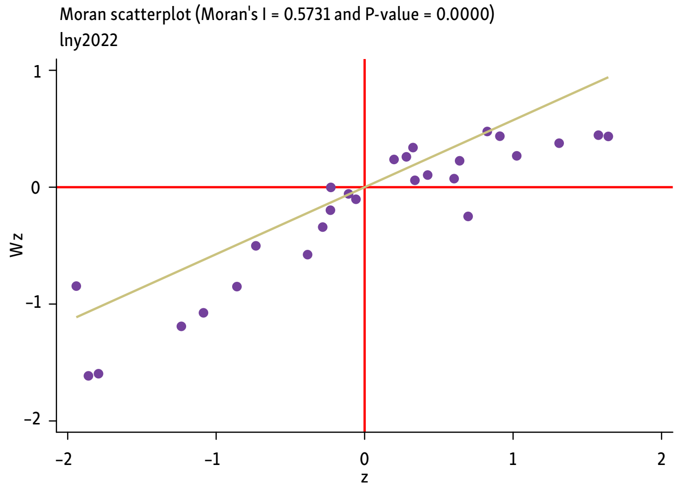

Figure 4. Moran scatterplot under spatial economic inverse distance matrix W4 in 2022

4.3. Construction of a spatial econometric model

Based on the above analysis of the spatial spillover effects of FDI and financial development on technological innovation, we constructed a generalized spatial econometric model incorporating the interaction term of FDI and financial development to examine the spatial spillover effects of FDI and financial development on technological innovation. The specific design of the model is as follows:

$$Y_{it} = \eta_0 + \rho \sum_{j=1, j\neq i}^{N} \omega_{ij} Y_{jt} + \eta_1 FDI_{it} + \eta_2 FIN_{it} + \eta_3 FDI_{it} xFIN_{it} + \eta_4 X_{it} + \eta_5 \sum_{j=1, j\neq i}^{N} \omega_{ij} FDI_{jt} + \eta_6 \sum_{j=1, j\neq i}^{N} \omega_{ij} FIN_{jt} + \eta_7 \sum_{j=1, j\neq i}^{N} \omega_{ij} FDI_{jt} xFIN_{jt} + \eta_8 \sum_{j=1, j\neq i}^{N} \omega_{ij} X_{jt} + \mu_i + \gamma_t + \varepsilon_{it}; \quad (8)$$

$$\varepsilon_{it} = \psi \sum_{j=1, j\neq i}^{N} \omega_{ij} \varepsilon_{jt} + \nu_{it}, \quad (9)$$

where i and j are the cross-sectional variables for each city; t is the year; ω_{ij} is the element of spatial weight matrix W; $\sum_{j=1, j\neq i}^{N} \omega_{ij} Y_{jt}$ is the spatial lag term of the explained variable; $\sum_{j=1, j\neq i}^{N} \omega_{ij} FDI_{jt}$, $\sum_{j=1, j\neq i}^{N} \omega_{ij} FIN_{jt}$, $\sum_{j=1, j\neq i}^{N} \omega_{ij} FDI_{jt} xFIN_{jt}$, and $\sum_{j=1, j\neq i}^{N} \omega_{ij} X_{jt}$ are the spatial lag terms of FDI, financial development level, interaction term of FDI and financial development, and other control variables, respectively; μ_i, γ_t, and ε_{it} are the individual effect, time effect, and random disturbance terms, respectively; $\sum_{j=1, j\neq i}^{N} \omega_{ij} \varepsilon_{jt}$ is the spatial lag term of the disturbance term. This model focuses on the economic interpretations of the spatial autoregressive coefficient of the explained variable (ρ) and the coefficients of the interaction term of FDI and financial development (η_3 and η_7).

In the spatial econometric test, we categorized the general spatial econometric model into various forms based on whether ρ, η, and ψ were 0, mainly including the spatial lag model (i.e., spatial autoregressive model, SAR) where $\rho \neq 0$, $\eta_5 = \eta_6 = \eta_7 = \eta_8 = 0$, and $\psi = 0$, the spatial error model (SEM) where $\rho = 0$, $\eta_5 = \eta_6 = \eta_7 = \eta_8 = 0$, and $\psi \neq 0$, and SDM where $\rho \neq 0$, $\eta_5 \neq 0$, $\eta_6 \neq 0$, $\eta_7 \neq 0$, $\eta_8 \neq 0$, and $\psi = 0$. These three spatial econometric models include exogenous and endogenous spatial interaction effects and are commonly used in spatial econometrics. Therefore, we aimed to select a spatial econometric model from SAR, SEM, and SDM.

4.4. Selection of the spatial econometric model

There are various types of spatial econometric models according to different sources of interaction effects. Referring to Qin et al. (2023), we selected the optimal spatial econometric model from particular to general and then from general to particular using Lagrange Multiplier (LM) test, Likelihood-Ratio (LR) test, Hausman test, and joint significance test. The specific steps are as follows:

(1) LM test

Table 4 lists the LM test results for spatial lag and spatial error. Most of the statistics under the four matrices indicate significant spatial lag and spatial error effects in the model. Therefore, we selected SDM for the spatial econometric analysis.

Table 4. LM test results

Statistic	W1	W2	W3	W4
Spatial LM-error	71.186***	43.404***	90.126***	89.995***
Spatial LM-lag	63.627***	39.033***	92.015***	183.080***
Spatial RLM-error	16.178***	26.019***	15.264***	1.074
Spatial RLM-lag	8.619***	1.727	17.152***	94.158***

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

(2) LR and Wald tests

The LM test results showed inconsistencies. To improve the model identification accuracy, we performed LR and Wald tests to further verify whether the initially selected SDM degraded into SAR or SEM.

Table 5. Results of LR and Wald tests

Original hypothesis	W1 LR Wald	W2 LR Wald	W3 LR Wald	W4 LR Wald
SAR	11.89** 12.16**	27.06*** 31.08***	22.31*** 23.39***	9.21 936
SEM	10.63* 10.87*	22.73*** 24.78***	19.67*** 20.28***	9.31* 9.47*

The results in Table 5 show that, under the influence of matrices W1, W2, and W3, the statistics derived from the LR and Wald tests explicitly rejected SAR and SEM at the 1% level, indicating that SDM cannot easily degrade to SAR or SEM. However, the model degrading to SAR should be accepted under W4.

(3) Hausman test

We performed the Hausman to select the fixed and random effect models, with different conclusions under various matrices. The results in Table 6 show that random effects should be rejected and a fixed effect model used under adjacency matrix W1, inverse distance matrix W2, and inverse distance square matrix W3. However, a random effect model was accepted under economic inverse distance matrix W4.

Table 6. Hausman test results

Original hypothesis	W1 Chi^2 statistic	W2 Chi^2 statistic	W3 Chi^2 statistic	W4 Chi^2 statistic
RE	9.18*	543.58***	438.85***	–1.24

Based on the results of the spatial econometric models in the previous section, we adopted the optimal model settings for each spatial weight matrix. For the geographic neighbor matrix (W1), geographic inverse distance matrix (W2), and geographic inverse square matrix (W3), the fixed-effects SDM was used for estimation. For the economic inverse distance matrix (W4), the random-effects SAR was adopted for estimation.

5. Results and discussions

5.1. Baseline regression results

The baseline regression results in Table 7 show that the effects of FDI on technological innovation exhibited stage-specific characteristics. Columns (1) and (2) present the results of the baseline model without controlling for fixed effects. The regression coefficient for the effect of FDI (lnFDI) on technological innovation (lnY) was significant and positive, indicating a clear association between foreign capital inflows and technological innovation. Column (3)

Table 7. Baseline regression results

Variables	lnY	lnY	lnY	lnY
	(1)	(2)	(3)	(4)
lnFDI	0.719*** (0.046)	0.118** (0.059)	0.128** (0.063)	-0.020 (0.051)
lnED	NO	1.115*** (0.133)	1.088*** (0.182)	0.567** (0.267)
lnPC	NO	0.438*** (0.052)	0.433*** (0.053)	0.156 (0.158)
Year FE	NO	NO	YES	NO
City FE	NO	NO	NO	NO
Observations	297	297	297	297
Adj-R^2	0.453	0.651	0.648	0.969

Notes: Standard errors are reported in parentheses. ***, **, and * indicate $p < 0.01$, $p < 0.05$, and $p < 0.1$, respectively. FE stands for fixed effects. The same applies to the following tables.

lists the results after year fixed effects were added. This column further shows that the coefficient of FDI stabilized at 0.128 and was significant at the 5% level, preliminarily verifying H1. Among the control variables, the economic development level and human capital also showed significant positive effects in line with our theoretical expectations.

However, in further analysis, city fixed effects tests (Wald = 693.54; Hausman = 30.2) confirmed the need to consider inter-city differences, and the effect of FDI became statistically insignificant after we controlled for both city and year fixed effects. These results were consistent with the findings of Lin and Kwan (2016), thereby demonstrating the existence of conditionality in the technology spillover effects of FDI. Thus, cities exhibited varying efficiency in utilizing FDI technology spillovers due to differences in absorptive capacity. We subsequently examined the moderating role of financial development level as a key factor of absorptive capacity.

5.2. Moderating effect test

As the moderating effect test results in Column (2) of Table 8 show, the interaction term of FDI and financial development (lnFDI x FIN) yielded a coefficient of 0.452 (significant at the 1% level) after we controlled for the financial development level. These results suggest that financial development is a crucial absorptive capacity moderator for the effects of FDI on technology innovation. Thus, higher financial development levels can significantly enhance the role of FDI in promoting technological innovation. Specifically, financial development can enhance local enterprises' ability to absorb and utilize FDI technology spillovers by providing better financial support, risk diversification mechanisms, and financial services. Therefore, financial development had a clear positive moderating effect on FDI-driven technological innovation in the YRD urban agglomeration. This finding verifies H2, thereby confirming that financial development is a key moderator in the relationship between FDI and technological innovation.

Table 8. Moderating effect test

Variables	(1)	(2)
	lnY	lnY
lnFDI	–0.020 (0.051)	–0.138** (0.064)
FIN		–0.275*** (0.069)
lnFDI x FIN		0.452*** (0.134)
Control variables	YES	YES
Year FE	YES	YES
City FE	YES	YES
Observations	297	297
Adj-R2	0.969	0.971

5.3. Analysis of static spatial spillover effects

Table 9 presents the regression estimates under four spatial weight matrices, including the SDM results for the adjacency matrix W1, inverse distance matrix W2, and inverse distance squared matrix W3, and the SAR results for the economic distance matrix W4. The consistently significant spatial autoregressive coefficients (ρ) of all the models confirm the significant spatial spillover effects of technological innovation in the YRD urban agglomeration, thereby supporting H3.

Further analysis revealed significant heterogeneity in the spillover effects across spatial dimensions. In the geographic adjacency dimensions (W1–W3), we consistently found negative spatial spillover coefficients, suggesting a siphoning effect. Thus, core cities such as Shanghai and Suzhou attract talent, capital, and other innovation factors from neighboring regions by virtue of their superior innovation environments and policy support, resulting in the loss of innovation factors in neighboring cities. In the economic linkage dimension (W4), the spatial spillover coefficient was 0.515 (significant at the 1% level), indicating a positive spillover effect among cities with similar economic development levels. This is mainly because cities with similar economic levels also have similar knowledge bases, matched technological absorption capacities, and pronounced industrial chain synergies, which fosters bidirectional knowledge and technology flows and synergistic improvements in innovation capacity.

Table 9. Regression results of spatial econometric models under different spatial weight matrices

Variables	W1 SDM	W2 SDM	W3	W4 SAR
	(1)	(2)	(3)	(4)
lnFDI	–0.102 (0.065)	–0.135** (0.057)	–0.147** (0.060)	–0.118** (0.059)
FIN	–0.210*** (0.069)	–0.260*** (0.070)	–0.293*** (0.065)	–0.234*** (0.069)
lnFDI x FIN	0.370*** (0.129)	0.365*** (0.127)	0.463*** (0.122)	0.467*** (0.123)
W lnFDI	0.146 (0.130)	0.562 (0.453)	0.029 (0.221)	
W FIN	0.119 (0.157)	–0.135 (0.755)	–0.433 (0.327)	
W lnFDI x FIN	–0.252 (0.239)	–2.102 (1.507)	–0.077 (0.655)	
Spatial rho	–0.187** (0.093)	–1.513*** (0.358)	–0.438** (0.173)	0.515*** (0.061)
Control variable	Control	Control	Control	Control
Individual-fixed effect	Yes	Yes	Yes	No
Time-fixed effect	Yes	Yes	Yes	No
N	297	297	297	297
Log-likelihood ratio	78.748	88.819	83.491	–21.553

5.4. Decomposition of direct and indirect effects

In this study, we used the partial differential method to systematically evaluate the effects of FDI and financial development on technological innovation. Specifically, we examined two effects: 1) the direct effect, measuring the effects of local FDI and financial development on regional innovation output, and 2) the indirect effect, measuring the spatial spillover effects of FDI and financial development from other regions on local innovation activities. The decomposition results in Table 10 show that under all spatial weight matrices, the interaction term of FDI and financial development exerted a significant positive direct effect on local technological innovation. These results align with those of the baseline model, confirming that the synergy between FDI and financial development can effectively increase local innovation. Notably, the indirect effects exhibited substantial variation under different spatial matrices, highlighting the clear spatial heterogeneity in the spatial spillover effects of FDI and financial development.

Under the framework of the economic distance matrix (W4), the interaction term of financial development and FDI showed a positive coefficient significant at the 1% level (0.687), verifying a significant positive spatial spillover effect across regions with similar economic development levels. Therefore, H4 was validated. The underlying mechanism is as follows: agglomeration of foreign-invested enterprises in core cities stimulates the demand for financial

Table 10. Decomposition of the spatial effects of FDI and financial development on technological innovation

Variables	W1	W2	W3	W4
	(1)	(2)	(3)	(4)
Direct effect				
lnFDI	–0.108 (0.066)	–0.167*** (0.061)	–0.150** (0.063)	–0.126** (0.063)
FIN	–0.222*** (0.060)	–0.277*** (0.061)	–0.289*** (0.058)	–0.257*** (0.066)
lnFDI x FIN	0.396*** (0.119)	0.488*** (0.119)	0.486*** (0.118)	0.514*** (0.121)
Indirect effect				
lnFDI	0.149 (0.107)	0.354* (0.197)	0.075 (0.155)	–0.118* (0.063)
FIN	0.145 (0.137)	0.116 (0.318)	–0.224 (0.247)	–0.245*** (0.086)
lnFDI x FIN	–0.312 (0.215)	–1.245* (0.684)	–0.254 (0.495)	0.488*** (0.159)
Aggregate effect				
lnFDI	0.042 (0.107)	0.188 (0.183)	–0.075 (0.144)	–0.244** (0.123)
FIN	–0.077 (0.152)	–0.161 (0.314)	–0.513** (0.249)	–0.502*** (0.143)
lnFDI x FIN	0.084 (0.240)	–0.757 (0.666)	0.232 (0.476)	1.001*** (0.261)

services, promoting the development of regional financial systems, and well-established financial services then provide financial guarantees for technology absorption, creating a virtuous cycle of "FDI introduction – financial development – technology absorption," which ultimately strengthens cross-regional innovation synergies.

However, the analysis of geographic adjacency matrices (W1–W3) reveals insignificant or even negative indirect effects, demonstrating a distinct siphoning phenomenon. This phenomenon stems from two factors: 1) excessive concentration of foreign investment and financial resources in core cities such as Shanghai and Nanjing, and 2) underdeveloped financial systems in neighboring regions, failing to satisfy the financial needs of multinational enterprises or support the technological innovation of local enterprises. Such resource misallocation leads to unidirectional flow of innovation factors from neighboring regions to core cities, which in turn inhibits the innovative development of neighboring regions and highlights the importance of coordinated regional development.

5.5. Robustness and endogenous tests

5.5.1. Endogenous treatment

(1) Instrumental variable approach

To address potential bi-directional causality between FDI, financial development, and technological innovation, we adopted one-period lagged variables as instrumental variables for analysis. Table 11 showed that the instrumental variables demonstrated strong validity (F-statistic = 36.88). Furthermore, the spillover effect of technological innovation showed regional

Table 11. Endogeneity treatment I: instrumental variable approach

Variables	(1)	(2)	(3)	(4)
	W1	W2	W3	W4
W. lnY	–0.212** (0.095)	–1.752*** (0.365)	–0.565*** (0.176)	0.535*** (0.059)
L.lnFDI	–0.062 (0.063)	–0.115** (0.052)	–0.119** (0.056)	–0.049 (0.055)
L. FIN	–0.189** (0.075)	–0.260*** (0.074)	–0.299*** (0.068)	–0.213*** (0.071)
L.lnFDI x FIN	0.195 (0.136)	0.219* (0.131)	0.327*** (0.125)	0.294** (0.128)
W L.lnFDI	0.101 (0.126)	0.346 (0.395)	–0.039 (0.203)	
W L. FIN	0.117 (0.174)	–0.374 (0.758)	–0.632* (0.334)	
W L. lnFDI x FIN	–0.292 (0.274)	–1.902 (1.494)	0.174 (0.669)	
Phase I F-statistic [P]	36.88 (0.000)			
Control variable	Control	Control	Control	Control
Individual-fixed effect	Yes	Yes	Yes	No
Time-fixed effect	Yes	Yes	Yes	No
N	297	297	297	297

differences, indicating a siphoning effect among geographically adjacent cities but a positive promoting effect among cities at similar economic levels. Finally, financial development can effectively enhance the role of FDI in promoting local technological innovation; however, the spillover effect on neighboring regions will remain limited. These results corroborate our findings above from the static spatial spillover analysis.

(2) Analysis of dynamic spatial spillover effects by Han-Phillips GMM

We leveraged dynamic spatial econometric modeling and Han and Phillip's (2010) Generalized Method of Moments (GMM) estimation to effectively address the endogeneity of technological innovation capacities affected by prior periods. This method is particularly suitable for small-sample analysis and can avoid estimation bias. Table 12 showed clear persistence characteristics in technological innovation, with the current innovation level significantly correlated with the prior period. Furthermore, FDI and financial development exerted stable and positive effects on local technological innovation, whereas their spillover effects on the neighboring regions were not apparent. These findings are consistent with our conclusions from the static spatial model, verifying the robustness of the results.

Table 12. Endogeneity treatment II: dynamic spatial econometric model (Han-Phillips GMM)

Variables	(1)	(2)	(3)	(4)
	W1	W2	W3	W4
L.lnY	0.560*** (0.11)	0.578*** (0.13)	0.542*** (0.13)	1.148*** (0.16)
lnFDI	–0.139 (0.09)	–0.087 (0.08)	–0.116 (0.08)	–0.016 (0.06)
FIN	–0.342*** (0.09)	–0.347*** (0.09)	–0.344*** (0.09)	–0.219*** (0.08)
lnFDI x FIN	0.544*** (0.19)	0.468** (0.18)	0.497*** (0.18)	0.169 (0.15)
wlnFDI	–0.243 (0.16)	–1.143*** (0.34)	–0.694*** (0.23)	
wFIN	–0.107 (0.21)	–1.241 (0.80)	–0.538 (0.42)	
w lnFDI x FIN	0.296 (0.31)	2.267* (1.37)	1.074 (0.72)	
W. lnY				0.806*** (0.06)
Control variable	Control	Control	Control	Control
Individual-fixed effect	Yes	Yes	Yes	No
Time-fixed effect	Yes	Yes	Yes	No
N	270	270	270	270
R^2	0.510	0.515	0.534	0.495

5.5.2. Replacement of geo-economic nested weight matrices

Geo-economic nested weight matrices W5 (W5 = 0.5 * W2 + 0.5 * W4) and W6 (W6 = W2 * W4) were used to perform spatial econometric regression. As the results in Table 13 shows, the spatial Durbin random effect model should be used for estimation when geo-economic nested weight matrices are adopted. The regression results show that the value, positive/negative sign, and significance level of the coefficients of the variables were generally consistent with the findings under the economic inverse distance matrix. Although the weight matrix was changed, the spatial spillover relationships of FDI, financial development, and technological innovation under the overall sample remained consistent, confirming the robustness of the estimation results.

Table 13. SDM regression results for geo-economic nested weight matrices

Variables	(1)			(2)		
	Geo-economic nested matrices (summation) W5			Geo-economic nested matrix (multiplication) W6		
	Direct effect	Indirect effect	Aggregate effect	Direct effect	Indirect effect	Aggregate effect
lnFDI	–0.178*** (0.06)	0.284 (0.44)	0.106 (0.43)	–0.171*** (0.07)	0.090 (0.23)	–0.081 (0.22)
FIN	–0.278*** (0.07)	0.380 (0.78)	0.102 (0.81)	–0.265*** (0.07)	0.237 (0.37)	–0.028 (0.39)
LnFDI x FIN	0.490*** (0.13)	–1.563 (1.57)	–1.073 (1.61)	0.484*** (0.13)	–0.510 (0.73)	–0.026 (0.76)
Rho	0.505*** (0.08)			0.412*** (0.06)		
Control variable	Control			Control		
fixed effect	No			No		
N	297			297		
R^2	0.780			0.835		
Number of cities	27			27		

5.5.3. Two-sided winsorization at 1%

To avoid bias in the results caused by outliers, we performed 1% two-sided winsorization on the variables and then re-regressed them. Table 14 shows that the value, positive/negative sign, and significance level of the core explanatory variables FDI and FIN, as well as the coefficient of their interaction effect, remained unchanged. Thus, the regression results are robust.

Table 14. Results of robustness test for two-sided winsorization of variables at 1%

Variables	W1 SDM	W2 SDM	W3 SDM	W4 SAR
	(1)	(2)	(3)	(4)
lnFDI	–0.061 (0.07)	–0.103* (0.06)	–0.112* (0.06)	–0.080 (0.06)
FIN	–0.202*** (0.07)	–0.243*** (0.07)	–0.273*** (0.07)	–0.197*** (0.07)

End of Table 14

Variables	W1 SDM	W2 SDM	W3 SDM	W4 SAR
	(1)	(2)	(3)	(4)
lnFDI x FIN	0.313** (0.13)	0.295** (0.13)	0.384*** (0.12)	0.392*** (0.12)
WlnFDI	0.059 (0.14)	0.317 (0.47)	–0.112 (0.23)	
WFIN	0.065 (0.16)	–0.402 (0.78)	–0.606* (0.34)	
W lnFDI x FIN	–0.098 (0.24)	–1.552 (1.55)	0.288 (0.66)	
Spatial rho	–0.198** (0.09)	–1.575*** (0.36)	–0.458*** (0.17)	0.537*** (0.06)
Control variable	Control	Control	Control	Control
Individual-fixed effect	Yes	Yes	Yes	No
Time-fixed effect	Yes	Yes	Yes	No
N	297	297	297	297

5.6. Heterogeneity analysis

5.6.1. Heterogeneity in the YRD urban agglomeration

We conducted separate empirical analyses for Anhui, Jiangsu, and Zhejiang Provinces in the YRD urban agglomeration, focusing on the synergistic effects of FDI and financial development on technological innovation. The regression results in Table 15 reveal distinct spatial spillover characteristics across the three provinces. Specifically, regarding geographic adjacency, technological innovation exhibited a significant negative spillover effect (all coefficients were negative), indicating a competitive relationship between geographically adjacent regions in terms of innovation factors. However, regarding economic similarity, a significant positive spillover effect emerged (all coefficients were positive), suggesting that regions with similar economic development levels tend to engage in collaborative innovation. These findings align with those of the YRD study overall.

Regarding direct effects, a gradient difference was observed in the synergistic effects of FDI and financial development among the three provinces. Specifically, Anhui Province experienced the most pronounced promoting effect (1.795 for the geographic distance matrix and 2.189 for the economic distance matrix), followed by Jiangsu Province (1.469 for geographic distance matrix and 1.859 for economic distance matrix). Zhejiang Province showed the weakest effect (only 0.530 under the economic distance matrix, which was significant). This regional disparity primarily stems from the distinct economic development characteristics of the three provinces. Anhui, as a late-developing province, attracts foreign investment through policy guidance to rapidly bridge its technological gaps. Jiangsu, as an economically developed province, focuses on the optimization and upgrading of its technological system. Finally, Zhejiang, dominated by the private economy, mainly relies on the endogenous innovation drive, thus exhibiting lower dependency on foreign investment.

Regarding spatial spillover effects, the interaction terms were insignificant for all geographically adjacent regions, indicating a siphoning effect, whereas economically similar regions showed significant positive spillovers (Anhui: 1.202, Jiangsu: 1.122, and Zhejiang: 0.292). This difference is because geographically adjacent regions face constraints from resource competition and uneven technological absorptive capacity, whereas economically similar regions benefit from industrial synergy and the construction of innovation networks. Notably, Anhui leverages its latecomer advantage while Jiangsu relies on its economic radiation capacity, with both contributing to stronger spillover effects. In contrast, Zhejiang's private economy results in relatively weaker spillover effects. These findings can provide an important basis for formulating regionally differentiated innovation policies.

Table 15. Heterogeneity within the YRD urban agglomeration

Variables	Geographic inverse distance matrix SDM-FE				Economic inverse distance matrix SAR-RE			
	YRD	Anhui	Jiangsu	Zhejiang	YRD	Anhui	Jiangsu	Zhejiang
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Spatial rho	–1.513*** (0.358)	–0.973*** (0.354)	–0.860** (0.344)	–2.553*** (0.223)	0.515*** (0.061)	0.375*** (0.101)	0.398*** (0.095)	0.356*** (0.115)
Direct effect								
lnFDI x FIN	0.488*** (0.119)	1.795** (0.699)	1.469*** (0.552)	0.133 (0.169)	0.514*** (0.121)	2.189*** (0.692)	1.859*** (0.674)	0.530*** (0.144)
Indirect effect								
lnFDI x FIN	–1.245* (0.684)	4.848 (3.118)	–3.105 (2.329)	–0.028 (0.288)	0.488*** (0.159)	1.202* (0.618)	1.122* (0.625)	0.292* (0.171)
Total effect								
lnFDI x FIN	–0.757 (0.666)	6.643* (3.447)	–1.636 (2.470)	0.105 (0.201)	1.001*** (0.261)	3.391*** (1.195)	2.981** (1.217)	0.822*** (0.275)
Control variable	Control	Control	Control	Control	Control	Control	Control	Control
N	297	88	99	99	297	88	99	99
Individual fixed	Yes	Yes	Yes	Yes	No	No	No	No
Time fixed	Yes	Yes	Yes	Yes	No	No	No	No

5.6.2. Heterogeneity in the level of urban economic development

Drawing on the approach of Xu et al. (2024), we classified the research sample into two groups, developed and less-developed cities, based on GDP per capita for comparative analysis. The regression results in Table 16 are discussed below.

(1) Geographic inverse distance matrix

First, spatial competition effects were universally observed. The empirical results indicate that less-developed and developed cities exhibited significant negative spatial dependence in technological innovation (coefficients: –0.892 and –0.860, respectively; $p < 0.01$). This suggests intense competition for innovation resources among neighboring cities, and no regional innovation synergy mechanism has been effectively formed.

Second, the synergy between FDI and financial development showed gradient differences in direct effects. Although both regions showed significant positive effects (lnFDI x FIN = 1.215 for less-developed cities; lnFDI x FIN = 0.343 for developed cities), the direct promoting effect was more pronounced in less-developed regions. This was mainly because of the lower initial innovation levels in less-developed cities, where the marginal boosting effect was more significant.

Third, the synergy between FDI and financial development showed significant differentiation in indirect effects. Less-developed regions exhibited positive spatial spillovers (lnFDI x FIN= 6.117), conforming to the pattern of technology gradient diffusion. However, developed regions demonstrated negative spillovers (lnFDI x FIN = –2.349), attracting innovation factors from neighboring regions to central regions and creating a siphoning effect.

(2) Economic inverse distance matrix

All cities demonstrated significant positive spatial correlations in technological innovation, with relatively similar effect intensities (coefficients: 0.291 and 0.288, respectively; $p < 0.01$). This suggests that cities with similar economic development levels are more likely to form an innovation community, this facilitating the optimal allocation of innovation resources.

Table 16. Heterogeneity in urban economic development levels

Variables	Geographic inverse distance matrix SDM-FE		Economic inverse distance matrix SAR-RE	
	Less-developed city	Developed city	Less-developed city	Developed city
	(1)	(2)	(3)	(4)
Spatial rho	–0.892*** (0.327)	–0.860*** (0.319)	0.291*** (0.080)	0.288*** (0.087)
Direct effect				
lnFDI x FIN	1.215*** (0.424)	0.343** (0.145)	0.811* (0.433)	0.698*** (0.132)
Indirect effect				
lnFDI x FIN	6.117*** (2.361)	–2.349*** (0.905)	0.315 (0.215)	0.271** (0.118)
Total effect				
lnFDI x FIN	7.332*** (2.564)	–2.006** (0.971)	1.125* (0.624)	0.969*** (0.210)
Control variable	Control	Control	Control	Control
N	143	154	143	154
Individual fixed	Yes	Yes	NO	NO
Time fixed	Yes	Yes	NO	NO

In contrast, although the synergy between FDI and financial development exhibited insignificant differences in its promoting effect on local technological innovation between regions with high and low economic development levels (less-developed cities: lnFDI x FIN = 0.811; developed cities: lnFDI x FIN = 0.698), the cross-regional spillover effects showed clear regional disparity (insignificant in less-developed cities and significant in developed cities). In economically developed cities, the synergistic effects of FDI and financial development can effectively promote technology spillovers among regions with similar development levels. However, less-developed cities experience relatively limited cross-regional spillovers. This difference may be attributable to the superior maturity of innovation networks, technology absorptive capacity, and financial system development in developed cities.

5.6.3. Heterogeneity among China's four major urban agglomerations

China's four prioritized national-level urban agglomerations, including the YRD (27 cities), BTH (13 cities), PRD (9 cities), and CC (16 cities), were comparatively analyzed to validate the generalizability of the spatial spillover effects of technological innovation and synergistic effects of FDI and financial development. As shown in Table 17, under the geographic inverse distance matrix, the spatial autoregressive coefficients of the four urban agglomerations were significantly negative, indicating that technological innovation had an inhibitory effect on the neighboring regions. However, under the economic inverse distance matrix, all urban agglomerations demonstrated a significant positive spillover effect among regions with similar economic levels, confirming the generalizability of the spatial spillover effects of technological innovation.

Regarding direct effects, the synergistic effects of FDI and financial development showed distinct regional differences. Under the geographic adjacency dimension, the YRD (0.488***) and PRD (0.455***) urban agglomerations exhibited significant promoting effects, whereas the BTH (–0.678***) and CC (–0.931***) urban agglomerations showed inhibitory effects. Similar results were observed in the economic similarity dimension. This suggests that the urban agglomerations in Eastern China could effectively transform technology spillovers by virtue of their high-quality financial systems and FDI, whereas the urban agglomerations in northern and western China remained constrained by insufficient financial efficiency and poor foreign investment structure, hindering the synergistic effects.

The analysis of indirect effects demonstrated negative spillovers across the four major urban agglomerations under the geographic matrix (YRD: –1.245*). However, a significant differentiation emerged under the economic matrix: positive effects for YRD (0.488***) and PRD (1.099**), negative for BTH (–1.892***), and insignificant for CC. These findings indicate that the direction and intensity of technological spillovers are influenced not only by geographic distance but more crucially by the cross-regional similarity of economic development levels, revealing significant spatial heterogeneity in the diffusion of technological innovation across China's urban agglomerations.

Although technological innovation spillovers exhibit common patterns, the synergic effect of FDI and financial development demonstrates significant regional heterogeneity. Specifically, the YRD and PRD urban agglomerations share similar patterns, whereas the BTH and CC urban agglomerations display significant differences.

Table 17. Heterogeneity among China's four major urban agglomerations

Variables	Geographic inverse distance matrix SDM-FE				Economic inverse distance matrix SAR-RE			
	YRD	BTH	PRD	CC	YRD	BTH	PRD	CC
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Spatial rho	–1.513*** (0.358)	–2.098*** (0.262)	–1.392*** (0.329)	–1.276*** (0.316)	0.515*** (0.061)	0.742*** (0.038)	0.693*** (0.060)	0.618*** (0.064)
Direct effect								
lnFDI x FIN	0.488*** (0.119)	–0.678*** (0.097)	0.455*** (0.123)	–0.913*** (0.214)	0.514*** (0.121)	–0.800*** (0.153)	0.583*** (0.157)	–0.463* (0.265)
Indirect effect								
lnFDI x FIN	–1.245* (0.684)	–0.124 (0.260)	–1.273** (0.517)	–1.397* (0.829)	0.488*** (0.159)	–1.892*** (0.531)	1.099** (0.497)	–0.703 (0.469)
Total effect								
lnFDI x FIN	–0.757 (0.666)	–0.802*** (0.243)	–0.818 (0.598)	–2.310*** (0.878)	1.001*** (0.261)	–2.691*** (0.659)	1.683*** (0.634)	–1.166 (0.712)
Control variable	Control	Control	Control	Control	Control	Control	Control	Control
N	297	143	99	176	297	143	99	176
Individual fixed	Yes	Yes	Yes	Yes	No	No	No	No
Time fixed	Yes	Yes	Yes	Yes	No	No	No	No

6. Conclusions

6.1. Main findings

Based on 2012–2022 panel data from the YRD urban agglomeration, this study constructed an econometric model incorporating financial development factors and systematically examined the impact mechanism and heterogeneous characteristics of the synergistic effects of FDI and financial development on technological innovation from the perspective of spatial spillovers. The main findings are discussed below.

First, the baseline regression results confirm the significant positive role of FDI in promoting technological innovation. The subsequent moderating effect test found that financial development positively moderates the relationship between FDI and technological innovation and can effectively enhance the positive effect of FDI on technological innovation, indicating that financial development is an important absorption variable of FDI to promote technological innovation.

Second, regarding spatial effects, the static spatial analysis yielded two key findings. The YRD urban agglomeration demonstrates a significant spatial spillover effect in technological innovation; however, its manifestation varies with the choice of spatial weight matrix. Specifically, geographically adjacent regions exhibit negative spatial spillovers and a siphoning effect, whereas regions with similar economic levels show positive spillovers. Furthermore, the synergistic effects of FDI and financial development have a significant direct effect on local technological innovation; however, its spatial indirect effect varies. Thus, this synergistic effect produces a positive spillover effect on technological innovation in neighboring regions under the economic distance matrix, whereas the spillover effect is insignificant or even negative under the geographic adjacency matrix.

Third, the heterogeneity analysis revealed three characteristics. Within the YRD urban agglomeration, the synergy between FDI and financial development consistently demonstrated direct promoting effects on technological innovation, with the effect decreasing in intensity from Anhui to Jiangsu and then to Zhejiang. Regarding indirect effects, positive spillovers in regions with comparable economic levels were more prominent in Anhui and Jiangsu. In addition, the differences in economic development levels led to spatial spillover differentiation. Thus, less-developed cities will exhibit more significant direct and indirect effects under the dimension of geographic adjacency, whereas developed cities display stronger technology spillovers under the dimension of economic geography. Finally, the comparative analysis among the four major urban agglomerations indicated that although the spatial spillovers of technological innovation shared common patterns, the synergistic effects of FDI and financial development exhibited regional differences. In particular, the YRD and the PRD urban agglomerations demonstrated similar patterns, whereas the BTH and CC urban agglomerations showed negative effects under both spatial matrices.

6.2. Theoretical contributions

This study systematically examining the synergistic mechanism between FDI and financial development in promoting technological innovation makes three main theoretical contributions. First, regarding the theoretical mechanism, financial development was verified as a key absorptive variable that can significantly enhance the promoting effect of FDI on technological innovation, thereby extending the theoretical research framework of FDI's technological spillover effect. Second, in terms of spatial effects, spatial heterogeneity was observed in the spillover effect of technological innovation, and the spillover patterns varied between geographic adjacency and economic linkage dimensions, thereby providing a new perspective for understanding regional innovation synergy. Third, with respect to policy implications, the analysis of regional heterogeneity yielded empirical evidence for the formulation of regionally differentiated innovation policies, offering guidance for less-developed regions to better utilize the synergistic effects of FDI and financial development.

6.3. Policy implications

Based on the empirical analysis of the YRD urban agglomeration, this study reveals the mechanism by which FDI, and financial development synergistically influence technological innovation. The main findings are as follows. First, the promoting effect of FDI on technological innovation exhibits a "financial threshold." Regional financial development level is a key factor influencing FDI technology spillovers, and a well-developed financial system can significantly improve the innovation-enhancing effect of FDI. Second, spatial spillovers demonstrate a "dual-track differentiation" pattern. Geographically adjacent regions experience a technological siphoning effect, whereas economically comparable regions exhibit positive spillovers. The synergy between FDI and financial development shows positive spillovers in economically connected regions but remains insignificant in geographically adjacent regions. Finally, regional differences are significant. Less-developed regions, such as Anhui Province, are more capable of absorbing FDI technology spillovers. Less-developed cities rely more on geographic adjacency effects compared to developed cities, which benefit more from technology diffusion through economic linkages. The synergistic effects in the YRD and PRD urban agglomerations are significantly stronger than those in the BJH and CC regions. The empirical findings provide a robust theoretical foundation and practical guidance for formulating regionally differentiated innovation policies. This can help in fully utilizing the synergistic innovation effects of FDI and financial development, thereby promoting the high-quality and coordinated development of regional technological innovation. Specific policy recommendations are provided below.

First, the financial support system should be improved to enhance FDI's technological spillover effect. Strengthening targeted credit support for high-tech industries and innovative enterprises should be prioritized. For local enterprises with the potential to absorb FDI-driven technologies, a multi-tiered financing support system, including dedicated science and technology loans and venture capital funds, should be established.

Second, spatial planning should be optimized to mitigate the siphoning effect. An innovation alliance should be formed among economically linked regions to facilitate collaboration among cities with similar economic levels (e.g., Nanjing, Hangzhou, and Hefei) within the YRD region. This will allow financial and FDI resources to be shared and enhance positive spillover effects. Additionally, industrial specialization and collaboration should be promoted in the region to guide each city's differentiated development. For example, Shanghai should focus on finance and R&D development, while Suzhou and Wuxi should focus on high-end manufacturing. Accordingly, resource scramble caused by homogeneous competition can be avoided.

Third, targeted regional innovation policies should be implemented. In the YRD region, Anhui Province should leverage its comparative advantage in FDI absorption and improve its policy support system by incorporating tax incentives and innovation subsidies. Jiangsu Province should rely on its manufacturing foundation to facilitate deep integration between FDI and local industrial chains and innovate financial services for the supply chain. Zhejiang Province should utilize its advantages in the digital economy to direct FDI toward digital technology and improve the intellectual property-based financial product system. In the BTH and CC urban agglomerations, where the synergistic effects of FDI and financial development remain weak, efforts should be made to optimize the financial ecosystem, eliminate market fragmentation, strengthen cross-regional financial cooperation, and effectively avoid negative spillovers.

Fourth, cross-regional coordinated development should be advanced. To facilitate the exchange of experience between the YRD and PRD, these two major urban agglomerations can learn from the Shenzhen-Hong Kong financial cooperation model to promote financial liberalization and innovation in cities such as Shanghai and Suzhou. Support for structural FDI optimization in the BTH and CC regions is also recommended to guide the transformation and upgrading of foreign investment from traditional manufacturing industries to high-technology industries. Furthermore, the regional financial infrastructure should be enhanced to mitigate negative spillovers effectively. For example, Chengdu and Chongqing can jointly develop a western financial center in China.

6.4. Limitations and future research

Three directions for future research can be derived from this study. First, thoroughly explore the relationship between high-quality FDI, financial system development, and technological innovation to broaden the scope of the existing research. Second, systematically examine the differentiated effects of financial development on FDI technology spillovers from the perspectives of financial scale, market structure, and operational efficiency. Third, explore the threshold effect of financial development level in moderating the relationship between FDI and technological innovation and identify the key threshold at which it promotes innovation.

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References

Aitken, B. J., & Harrison, A. E. (1999). Do domestic firms benefit from direct foreign investment? Evidence from Venezuela. *American Economic Review*, *89*(3), 605–618. https://doi.org/10.1257/aer.89.3.605

Alfaro, L., Chanda, A., Kalemli-Ozcan, S., & Sayek, S. (2004). FDI and economic growth: The role of local financial markets. *Journal of International Economics*, *64*(1), 89–112. https://doi.org/10.1016/S0022-1996(03)00081-3

Ali, N., Phoungthong, K., Khan, A., Abbas, S., Dilanchiev, A., Tariq, S., & Sadiq, M. N. (2023). Does FDI foster technological innovations? Empirical evidence from BRICS economies. *PLoS ONE*, *18*(3), Article e0282498. https://doi.org/10.1371/journal.pone.0282498

Asamoah, M. E., & Alagidede, I. P. (2023). Foreign direct investment, real sector growth and financial development. *International Journal of Finance & Economics*, *28*(1), 626–643. https://doi.org/10.1002/ijfe.2440

Balland, P.-A., Boschma, R., Crespo, J., & Rigby, D. L. (2019). Smart specialization policy in the European Union: Relatedness, knowledge complexity and regional diversification. *Regional Studies*, *53*(9), 1252–1268. https://doi.org/10.1080/00343404.2018.1437900

Blalock, G., & Gertler, P. J. (2008). Welfare gains from Foreign Direct Investment through technology transfer to local suppliers. *Journal of International Economics*, *74*(2), 402–421. https://doi.org/10.1016/j.jinteco.2007.05.011

Brenner, T., & Broekel, T. (2011). Methodological issues in measuring innovation performance of spatial units. *Industry and Innovation*, *18*(1), 7–37. https://doi.org/10.1080/13662716.2010.528927

Capello, R., & Lenzi, C. (2013). Territorial patterns of innovation and economic growth in European regions. *Growth and Change*, *44*(2), 195–227. https://doi.org/10.1111/grow.12009

Cheung, K.-Y., & Lin, P. (2004). Spillover effects of FDI on innovation in China: Evidence from the provincial data. *China Economic Review*, *15*(1), 25–44. https://doi.org/10.1016/S1043-951X(03)00027-0

Cohen, W. M., & Levinthal, D. A. (1989). Innovation and learning: The two faces of R & D. *The Economic Journal*, *99*(397), 569–596. https://doi.org/10.2307/2233763

Crescenzi, R., Rodriguez-Pose, A., & Storper, M. (2007). The territorial dynamics of innovation: A Europe-United States comparative analysis. *Journal of Economic Geography*, *7*(6), 673–709. https://doi.org/10.1093/jeg/lbm030

Deng, X., Li, J., Huang, Y., & Wang, L. (2023). How is paradoxical leadership linked to exploratory innovation?: The mediating role of knowledge sharing and the moderating role of environmental dynamism. *Journal of Organizational and End User Computing*, *35*(1), 1–14. https://doi.org/10.4018/JOEUC.326766

Duan, Y., Huang, L., Cheng, H., Yang, L., & Ren, T. (2021). The moderating effect of cultural distance on the cross-border knowledge management and innovation quality of multinational corporations. *Journal of Knowledge Management*, *25*(1), 85–116. https://doi.org/10.1108/JKM-11-2019-0656

Dunning, J. H. (1977). Trade, location of economic activity and the MNE: A search for an eclectic approach. In B. Ohlin, P. O. Hesselborn, & P. M Wijkman (Eds.), *The international allocation of economic activity* (pp. 395–418). Palgrave. https://doi.org/10.1007/978-1-349-03196-2_38

Erdal, L., & Göçer, İ. (2015). The effects of foreign direct investment on R&D and innovations: Panel data analysis for developing Asian countries. *Procedia*, *Social and Behavioral Sciences*, *195*, 749–758. https://doi.org/10.1016/j.sbspro.2015.06.469

Feng, Y., Wang, X., Du, W., Wu, H., & Wang, J. (2019). Effects of environmental regulation and FDI on urban innovation in China: A spatial Durbin econometric analysis. *Journal of Cleaner Production*, *235*, 210–224. https://doi.org/10.1016/j.jclepro.2019.06.184

Fosfuri, A., Motta, M., & Rønde, T. (2001). Foreign direct investment and spillovers through workers' mobility. *Journal of International Economics*, *53*(1), 205–222. *Journal of International Economics*, *53*(1), 205–222. https://doi.org/10.1016/S0022-1996(00)00069-6

Fu, X. (2008). Foreign direct investment, absorptive capacity and regional innovation capabilities: Evidence from China. *Oxford Development Studies*, *36*(1), 89–110. *Oxford Development Studies*, *36*(1), 89–110. https://doi.org/10.1080/13600810701848193

Fu, X., & Gong, Y. (2011). Indigenous and foreign innovation efforts and drivers of technological upgrading: Evidence from China. *World Development*, *39*(7), 1213–1225. https://doi.org/10.1016/j.worlddev.2010.05.010

García, F., Jin, B., & Salomon, R. (2013). Does inward foreign direct investment improve the innovative performance of local firms? *Research Policy*, *42*(1), 231–244. https://doi.org/10.1016/j.respol.2012.06.005

Girma, S., Gong, Y., & Görg, H. (2008). Foreign direct investment, access to finance, and innovation activity in Chinese enterprises. *The World Bank Economic Review*, *22*(2), 367–382. https://doi.org/10.1093/wber/lhn009

Han, C., & Phillips, P. C. B. (2010). GMM estimation for dynamic panels with fixed effects and strong instruments at unity. *Econometric Theory*, *26*(1), 119–151. https://doi.org/10.1017/s026646660909063x

Huang, L., Liu, X., & Xu, L. (2012). Regional innovation and spillover effects of foreign direct investment in China: A threshold approach. *Regional Studies*, *46*(5), 583–596. https://doi.org/10.1080/00343404.2010.520694

Konings, J. (2001). The effects of foreign direct investment on domestic firms: Evidence from firm-level panel data in emerging economies. *Economics of Transition and Institutional Change*, *9*(3), 619–633. https://doi.org/10.1111/1468-0351.00091

Levine, R. (2002). Bank-based or market-based financial systems: Which is better? *Journal of Financial Intermediation*, *11*(4), 398–428. https://doi.org/10.1006/jfin.2002.0341

Lin, M., & Kwan, Y. K. (2016). FDI technology spillovers, geography, and spatial diffusion. *International Review of Economics & Finance*, *43*, 257–274. https://doi.org/10.1016/j.iref.2016.02.014

Liu, X., & Buck, T. (2007). Innovation performance and channels for international technology spillovers: Evidence from Chinese high-tech industries. *Research Policy*, *36*(3), 355–366. https://doi.org/10.1016/j.respol.2006.12.003

Lucas, R. E. (1988). On the mechanics of economic development. *Journal of Monetary Economics*, *22*(1), 3–42. https://doi.org/10.1016/0304-3932(88)90168-7

Miguélez, E., & Moreno, R. (2015). Knowledge flows and the absorptive capacity of regions. *Research Policy*, *44*(4), 833–848. https://doi.org/10.1016/j.respol.2015.01.016

Osabuohien-Irabor, O., & Drapkin, I. M. (2024). The spillover effects of outward FDI on environmental sustainability in developing countries: Exploring the channels of home country institutions and human capital. *Environment*, *Development and Sustainability*, *26*(8), 20597–20627. https://doi.org/10.1007/s10668-023-03494-5

Ozsahin, S., & Uysal, D. (2017). Financial deepening and economic development in MENA countries: Empirical evidence from the advanced panel method. *international Journal of Economics and Finance*, *9*(4), 152–162. https://doi.org/10.5539/ijef.v9n4p152

Pan, W., Miao, L., & Lin, Z. (2023). Analysis of enterprise data-driven innovation diffusion supervision system based on the perspective of green supply chain. *Journal of Organizational and End User Computing*, *35*(1), 1–28. https://doi.org/10.4018/JOEUC.333894

Qin, X., Wang, X., & Kwan, M.-P. (2023). The contrasting effects of interregional networks and local agglomeration on R&D productivity in Chinese provinces: Insights from an empirical spatial Durbin model. *Technological Forecasting and Social Change*, *193*, Article 122608. https://doi.org/10.1016/j.techfore.2023.122608

Qing, L., Dagestani, A. A., Nam, E. Y., & Wang, C. (2024). Does firm-level exposure to climate change influence inward foreign direct investment? Revealing the moderating role of ESG performance. *Corporate Social Responsibility and Environmental Management*, *31*(6), 6167–6183. https://doi.org/10.1002/csr.2917

Romer, P. M. (1990). Endogenous technological change. *Journal of Political Economy*, *98*(5), S71–S102. https://doi.org/10.1086/261725

Schumpeter, J. A. (1912). *The theory of economic development* (1934 ed.). Harvard University Press.

Sugiharti, L., Yasin, M. Z., Purwono, R., Esquivias, M. A., & Pane, D. (2022). The FDI spillover effect on the efficiency and productivity of manufacturing firms: Its implication on open innovation. *Journal of Open Innovation Technology Market and Complexity*, *8*(2), Article 99. https://doi.org/10.3390/joitmc8020099

Sun, H., Pofoura, A. K., Adjei Mensah, I., Li, L., & Mohsin, M. (2020). The role of environmental entrepreneurship for sustainable development: Evidence from 35 countries in Sub-Saharan Africa. *The Science of the Total Environment*, *741*, Article 140132. https://doi.org/10.1016/j.scitotenv.2020.140132

Tang, M., Wang, X., Niu, W., Fu, J., & Zhu, M. (2023). How financial development scale and R&D influence regional innovation efficiency: Empirical evidence from the financial industry. *Environmental Science and Pollution Research International*, *30*(22), 61257–61270. https://doi.org/10.1007/s11356-021-16862-3

Wang, Z., Fu, H., Liu, H., & Liao, C. (2023). Urban development sustainability, industrial structure adjustment, and land use efficiency in China. *Sustainable Cities and Society*, *89*, Article 104338. https://doi.org/10.1016/j.scs.2022.104338

Xu, S., Zhong, M., & Wang, Y. (2024). Can innovative industrial clusters enhance urban economic resilience? A quasi-natural experiment based on an innovative pilot policy. *Energy Economics*, *134*, Article 107544. https://doi.org/10.1016/j.eneco.2024.107544

Yue, W. (2022). Foreign direct investment and the innovation performance of local enterprises. *Humanities and Social Sciences Communications*, *9*, Article 252. https://doi.org/10.1057/s41599-022-01274-6