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RESEARCH ARTICLE

Does digital finance promote the "quantity" and "quality" of green innovation? A dynamic spatial Durbin econometric analysis

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Abstract
Based on the panel data of 284 prefecture-level cities in China, this paper uses the dynamic spatial Durbin model to explore the impact of digital finance on green innovation from the dimensions of "quantity" and "quality." The results show that digital finance has a positive impact on both the quality and quantity of green innovation in local cities, but the development of digital finance in neighboring cities has a negative impact on the quantity and quality of green innovation in local cities, and the impact on the quality of green innovation is greater than that on the quantity of green innovation. And after a series of robustness tests, it was shown that the above conclusions are robust. In addition, digital finance can have a positive impact on green innovation mainly through industrial structure upgrading and informatization level. Heterogeneity analysis shows that the breadth of coverage and the degree of digitization are significantly related to green innovation, and digital finance has a more significant positive impact in eastern cities than in mid-western cities.

Keywords Digital finance · Dynamic spatial Durbin model · Green innovation · Spatial spillover effects

Introduction

At present, green innovation not only accelerates the progress of ecological civilization but also is an important path to high-quality development and has also become a new station for the global new scientific and technological revolution (Dong et al. 2018; Wu et al. 2020). How to promote green technology innovation is an important proposition in academia. Compared to traditional innovation, green innovation requires higher technical standards, higher financing costs, and higher risk bearing (Doran and Ryan 2012), so the threshold standard for achieving green innovation is very high, it is difficult to succeed by relying solely on innovative individuals, and more financial support from outside the main body is needed (Bai et al. 2019). However, traditional finance is limited by space and time constraints, making it difficult for enterprises to finance (Gomber et al. 2018). On the other hand, the information asymmetry of traditional finance is prominent, the contradiction between supply and demand is difficult to alleviate, and the degree of inclusiveness is low, so it is difficult for traditional finance to provide accurate and sufficient financial support (Bharath et al. 2020).

Digital technical means help promote the geographical coverage and depth of inclusive finance (Demertzis et al. 2018). As a new financial technology, it has high efficiency and wide coverage. Digital finance offers many opportunities to address the funding gap for corporate green innovation (Zulfiqar and Thapa 2018). It uses internet technology to break the barriers of time and space and reduce the threshold of accessing financial services. This, in turn, reduces the cost of financial services and improves efficiency (Corrado and Corrado 2017), thereby providing important support for green innovation. Meanwhile, digital finance alleviates the degree of information asymmetry, which can accurately match the flow of funds and capital needs, decrease the probability of resource mismatch (Norden et al. 2014), and reduce innovation costs. Digital finance can contribute to the low-carbon energy transition by strengthening financial regulation, bridging the digital access divide, and optimizing the availability of finance (Li

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et al. 2023). Digital finance can contribute to sustainable urban development by reducing carbon emissions through technological innovation and improving the energy mix (Sun et al. 2023). From a more micro perspective, digital finance can drive green growth by facilitating the digital transformation of businesses (Razzaq and Yang 2023). It is necessary to research the implications of digital finance for green innovation and the mechanism between the two, which is of great significance for realizing the comprehensive transformation of the economy and accelerating the construction of an innovative country (Reardon 2007).

At present, more literature only pays attention to the quantitative aspects (Wang et al. 2022c; Sun et al. 2022; Zhang and Ma 2021; He et al. 2021; Wang et al. 2023a) and fails to discuss from both the aspects of quantity and quality, and high-quality development is not only to improve the quantity but also to make a big leap in quality, so this paper also pays attention to the increase in quantity and the improvement of quality. There is a great difference between the categories of green patents and granted or not. Therefore, this paper distinguishes the quantity and quality according to the characteristics of green patents based on previous studies. According to the current literature, many studies focus only on the development of digital finance in local cities (Cao et al. 2021; Feng et al. 2022; Liu et al. 2022; Ma et al. 2022a, b; Liu and Chen 2022; Ren et al. 2023b); however, according to Tobler's First Law, anything correlates closely with other things, but the relationship between near and far is stronger than that of distant things (Tobler 2004; Ma et al. 2022a, b; Rao et al. 2022). The characteristics of open sharing of big data indicate that digital finance must have the characteristics of economic externality. Therefore, when one subject uses digital finance for economic activities, other subjects will also benefit or lose. This impact is also called the spillover effect. Digital finance in one region always affects green innovation activities in another region, so it is inappropriate to ignore spatial spillovers when assessing the effects of digital finance policies (Ying 2003; Wang et al. 2022; Wang et al. 2023b). Therefore, it is inevitable that there will be errors in isolated research on cities, but this paper fully considers the spatial correlation that exists between cities, uses spatial measurement methods to conduct more accurate research on the relationship between the two, and explores the local-neighborhood effect.

By summarizing the previous literature, digital finance can have an impact in terms of financing costs, productivity, and information advantages. This paper finds that the distinction between the quantity and quality in terms of the characteristics of green patent applications and grants needs further reflection. Most of the literature tends to ignore the spatial spillover effect when examining the impact of digital finance leading to errors in the assessment of its impact. Therefore, the main purpose is to further explore the impact of digital finance on green innovation from both quantitative and qualitative perspectives and to investigate whether spatial spillover effects exist between cities.

Therefore, we employ the dynamic spatial Durbin model (DSDM). The main marginal contributions are as follows: first, breaking through the limitations of existing research focusing on the quantitative dimension of green innovation. Unlike previous literature that uses a single indicator to measure green technology innovation per se, this paper makes a quantitative and qualitative distinction between green innovations. This paper puts digital finance endogenously in a green innovation research framework, which expands and deepens the literature in the field of green innovation influencing factors; second, different from previous studies that were limited to the local green innovation effect of digital finance, this paper innovatively starts from the "local-neighborhood" linkage perspective. For the sake of verifying the spatial spillover effect, this paper establishes a dynamic spatial Durbin model. Third, from the perspective of industrial structure, information level, and resource allocation, this paper deduces the internal logic of digital finance affecting green innovation and empirically tests the causal relationship and mechanism of action between the two, which provides policy focus for promoting the progress of digital finance.

The remaining chapters are organized as follows: the "Literature review" section has carried on the literature review, the introduction of the "Theoretical mechanism and hypothesis" section has carried on the theoretical mechanism and put forward theoretical hypotheses, the "Methodology and data" section describes empirical methods and data sources, the empirical results are discussed in the "Empirical results and discussions" and "Analysis of mediation effects" sections, and the "Conclusion and policy implications" section is conclusion and suggestions.

Literature review

Most of the current literature explores the factors affecting green innovation from the viewpoint of the development of financial technology, the effect of environmental regulation, government subsidies, and the development of financial and internet technologies. The improvement of financial service efficiency can reduce the cost (Chen and Peng 2021; Ding et al. 2021; Chen 2020; Lin and Ma 2022), thereby accelerating the speed of green innovation. The development of financial technology can effectively reduce financial friction (Cai 2022), promote the efficiency of information transmission (Sorin et al. 2021; Jia and Wang 2020), and then improve the efficiency of the transformation of green results (Söderlund and Tingvall 2016). In the "regulation" effect, the additional costs caused by environmental regulations will lead to an increase in the cost of enterprises (Dou et al. 2022; Qiao et al. 2022; Cheng and Li 2022), so enterprises have to seek energy-saving and emission-reduction measures (Zhang et al. 2022b; Li and Du 2022). Through the development of green technology research and development, green innovation can obtain an innovation compensation effect (Xie et al. 2021; Fan et al. 2021; Horbach 2008). As a key entity affecting green innovation, government R&D subsidies can bring non-operating income to enterprises (Yang et al. 2021; Fu et al. 2022; Sun et al. 2022; Ren et al. 2023c), thereby reducing the cost of enterprises' green innovation, and government R&D subsidies can have a "leverage effect" (Bai et al. 2019; Wang et al. 2022b). As an effective way to disseminate information and knowledge (Fang 2022; Guo et al. 2022), internet technology has improved the impact of R&D efficiency from three aspects: collection, communication, and absorption capacity (Viktor 2022; Abderahman et al. 2022). This confirms that the internet can improve a company's capacity for green innovation (Kafouros 2006; Chetna et al. 2022; Xu et al. 2022).

The positive effects are manifested in several ways. Insufficient corporate credit funds limit enterprises' R&D investment and reduce their willingness to innovate green (Li and Shen 2022; Zhang et al. 2022c), while digital finance can alleviate corporate financing constraints (Yi et al. 2019; Yu et al. 2022; Ozili 2017; Karaivanov 2011). Modern financial development has an impact on corporate innovation. We know that digital finance can encourage scientific and technological innovation from many studies (Helen et al. 2021; Kristin and Peter 2020; Wang 2018), and the digital economy is an important aid to regional green innovation and development (Demertzis et al. 2018; Zhao and He 2022). Digital finance mainly relies on big data, cloud computing, and other technological means (Alabbasi 2020; Zhao and He 2022). Financial products are rapidly derived, and the supply and demand of funds are accurately matched (Xia et al. 2022; Wu and Huang 2022; Jeanneney and Kpodar 2011), meet the needs of personalized financing, and become a powerful boost for enterprise green innovation (Kapoor 2014; Li 2021). Based on Huang et al. digital finance can obtain more financial and non-financial information (Huang and Li 2015; Oh and Kwon 2020), thereby alleviating the problem of information asymmetry and encouraging enterprises to elevate their ability (Ma et al. 2021; Liu and Chen 2022).

Related studies are mostly limited to the regional and enterprise level (Rao et al. 2022); however, many articles show that green innovation has an obvious spatial spillover effect and agglomeration effect (Yang and Liu 2020; Zhao and Li 2022; Lu et al. 2022). Economic geography is one of the most striking features of the real economy (Zahed and Hashem 2020), where digital financial activities have external spillover effects that affect other entities, organizations, or societies differently (Truffer and Coenen 2012; Zhu et al. 2022; Shen et al. 2021; Ren et al. 2023a). This has a variety of learning effects. Studies have shown that Fintech development can optimize the allocation of local resources (Gilles 1992), thereby improving the factor structure of the financial system in neighboring areas so that it can drive green innovation in surrounding areas (Tian et al. 2017). However, it may also have a siphon effect, hindering green innovation in neighboring areas (Su et al. 2021; Feng and Zhang 2022). As a kind of financial technology, digital finance has reduced the limitations of the geographical structure in promoting green innovation and development (Bernhard 2022), thus showing a strong geospatial spillover effect (Krugman 1991; Ewers 2018). This strong diffusion effect accelerates the imitation effect in local competition (Li 2022). Therefore, it is inappropriate to limit the effect to a region, and the mechanism of space spillover should be studied.

Through the combing of the literature, this paper finds that previous literature rarely takes the existence of spatial overflow into account, so the corresponding discussion and analysis are incomplete. We use the dynamic space Durbin model to probe the local-neighborhood effect. In terms of green innovation indicators, most of the literature only studies quantitative growth from a single perspective. However, this paper considers the prospect of quality development by incorporating quality of green innovation into the framework. The research perspective is more complete.

Theoretical mechanism and hypothesis

Theoretical mechanism

Endogenous economic growth theory is used to explore three intermediary variables (Wang et al. 2022a): industrial structure upgrading, information level, and optimal allocation of resources. We can obtain the following form of production: $Y(t) = F[K(t), A(t)L(t)]$ (Solow 1956).

We have also extended the production function by combining variables such as digital financial inclusion (*Lnindex*), industrial structure (*Indus*), economic development level (*Lngdp*), number of scientific and technological employees (*Lnsciemploy*), population density (*Lnpop*), and financial development level (*Findev*):

$$Y(t) = F[k(t), A(t)L(t), Lnindex(t), Indus(t), Lngdp(t), Lnsciemploy(t), Lnpop(t), Findev(t)] \tag{1}$$

Suppose Equation (1) is the Cobb–Douglas form with constant scale returns (Zhao et al. 2020). Combined with the theory in this paper, we set up the following equation:

$$Y(t) = K^{\sigma}(AL)^{\tau} Lnindex^{\nu} Indus^{\omega} lngdp^{\iota} Lnsciemploy^{\kappa} Lnpop^{\zeta} \mathrm{Findev}^{\eta} \tag{2}$$

where $\sigma + \tau + \upsilon + \omega + \iota + \kappa + \zeta, + \eta = 1, 0 < \sigma, \tau, \upsilon, \omega, \iota, \kappa, \zeta, \eta < 1$.

The capital depreciation rate is δ; then the change of capital can be represented as

$$\dot{K} = sY - \delta K\text{–}Lnindex \tag{3}$$

The growth rates of labor and knowledge remain unchanged, that is:

$$\dot{L} = nL, \dot{A} = gA \tag{4}$$

Among them, Y is the total output, K is the total capital input, and L is the labor input. $A \bullet L$ indicates an effective workforce, *Lnindex* represents digital finance, *Indus* represents industrial structure upgrading, *Lngdp* represents economic growth, *Lnsciemploy* represents the number of tech workers, *Lnpop* represents population density, and *Findev* represents the level of financial development.

Supposing that

$y = \frac{Y}{AL}, k = \frac{K}{AL}, lnindex = \frac{Lnindex}{AL}, indus = \frac{Indus}{AL}, lngdp = \frac{Lngdp}{AL}, lnsciemploy = \frac{Lnsciemploy}{AL}, lnpop = \frac{Lnpop}{AL}$, and $findev = \frac{Findev}{AL}$

then Equation (2) can be written as

$$y = k^{\sigma} lnindex^{\upsilon} indus^{\omega} lngdp^{\iota} lnsciemploy^{\kappa} lnpop^{\zeta} findev^{\eta} \tag{5}$$

Assume that $k = K/AL$, meaning

$$\dot{k} = \frac{\dot{K}\cdot AL - K(\dot{A}\cdot L + A\cdot \dot{L})}{(AL)^2} = \frac{\dot{K}}{AL} - k\left(\frac{\dot{A}}{A} + \frac{\dot{L}}{L}\right) = \frac{sY - \delta K - Lnindex}{AL} - k(g+n) = sy - (\delta + g + n)k - lnindex \tag{6}$$

Hence, Equation (6) can be indicated as follows:

$$\dot{k} = sk^{\sigma} lnindex^{\upsilon} indus^{\omega} lngdp^{\iota} lnsciemploy^{\kappa} lnpop^{\zeta} findev^{\eta} - (\delta + g + n)k\text{–}lnindex \tag{7}$$

Suppose $\dot{k} = 0$, so that

$$sk^{\sigma} lnindex^{\upsilon} indus^{\omega} lngdp^{\iota} lnsciemploy^{\kappa} lnpop^{\zeta} findev^{\eta} - (\delta + g + n)k\text{–}lnindex = 0 \tag{8}$$

Then further calculate and simplify

$$s\sigma k^{\sigma-1} lnindex^{\upsilon} indus^{\omega} lngdp^{\iota} lnsciemploy^{\kappa} lnpop^{\zeta} findev^{\eta} \frac{\partial k}{\partial lnindex} + s\upsilon k^{\sigma} lnindex^{\upsilon-1} indus^{\omega} lngdp^{\iota} lnsciemploy^{\kappa} lnpop^{\zeta} findev^{\eta} + s\omega k^{\sigma} lnindex^{\upsilon} indus^{\omega-1} lngdp^{\iota} lnsciemploy^{\kappa} lnpop^{\zeta} findev^{\eta} \frac{\partial indus}{\partial lnindex} - (\delta + g + n)\frac{\partial k}{\partial lnindex} - 1 = 0 \tag{9}$$

Equation (9) can be further rewritten and simplified as follows:

$$\frac{\partial indus}{\partial lnindex} = \frac{(\delta+g+n) - s\sigma k^{\sigma-1} lnindex^{\upsilon}\ indus^{\omega} lngdp^{\iota} lnsciemploy^{\kappa} lnpop^{\zeta} findev^{\eta}}{s\omega k^{\sigma} lnindex^{\upsilon} indus^{\omega-1} lngdp^{\iota}\ lnsciemploy^{\kappa} lnpop^{\zeta} findev^{\eta}} \frac{\partial k}{\partial lnindex} - \frac{s\upsilon k^{\sigma} lnindex^{\upsilon-1}\ indus^{\omega} lngdp^{\iota} lnsciemploy^{\kappa} lnpop^{\zeta} findev^{\eta} - 1}{s\omega k^{\sigma} lnindex^{\upsilon} indus^{\omega-1} lngdp^{\iota}\ lnsciemploy^{\kappa} lnpop^{\zeta} findev^{\eta}} \tag{10}$$

Supposing $f(k, lnindex, indus) = \frac{(\delta+g+n) - s\sigma k^{\sigma-1} lnindex^{\upsilon}\ indus^{\omega} lngdp^{\iota} lnsciemploy^{\kappa} lnpop^{\zeta} findev^{\eta}}{s\omega k^{\sigma} lnindex^{\upsilon} indus^{\omega-1} lngdp^{\iota}\ lnsciemploy^{\kappa} lnpop^{\zeta} findev^{\eta}}$ and $g(k, lnindex, indus) = \frac{s\upsilon k^{\sigma} lnindex^{\upsilon-1}\ indus^{\omega} lngdp^{\iota} lnsciemploy^{\kappa} lnpop^{\zeta} findev^{\eta} - 1}{s\omega k^{\sigma} lnindex^{\upsilon} indus^{\omega-1} lngdp^{\iota}\ lnsciemploy^{\kappa} lnpop^{\zeta} findev^{\eta}}$, then Equation (10) can be further expressed as

$$\frac{\partial indus}{\partial lnindex} = f(k, lnindex, indus)\frac{\partial k}{\partial lnindex} - g(k, lnindex, indus) \tag{11}$$

According to Equation (11), digital financial inclusion includes the size of $f(k, lnindex, indus)$, $g(k, lnindex, indus)$, and $\frac{\partial k}{\partial lnindex}$. It is known that digital finance will effectively affect industrial structure upgrading.

Suppose there is an open economy with two sectors and that there is a free exchange between sectors. Both sectors are engaged in green innovation and are represented by C1 and C2 (Wang et al. 2022a). The expression is

$C1[Lnindex, \Phi\text{Indus}(\text{Lnindex})]$, $C2[Lnindex, (1 - \Phi Indus(Lnindex)]$.

It is worth noting that Φ indicates the share of the tertiary industry output value of one sector in the output value of the secondary industry and $(1-\Phi)$ indicates the share of another sector.

Supposing $C = C_1/C_2$ and in both sides of the deduction of Indus, the following formula is obtained, indicating that the upgrading of industrial structure may have some influence on green innovation:

$$\frac{\partial C}{\partial Indus(Lnindex)} = \frac{C_{12}C_2\Phi - C_1C_{22}(1-\Phi)}{C_2^2} \tag{12}$$

We can direct both sides of the equation to *Lnindex*:

$$\frac{\partial C}{\partial Lnindex} = \frac{C_{11}C_2 - C_1C_{21}}{C_2^2} + \frac{C_{12}C_2\Phi - C_1C_{22}(1-\Phi)}{C_2^2}\frac{\partial Indus(Lnindex)}{\partial Lnindex} \tag{13}$$

Drag Equation (12) combined with Equation (13), and the following equation can be obtained:

$$\frac{\partial C}{\partial Lnindex} = \frac{C_{11}C_2 - C_1C_{21}}{C_2^2} + \frac{\partial C}{\partial Indus(Lnindex)}\frac{\partial Indus(Lnindex)}{\partial Lnindex} \tag{14}$$

From the equations, we can find $\frac{C_{11}C_2 - C_1C_{21}}{C_2^2}$ and $\frac{\partial C}{\partial \text{Indus(Lnindex)}}\frac{\partial \text{Indus(Lnindex)}}{\partial \text{Lnindex}}$. Each represents the direct and indirect impact. After that, the industrial structure of the equation is replaced by the level of informatization and the intensity of scientific and technological expenditures. Through the same calculation process, we obtained the following two formulas:

$$\frac{\partial C}{\partial \text{Lnindex}} = \frac{C_{11}C_2 - C_1C_{21}}{C_2^2} + \frac{\partial C}{\partial \text{lninternet(Lnindex)}}\frac{\partial \text{Lninternet(Lnindex)}}{\partial \text{Lnindex}} \tag{15}$$

$$\frac{\partial C}{\partial \text{Lnindex}} = \frac{C_{11}C_2 - C_1C_{21}}{C_2^2} + \frac{\partial C}{\partial \text{Scitec(Lnindex)}}\frac{\partial \text{Scitec(Lnindex)}}{\partial \text{Lnindex}} \tag{16}$$

Lninternet stands for the level of informatization, *Scitec* stands for optimal allocation of resources, and from Equation (15) and Equation (16), we can find that the optimal allocation of informatization and individual resources can be an intermediary variable.

Theoretical hypotheses

Digital finance may have a direct impact on the level of green innovation in the following ways. First, digital finance has expanded financial coverage, facilitated financial services and enriched financial products, which is conducive to alleviating the challenges faced by some companies, and has greatly promoted the advancement of green innovation (Brown et al. 2009). As the service distance of traditional bank outlets is limited to local cities, the cost of collecting and processing borrowers' information by banks increases, and the problem of information asymmetry becomes more serious (Jiménez et al. 2008). Digital finance is conducive to solving this information asymmetry. It is beneficial to optimize resource allocation and thus drive the output of green innovation. Second, digital finance has brought about the subversive innovation of traditional finance, including business model innovation, financial product innovation, and financial service innovation. Ultimately, it promoted the service quality of the financial industry (Beck et al. 2016), thereby improving the efficiency of the financial industry as a whole and improving the efficiency and growth rate in the service entity industry. Through the above analysis, we put forward the first hypothesis:

Hypothesis 1: Digital finance has a positive impact on the quantity and quality of green innovation.

Digital finance may influence green innovation through three intermediary channels. First, digital means can be seen everywhere to promote the evolution of product forms and changes in industrial ecology. The digital information-sharing platform created by digital finance has also stimulated the dissemination of technical knowledge (Ngai and Pissarides, 2007). To obtain a dominant position, enterprises further promote the reduction of costs in the industry, embarking on the road of industrial structure advancement while achieving the purpose of resource conservation and environmental protection. Digital finance uses the internet to integrate digital technology and traditional financial industry (Bruhn and Love 2014), establishes an evaluation system for various projects, and pays more attention to emerging projects with innovative potential and green effects (Rin and Hellmann 2002). Digital finance can reduce the service threshold and service cost, effectively alleviate the problem of financing constraints, continuously improve financing efficiency, and provide backup support for industrial upgrading (Du et al. 2020). The traditional assessment method of the financial sector makes it impossible for enterprises in the rising period to obtain more financial support. Relying on digital financial platforms, the information asymmetry between supply and demand can be solved. It can accurately arrange the flow of funds and then achieve industrial transformation and upgrading (Beck et al. 2002). Differentiated digital financial products and services can drive consumption upgrading (Li et al. 2020), which in turn forces enterprises to innovate in green technology, improve the industrial development model with high energy consumption and low efficiency, and further promote industrial upgrading. Digital finance has satisfied the needs of the "long tail group" in financial markets and thus provided a continuous supply of funds for industrial structure optimization (Demertzis et al. 2018).

Second, the improvement of the informatization level promotes the widespread use of new information technology (Acemoglu and Restrepo 2019). Another advantage of the level of informatization is that it can be accurately controlled and integrated so that various industries can intelligently optimize the layout (Chen and Zhang 2021). With the increase in digital finance application scenarios, the rapid development of new infrastructure has led to an increase in the supply and demand of information technology services, enhanced the degree of support for infrastructure, and enhanced the foundation for green innovation (Ji et al. 2021). To maximize the role of digital finance, we must first build a green and efficient data center, strengthen energy consumption data detection and management, provide underlying basic support for various financial scenarios, and accelerate the pace of technology application, thereby promoting green innovation (Song et al. 2021b). Digital finance can drive the creation and improvement of financial technology facilities, which is applied to many financial service platforms, which can carry out real-time dynamic supervision and timely promotion, providing a real-time dynamic development guarantee (Eugenia and Michele 2022). Digital finance can help build a huge information network between regions, and the construction of information network infrastructure can effectively break the time and space constraints of information exchange and promote exchanges and cooperation among various regions. It also promotes the exchange and spillover of green technology innovation knowledge (Khuong 2011). Digital finance can overcome geographical obstacles by building network infrastructure, improving the extension capacity of inclusive finance, and providing quality services for green innovation (Zheng 2020).

Green innovation activities need to be carried out with a large number of funds, and digital finance can have a full understanding of the internal situation of enterprises through the accurate control of big data, according to which the government, financial institutions, etc. can make reasonable assessments (Takalo and Tanayama 2010), and mobilize enthusiasm for social green innovation through the assistance of technology expenditures. Digital finance has disrupted the way traditional resources are allocated, promoting accurate matching and inclusiveness. Digital finance can mine massive amounts of data, accurately assess risks and benefits, and improve resource allocation efficiency by reducing information asymmetry (Gabor and Brooks 2017). This improves the efficiency of green innovation. The inclusive characteristics of digital finance have enabled financial institutions to provide more credit support for private enterprises (Yue et al. 2022). Digital finance has induced the "catfish effect" and "demonstration effect," which have activated the vitality of green innovation industries. Thanks to the rapid development of digital financial technologies, resource allocation can directly capture capital needs through the internet economic platform. In terms of inclusiveness, digital finance gives more opportunities to small businesses, broadens the scope of resource allocation, and provided basic support for a wide range of green innovation (Restuccia and Rogerson 2008). The online financial service model has replaced the offline financial service model to a certain extent so that the improvement of the efficiency of resource allocation has improved the level of financial services. It provides a sound environment for green innovation (Wang and Ji 2022). This paper presents a second hypothesis.

> Hypothesis 2: Digital finance can promote green innovation through industrial structure optimization, information-level construction, and resource allocation optimization.

Due to the geographical proximity of cities, cities within the same cluster are more likely to obtain new ideas and new ideas, and when a city is in an advantageous position in terms of digital finance, it is easy to imitate and learn from other cities (Beaudry and Breschi 2003), so that continuous green innovation can be formed within the cluster. Digital finance technology and green innovation can be maximized and disseminated (Zhang et al. 2022a). The migration of labor can effectively drive the spillover of knowledge of digital finance, which is the engine of sustained growth of local green innovation (Romer 1986), and the city, as a market of natural resources and factors flowing freely, can create more green wealth. Digital finance spillover is more active in the city (Henderson 1986), and it is easier to overflow knowledge in large cities. Its spillover effect is also more pronounced (Gao and Yuan 2022).

Local governments maintain a competitive advantage through green innovation (Zhao et al. 2021), and this competition can obtain more limited resources to drive green economic development. Government finance innovation is an important way to attract all kinds of resources related to green development (Li and Zhou 2005). To gain a competitive advantage in the "championship" of economics, local governments are motivated to develop digital finance, and this effect can spread rapidly in the region (He and Li, 2017). The scientific and technological output indicators in areas with high financial innovation efficiency often have a strong demonstration effect. To catch up with each other, other cities will bring digital financial policy imitations (Su et al. 2022). All of the above suggests that it is necessary to consider the role of spatial spillover when considering the corresponding effects. This leads to a third hypothesis:

Hypothesis 3: The impact of digital finance on green innovation has spatial spillover effects.

Methodology and data

Dynamic spatial Durbin metrology

Due to the significant spatial relevance of green innovation, green innovation is not only affected by local digital financial factors but is also affected by other cities. To investigate whether green innovation is dynamic and continuous, this paper introduces the time lag term of the explanatory variables in the model. According to Elhorst's (2011) research, a dynamic space Durbin model was established. The general dynamic spatial Durbin model formula is as follows:

$$Y = \gamma Y_{t-1} + \rho WY_{t-1} + \theta WY_t + \beta X_t + \delta WX_t + \omega i + \upsilon t + \varepsilon it \tag{17}$$

Spatial weight matrix

The calculation of spatial autocorrelation needs to rely on the setting of the spatial weight matrix. The setting form of spatial weights mainly includes the adjacency weight matrix, in which the principle is geographical proximity to the city, and the geographical distance weight matrix, which is based on the length of the distance between cities. There is also an economic distance weight matrix. It is calculated according to the differences in economic development levels between cities. How to choose the matrix is mainly to see the needs of the article. The variables in this paper are all related to the level of economic development of the city (Liu and Chen 2022), and the more similar the economic development level, the more economic connections there are, so the more it can show a strong spatial correlation, so we select the economic distance weight matrix for calculation (Shao et al. 2016), and the established weight matrix is usually expressed as follows:

$$W_{ij} = \begin{cases} \frac{1}{GDP_i - GDP_j}, i \neq j \\ 0, i = j \end{cases} \tag{18}$$

where GDP_i represents the average GDP per capita of a city from 2011 to 2019.

Data

Based on the data available in this paper, samples with serious missing data were removed to ensure that the data were reliable. Finally, we use the data of 284 cities from 2011 to 2019 for analysis, and the individual missing values are supplemented by interpolation.

This paper uses the Digital Financial Inclusion Index of the Digital Finance Research Center of Peking University to characterize digital finance (Wen et al. 2022; Pan et al. 2021). The agent index of the number of green innovations is the total number of applications for the number of green patents (Guo et al. 2021, b). Green invention patents are related to green utility model patents and green design patents, which have higher requirements for novelty and originality in patent reviews, and the review is more stringent. Authorized green invention patents refer to the examination of the State Intellectual Property Office. Its technology is in line with the authorization requirements of the patent. The authorized green invention patent is a valid patent, and there is no technical problem, so the quality of the patent that can be authorized is guaranteed.

Based on the existing literature, this paper selects some factors affecting green innovation, so the control variables include the economic situation, the number of scientific practitioners, population size, and the level of financial development. The agent index of the level of economic development is the logarithm of city's per capita GDP (Zhang et al. 2021a). Scientific practitioners are the number of practitioners in the internet industry, and the scientific research industry is summed up and taken as a logarithm (Song et al. 2021a, b). Population size is mainly measured using the logarithm of the urban household registration population as an agent indicator (Wei et al. 2022), and the level of financial development is measured by the ratio of the sum of deposits and loans of financial institutions to the city's GDP (Feng et al. 2021).

All green patent data refer to the practices of Dong and Wang (2021). Patent information at the city level is obtained by collecting patent information published by national IP offices and according to the green patent lists and international classification codes provided by the WIPO (Dong and Wang 2021). The data for the remaining variables are derived from the China Urban Statistical Yearbook, the annual statistical bulletin of each city, and the EPS data platform.

Table 1 shows the expression and measurement of the main variables in this paper. Table 2 shows the results of the descriptive statistics of various variables. The variance of the indicators of green innovation quantity and quality is large, indicating that the gap between green innovation levels between cities is larger. The variance between the numbers of scientific researchers is also larger, indicating that the difference between the scientific research levels between cities is also large, so it is meaningful to explore the differences between digital finance and the level of green innovation between cities Fig. 1.

Empirical results and discussions

Spatial metrological tests

To test the spatial correlation between variables, we calculate Moran's *I* index of the data. A positive correlation refers to the aggregation of spatial distance; the correlation is significantly enhanced (Cai et al. 2022), and the negative correlation is the opposite; as the spatial position is more and more dispersed, the correlation is significantly enhanced. Therefore, this paper uses Stata 16.0 software to calculate Moran's *I* index of green innovation quality and green innovation quantity in Chinese cities from 2011 to 2019, and the calculation results are shown in Table 3. Moran's *I* index is significantly positive, so there is a significant spatial correlation between green innovations.

Second, this paper also plots Moran's scatters for 2011 and 2019. As shown in Fig. 2, the horizontal axis is represented, the vertical axis is indicated, and the distribution of the scatter plot indicates that there is a spatially positive correlation between green innovations between the sample cities.

Benchmark regression results

To select the appropriate spatial econometric model, we first needed to run the Hausman, LR, LM, and Wald tests. The results of the inspection are shown in Table 4. The double-fixed-effect model should be adopted in this study because it rejects the null hypothesis. The spatial Durbin model cannot degenerate into a spatial lag model or a spatial error model. This suggests that the double-fixed dynamic spatial Durbin model should be applied. The model settings are as follows (Elhorst et al. 2010):

$$\begin{aligned} Lngre1_{it} &= \alpha Lngre1_{it-1} + \sigma \Sigma_j w_{ij} lngre1_{it-1} \\ &+ \rho \Sigma_j w_{ij} Lngre1_{jt} + \beta_1 Lnindex_{it} \\ &+ \beta_2 \Sigma_j w_{ij} lnindex_{jt} + \gamma X_{it} + \psi \Sigma_j w_{ij} X_{jt} + u_i + \varepsilon_{it} \end{aligned} \tag{19}$$

$$\begin{aligned} Lngre2_{it} &= \alpha Lngre2_{it-1} + \sigma \Sigma_j w_{ij} lngre2_{it-1} + \rho \Sigma_j w_{ij} Lngre2_{jt} \\ &+ \beta_1 Lnindex_{it} + \beta_2 \Sigma_j w_{ij} lnindex_{jt} + \gamma X_{it} + \psi \Sigma_j w_{ij} X_{jt} + u_i + \varepsilon_{it} \end{aligned} \tag{20}$$

Table 5 shows the results of the benchmark regression, and the regression coefficients of the lag terms of the quantity and quality of green innovation are significantly

Table 1 Variable representation and its measurement

Variables	Implication	Measurement method
Lngre1	Quantity of green innovations	Total number of green patent applications
Lngre2	Quality of green innovation	Authorized green invention patents
Lnindex	Total digital finance index	Digital financial inclusion index of the Digital Finance Research Center of Peking University
Lncover	Breadth of digital finance coverage	Digital Financial Inclusion Index of the Digital Finance Research Center of Peking University
Lndepth	Depth of digital finance usage	Digital Financial Inclusion Index of the Digital Finance Research Center of Peking University
Lndigit	Digitization of digital finance	Digital Financial Inclusion Index of the Digital Finance Research Center of Peking University
Lngdp	GDP per capita	Logarithm of urban GDP per capita
Lnsciemploy	Number of scientific practitioners	The totals of the number of employees in the Internet industry and the research industry are taken as logarithms
Lnpop	Size of population	Logarithm of urban household population
Findev	Level of financial development	Ratio of the sum of deposits and loans of financial institutions to urban GDP

positive, indicating that green innovation is a dynamic, continuous process with a clear trend. Previous green innovations can contribute to current green innovations. The regression coefficient of digital finance on the quantity and quality of green innovation is significantly positive, indicating that local digital finance can increase the quantity and improve the quality of local green innovation. Cao et al. (2021) also show that the findings are reliable. The rho value is significantly positive, indicating that there is a significant spatial spillover effect on the increase in the quantity of green innovation and the improvement in the quality of green innovation between cities. This indicates the significant presence of spatial effects of green innovation in digital finance. The regression coefficient of the spatial lag term is significantly negative indicating the negative spillover effect of digital finance in neighboring regions on the quantity and quality of green innovation in local cities. Other studies have drawn similar conclusions that digital finance has a significant direct contribution to regional economic growth and negative spatial spillover effects (Ding et al. 2022). The economic significance expressed by the benchmark results is that the development of digital finance in the previous stage can have a catalytic effect on the development of digital finance in the next stage. Digital finance in the local city can have a positive impact on green innovation in the local city. However, when digital finance in other cities flourishes there is a negative impact on local green innovation, there is a negative spatial spillover effect. With the promotion of financial technology, digital finance can reduce the phenomenon of information asymmetry, effectively support small and micro enterprises' innovation and entrepreneurship, and effectively identify green financing needs (Dupas and Robinson 2013). Digital finance in other cities has promoted the improvement of the city's infrastructure, the improvement of information structure, and the reduction of risks and costs, thereby enhancing the local market vitality (Zhou et al. 2018) and optimizing local market structure so it can promote the expansion of local market demand. Therefore, through the local market effect, it further expands its own advantages and has a siphon effect on neighboring areas (Wei et al. 2010) so that local digital finance will reduce the quality of green innovation in the surrounding areas.

Table 2 Descriptive statistics for variables

Variables	Obs	Mean	Std. Dev.	Min	Max
Lngre1	2556	5.236	1.606	0	10.508
Lngre2	2556	2.869	1.712	0	8.872
Lnindex	2556	5.001	0.514	2.834	5.773
Lncover	2556	4.927	0.566	0.631	5.740
Lndepth	2556	4.983	0.518	1.456	5.805
Lndigit	2556	5.167	0.627	0.993	6.365
Lngdp	2556	10.693	0.573	8.773	12.322
Lnsciemploy	2556	9.182	1.107	6.215	14.259
Lnpop	2556	5.890	0.696	2.970	8.136
Findev	2556	2.395	1.110	0.588	7.519

Robustness

Subsequently, robustness tests were carried out to ensure that the conclusions of this article are reliable (as shown in Table 6).

First, we exclude the samples of the four municipalities (Guo et al. 2021, b), which often have large built-up areas, more residential populations, and an important position in the country's politics, economy, science,

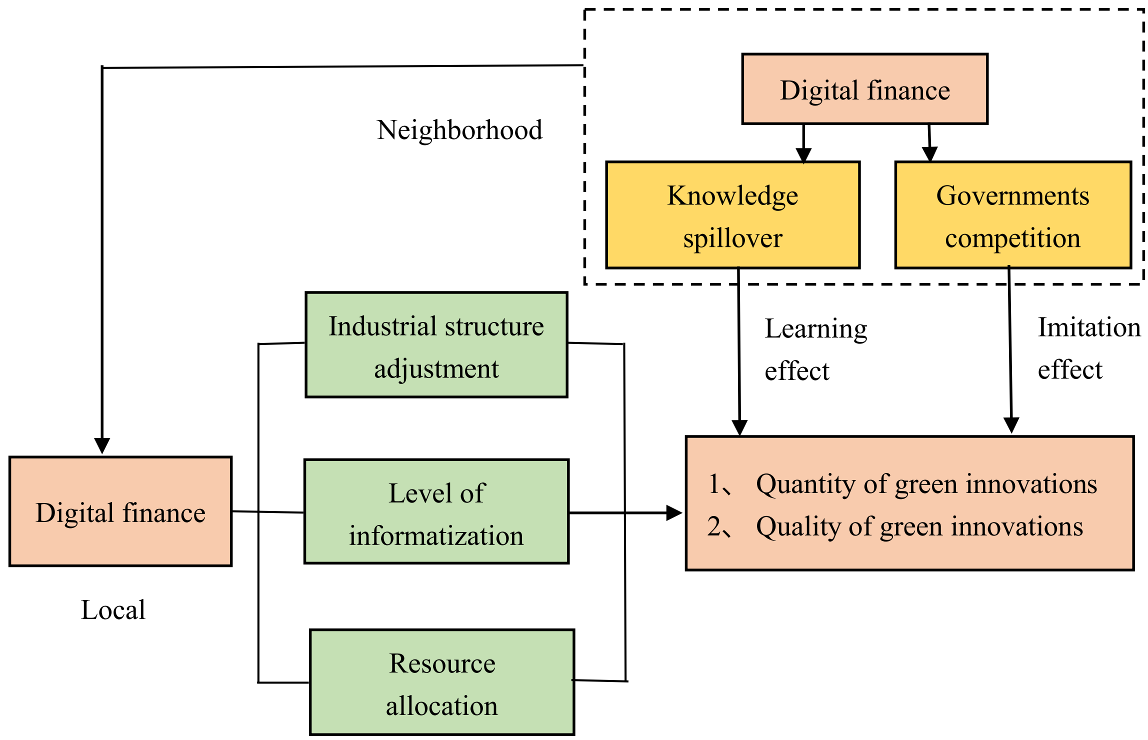


Fig. 1 Intermediary channels for digital finance and green innovation

Table 3 Moran's *I* of green innovations

Year	Lngre1			Lngre2		
	I	*z*	*p*-value*	*I*	*z*	*p*-value*
2011	0.315	13.025	0.000	0.184	7.670	0.000
2012	0.310	12.809	0.000	0.212	8.817	0.000
2013	0.295	12.209	0.000	0.221	9.180	0.000
2014	0.317	13.131	0.000	0.203	8.442	0.000
2015	0.323	13.360	0.000	0.236	9.815	0.000
2016	0.328	13.571	0.000	0.264	10.947	0.000
2017	0.349	14.434	0.000	0.254	10.544	0.000
2018	0.369	15.253	0.000	0.275	11.378	0.000
2019	0.352	14.542	0.000	0.293	12.107	0.000

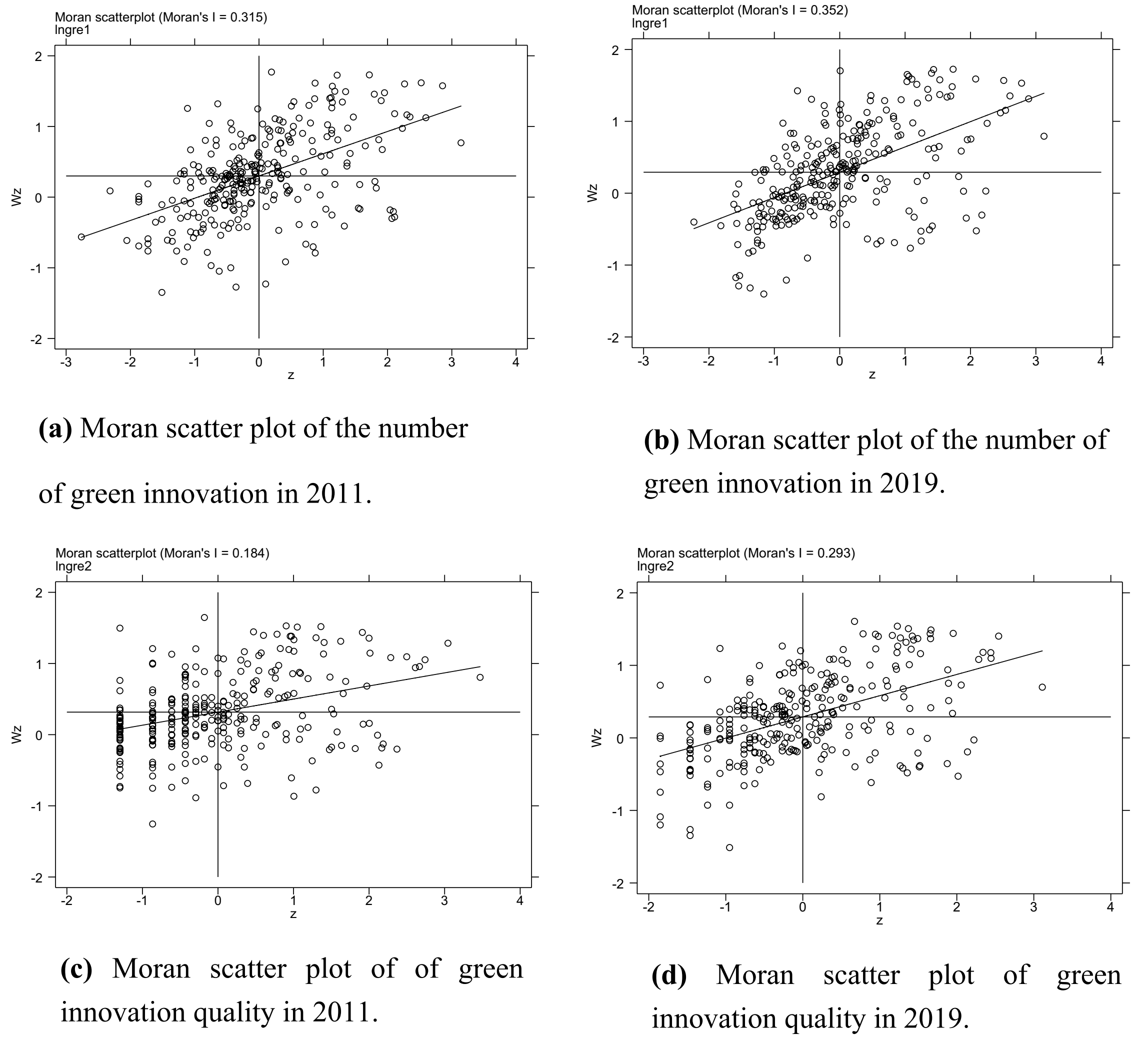
culture, transportation, etc. The municipalities in all of the sample cities have particularities, and after removing the sample city data of the municipalities, this paper still gets the same conclusion.

Second, this paper replaces the agent index of the interpreted variable (Cui and Liu 2022), uses the logarithm of the total number of green patents granted to characterize the number of green innovations, and uses the proportion of green invention patents granted to the total number of green patents granted to characterize the quality of green innovation.

After that, the dynamic spatial autoregressive model (DSAR) is used instead of the DSDM model for regression (Gao et al. 2022), and the results of the test show that the digital finance index still has obvious positive effects on green innovation. The spatial rho value is still positive and significant, which proves that the previous conclusions are stable.

Endogenous test

To further alleviate the endogeneity problem in this paper, the number of landline telephones in China at the end of 1984 is used as an instrumental variable (Bai and Yu 2021). The number of landline telephones serves as a traditional telecommunication tool. Its infrastructure, the level of technology, affects the development of Internet



(a) Moran scatter plot of the number of green innovation in 2011.

(b) Moran scatter plot of the number of green innovation in 2019.

(c) Moran scatter plot of of green innovation quality in 2011.

(d) Moran scatter plot of green innovation quality in 2019.

Fig. 2 Moran's scatterplot of the quantity and quality of green innovation. **a** Moran's scatter plot of the number of green innovation in 2011. **b** Moran's scatter plot of the number of green innovation in 2019. **c** Moran's scatter plot of green innovation quality in 2011. **d** Moran's scatter plot of green innovation quality in 2019

technology in subsequent stages. This instrumental variable satisfies the correlation condition. The number of fixed phones in 1984 as historical data has no influence on green innovation in 2011. Also, the frequency of landline telephone use today is too low to have an impact on regional green innovation development. Therefore, this instrumental variable satisfies the exogeneity condition. In order to avoid the problem of collinearity, the provincial fixed effect was controlled this time (Zhang et al. 2021b). The missing values of some cities have also been eliminated.

Table 4 Hausman, LR, and Wald tests

Test	Lngre1	Lngre2
Hausman test	540.99 (0.0000)	713.75 (0.0000)
LM SAR	120.01 (0.0000)	86.52 (0.0000)
LM SDM	3545.03 (0.0000)	3054.60 (0.0000)
Wald SEM	32.82 (0.0000)	45.87 (0.0000)
Wald SAR	26.00 (0.0001)	52.40 (0.0000)
LR SEM	24.34 (0.0417)	53.83 (0.0000)
LR SAR	32.84 (0.0030)	45.63 (0.0000)

In Table 7, the higher the number of landline telephones in 1984, the higher its level of digital finance development. The coefficients of green innovation quantity and green innovation quality are still significantly positive from the regression results of the second stage. It indicates that the conclusions of this paper are still reliable. From the results of the instrumental variable test, this instrumental variable rejects the unidentifiable test and there is no weak instrumental variable.

Table 5 Benchmark regression results

Variables	Lngre1	Lngre2
L.lngre1	0.386***	
	(−0.019)	
L.lngre2		0.317***
		(−0.021)
Lnindex	0.466***	0.619***
	(−0.161)	(−0.236)
Lngdp	0.275***	0.040
	(−0.067)	(−0.098)
Lnsciemploy	−0.002	0.015
	(−0.009)	(−0.013)
Lnpop	0.148	0.273
	(−0.141)	(−0.206)
Findev	0.054**	−0.055
	(−0.024)	(−0.034)
W-Lnindex	−0.544*	−0.823*
	(−0.292)	(−0.426)
W-Lngdp	−0.319**	0.146
	(−0.126)	(−0.184)
W-Lnsciemploy	0.029	0.031
	(−0.023)	(−0.034)
W-Lnpop	−0.021	1.032***
	(−0.265)	(−0.396)
W-Findev	−0.065	0.034
	(−0.051)	(−0.075)
Rho	0.364***	0.114**
	(−0.039)	(−0.048)
sigma2_e	0.081***	0.173***
	(−0.002)	(−0.005)
Log-likelihood	−663.515	−1452.530
Observations	2272	2272
R-squared	0.935	0.603
Number of ID	284	284

Standard errors in parentheses; ***$p<0.01$, **$p<0.05$, and *$p<0.1$

Heterogeneity analysis and discussion

Regional heterogeneity

There are enormous differences in population size, economic and technological level, and natural environment between the eastern and mid-western cities, so according to Tang (2022), the sample is divided into eastern and mid-western cities. The results in Table 8 show that the digital finance composite index has a significant positive effect on the quantity and quality of green innovations in eastern cities, and for the mid-western regions, the regression coefficient is not significant. The main reason may be that eastern cities have faster economic growth and more various types of enterprises. The speed of technological development and the speed of technological transformation are faster, which is an important engine for green innovation. For several green innovations, itself is in the east and mid-west has spatial spillover effects (Liu et al. 2021b), which may be because of an increase in the number of the requirements of the green innovation technology difficulty is relatively low, the speed of technology spillovers, and fewer barriers (Miao et al. 2021). However, the mid-western green innovation quality rho value was not significant, which may be the cause of the mid-western cities' own technology research and development strength is low, knowledge spillover is difficult, and government system and market environment are not as good as eastern cities, forming all kinds of communication obstacles (Song et al. 2020).

Different dimensions of digital finance

Digital finance can be divided into three subdimensions: breadth of coverage, depth of use, and degree of digitization (Han and Gu 2021; Wen et al. 2022). As the results in Table 9 show, the breadth of digital finance's coverage has had a positive impact on the increase in the number of green innovations. The expansion of the coverage of digital finance in surrounding cities has a significant inhibitory effect on the improvement of the number of local green innovations, while the other two dimensions are not significant. The degree of digitization can significantly improve the quality of green innovation in a city (Rao et al. 2022), and the other two dimensions show little effect. The reason may be that the larger the industries and regions that digital financial inclusion can cover, and the more perfect the financial infrastructure, the more enterprises can benefit, which can rely on the advantages of big data platforms, get more financial support and other policy preferences, and the more motivated they are to develop their ability (Luo et al. 2022). However, the number of green innovations emphasizes quantitative growth and in some ways will ignore the originality of green innovation, so the coverage breadth of digital finance will make the quantity increase significantly, but it will not necessarily improve the quality. The degree of digitization of digital finance promotes the accessibility and continuity of financial services and can accurately identify the needs of target customers, thereby promoting the balance of resource allocation, reducing traditional risks, and improving operational efficiency (Mikhail et al. 2021), so that for project activities with high-quality green innovation, relying on cutting-edge technology can improve capital availability and technical support.

Analysis of mediation effects

Having validated the intrinsic link between the kernel variables, this paper will analyze the possible influencing factors between them. The model settings are as follows:

Table 6 Robustness test results

Variables	Exclude the municipalities		D-SAR		Substitution variables	
	Lngre1	Lngre2	Lngre1	Lngre2	Lngre1	Lngre2
L.lngre1	0.383***		0.388***		0.435***	
	(−0.019)		(−0.019)		(−0.019)	
L.lngre2		0.316***		0.329***		0.237***
		(−0.021)		(−0.020)		(−0.019)
Lnindex	0.440***	0.593**	0.307**	0.375*	0.978***	0.106**
	(−0.163)	(−0.239)	(−0.142)	(−0.208)	(−0.172)	(−0.049)
W-Lnindex	−0.536*	−0.808*			−0.778**	−0.165*
	(−0.296)	(−0.433)			(−0.311)	(−0.089)
Rho	0.363***	0.117**	0.354***	0.147***	0.243***	0.161***
	(−0.039)	(−0.048)	(−0.038)	(−0.046)	(−0.040)	(−0.044)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Individual fixed	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes	Yes	Yes	Yes
Log-likelihood	−696.280	−1453.712	−327.627	−1191.21	−694.355	2397.521
R-squared	0.933	0.586	0.888	0.815	0.871	0.047
Number of ID	280	280	284	284	284	284

$$M_{it} = \alpha_1 M_{it-1} + \sigma\Sigma_j w_{ij}M_{it-1} + \rho_1\Sigma_j w_{ij}M_{jt} + \beta_1 \text{Lnindex}_{it} + \theta_1\Sigma_j w_{ij}\text{Lnindex}_{jt} + \gamma_1 X'_{it} + \psi_2\Sigma_j w_{ij}X'_{jt} + u_i + \varepsilon_{it} \quad (21)$$

Digital finance increases the range of financial availability and financial technology to help with the rapid flow of capital and information. On the other hand, through big data and other functions, so that information visibility is higher, can improve the allocation efficiency of capital, so that capital can be flowed between industries with maximum social benefits, the industrial structure can be effectively adjusted (Liu et al. 2021a).

Table 7 Results of instrumental variable tests

Variables	(1) Lnindex	(2) Lngre1	(3) Lngre2
IV	0.013***		
	(0.002)		
Lnindex		8.886***	14.529***
		(−1.920)	(−2.925)
Constant	2.204***	−38.510***	−56.592***
	(0.059)	(−4.163)	−6.314
Control variables	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Kleibergen-Paap rk LM statistic		29.181***	29.182***
Cragg-Donald Wald *F* statistic		26.288	27.288
Observations	2016	2016	2016
R-squared	0.977	0.777	0.519

We use the proportion of the output value of the tertiary industry and the output value of the secondary industry to measure the advanced level of the industrial structure (Zhang et al. 2021a). The regression results of the table show that the regression coefficient of digital finance to the seniority of industrial structure is significantly positive. This shows that digital finance is beneficial to the optimization of industrial structure (Wang et al. 2022a). The high-level industrial structure is reflected in the rapid development of high-tech manufacturing and the increase in enterprise investment in technological research, and the level of urban innovation can be effectively improved (Li and Ma 2021). The advanced industrial structure means that the proportion of value added in the service sector has increased significantly. The service industry has lower energy consumption and a higher technical level than the industrial manufacturing industry, and the urban industrial spatial layout and environmental level can be continuously optimized. The upgrading of the industrial structure means that the green and low-carbon advantageous industries can get better development opportunities (Liang 2020), the level of carbon dioxide emissions has been significantly reduced, and the new field of the green technology industry will become an important economic growth point.

Therefore, digital finance can strengthen the innovation and application of green technology in production and manufacturing through the use of digital intelligence and other means, empower green creation, optimize the urban industrial layout, accelerate the speed of structural green transformation, accelerate the pace of upgrading the industrial structure, and ultimately improve the level of green innovation (Zhong, 2022).

Table 8 Regional heterogeneity regression results

Variables	Region			
	Lngre1		Lngre2	
	Eastern cities	Mid-west cities	Eastern cities	Mid-west cities
L.lngre1	0.446***	0.347***		
	(−0.029)	(−0.024)		
L.lngre2			0.364***	0.290***
			(−0.032)	(−0.027)
Lnindex	1.117***	0.175	0.913**	0.384
	(−0.278)	(−0.207)	(−0.399)	(−0.306)
W-Lnindex	−2.227***	−0.233	−0.772	−0.918
	(−0.515)	(−0.436)	(−0.749)	(−0.636)
Control variables	Yes	Yes	Yes	Yes
Rho	0.453***	0.293***	0.216***	0.035
	(0.055)	(0.049)	(0.073)	(0.057)
Log-likelihood	−1119.837	−597.309	−394.769	−1168.092
Observations	912	1360	912	1360
R-squared	0.699	0.912	0.872	0.31
Number of ID	114	170	114	170

This paper also uses the logarithm of the number of urban internet users to characterize the information support effect of the city (Song et al. 2021a). Digital finance has a significant positive effect on the level of informatization. One possible reason is that digital finance has led to the improvement of various related infrastructures, especially digital finance, which relies on information sharing of various types of big data, to create excellent interaction between

Table 9 Regression results for the subdimension of digital finance

Variables	Dimensions of digital financial inclusion					
	Lngre1	Lngre1	Lngre1	Lngre2	Lngre2	Lngre2
L.lngre1	0.380***	0.390***	0.390***			
	(−0.019)	(−0.019)	(−0.019)			
L.lngre2				0.317***	0.316***	0.316***
				(−0.020)	(−0.021)	(−0.020)
Lncover	0.531***			0.105		
	(−0.121)			(−0.177)		
Lndepth		0.011			−0.0786	
		(−0.102)			(−0.148)	
Lndigit			0.0229			0.311***
			(−0.060)			(−0.089)
W-Lncover	−0.768***			−0.269		
	(−0.252)			(−0.371)		
W-Lndepth		0.177			−0.131	
		(−0.163)			(−0.238)	
W-Lndigit			−0.087			−0.125
			(−0.108)			(−0.156)
Rho	0.365***	0.357***	0.360***	0.113**	0.107**	0.110**
	(0.039)	(0.040)	(0.039)	(0.048)	(0.049)	(0.049)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Log-likelihood	−920.302	−399.629	−658.923	−1423.93	−1492.45	−1215.42
Observations	2272	2272	2272	2272	2272	2272
R-squared	0.933	0.9	0.92	0.591	0.583	0.577
Number of ID	284	284	284	284	284	284

online and offline financial platforms, to promote the accurate supply of finance and the satisfaction of personalized needs (Kelikume, 2021). It is necessary to strengthen various types of digital construction and promote the continuous innovation of digital technology, so that the level of informatization in the city will inevitably be greatly improved (Kohli and Melville 2019). The improvement of the level of urban informatization provides a fast way for capital flow and an effective channel for technology sharing, thereby improving the speed of information transmission and technology spillover between R&D departments and production departments, thus providing an information support effect for green innovation (Cindori et al. 2021).

The limitations of time and space have been broken by digital finance due to its own characteristics, expanding the scope of services, reducing transaction costs, and alleviating the problem of information asymmetry, so digital finance can accurately identify different needs, which is more conducive to resource allocation optimization (Cindori et al. 2021). To measure the effect of resource allocation, the indicator we chose is the proportion of science and technology expenditure in local fiscal expenditure. Digital finance has no statistical significance for the regression coefficient of the intensity of scientific research expenditure; the possible reason is that the resources of government science and technology expenditure are not properly allocated. The capital flow needs to be adjusted, and resource allocation needs to be more inclined toward key areas (Hu 2021). Other reasons may also be that scientific and technological expenditure on scientific and technological achievements requires a relatively long research and development process. The improvement of green innovation is not an overnight thing, which requires manpower, material resources, and multifaceted efforts (Spence 2021). The role of local government science and technology spending needs to be observed over time Table 10.

Conclusion and policy implications

As a new format of financial and technological integration and development, digital finance overcomes the drawbacks of traditional finance. This paper uses panel data from 284 cities in China from 2011 to 2019 to analyze the impact of digital finance on green innovation in dynamic space Durbin and examines the three possible intermediary effects of industrial structure adjustment, informatization level, and resource allocation. Heterogeneity analysis and robustness tests are also carried out. The conclusion of this paper is as follows:

1. Digital finance can promote the improvement of the quantity and quality of green innovations in local cities. After deleting some samples, replacing the DSDM model with the DSAR model, and replacing the explanatory variables, three kinds of robustness tests show that the conclusions of this paper are robust.
2. Digital finance in neighboring cities has inhibited local green innovation levels, which may be due to the siphon effect, and the local market effect of neighboring cities is still in play. Compared with the quantity of green innovation, the impact on the quality is more significant.
3. The results of this paper are heterogeneous. The positive impact is more significant in the eastern region with a high economic level, good infrastructure, and good market environment, and in terms of heterogeneity of subdimensions, the positive impact of coverage breadth on the number of green innovations is more significant.
4. Through the testing of the intermediary mechanism, digital finance can positively affect green innovation through the upgrading of the industrial structure and the level of informatization. However, due to the unreasonable allocation of resources, the mediating effect of the resource allocation mechanism does not exist.

We obtain the following suggestions for the research conclusions: first, governments should promote the popularization of digital finance in China, broaden the coverage, and strengthen the degree of digitalization and thus provide a good financial environment. We also confirm the existence of spatial spillover effects, so this is an effective move to strengthen regional cooperation and linkage. The government should exert the leading role of key cities, radiate the development of other cities, and avoid further expansion of

Table 10 Mediation effect analysis results

Variables	Indus	Lninternet	Scitec
L.indus	0.835***		
	(−0.021)		
L.lninternet		0.460***	
		(−0.019)	
L.scitec			0.878***
			(−0.020)
lnindex	0.366***	0.650***	−0.00326
	(−0.095)	(−0.122)	(−0.003)
W-Lnindex	0.113	−0.317	−0.001
	(−0.172)	(−0.217)	(−0.005)
Control variables	Yes	Yes	Yes
Rho	0.296*** (0.037)	0.253*** (0.041)	0.061* (0.033)
Log-likelihood	−80.182	342.995	8882.797
Observations	2272	2272	2272
R-squared	0.665	0.71	0.864
Number of ID	284	284	284

the "polarization effect." Second, the government needs to utilize technology to improve the level of urban informatization, improve relevant infrastructure, deepen the central service level and corresponding technical support of digital finance, rationally allocate government funds, and provide long-term support. Third, according to the heterogeneity analysis results of this paper, high-grade, large-scale cities in the east should continue to exert their advantages and develop digital finance, and low-grade, small-scale cities in the central and western should avoid the expansion of siphon effects, seize opportunities, and develop themselves.

Authors' contributions Jinyu Chen: supervision, project administration, and writing—reviewing and editing. Dandan Zhu: data curation, investigation, and writing—original draft preparation. Xiaohang Ren: methodology, conceptualization, validation, and writing—reviewing and editing. Wenjing Luo: conceptualization and writing—reviewing and editing

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Data availability Most of the basic data are publicly available, mainly from China Statistical Yearbook, China Energy Statistical Yearbook, China Science and Technology Statistical Yearbook, and provincial statistical yearbooks. Other data are calculated by the authors, and the calculation method is shown in the text of this paper.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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