Heliyon 10 (2024) e33966

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

With whom should I work? Partners' network characteristics and innovation persistence

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ARTICLE INFO

Keywords:
Innovation persistent
Partners' network centrality
Partners' structural holes
Diversity of knowledge recombination
Novelty of knowledge recombination

ABSTRACT

In studying the implications of collaboration networks on innovation persistence, previous research has primarily focused on the network characteristics of focal inventors, often overlooking those of their partners. The purpose of this study is to demonstrate what and how partners' network characteristics—specifically, network centrality and structural holes—affect the focal inventor's innovation persistence, by positing and testing the diversity and novelty of knowledge recombination as important mediators. We collected a panel patent dataset in the lithography industry between 2000 and 2023 and conducted data analysis using ordinary least squares (OLS) regression model, robustness test, and endogeneity test. Results indicate that partners' network centrality has an inverted U-shaped impact on innovation persistence, whereas partners' structural holes positively influence innovation persistence. The findings further show how the diversity and novelty of knowledge recombination mediate the relationships between partners' network characteristics and innovation persistence. This paper provides valuable insights for inventors, researchers, and policymakers, emphasizing the crucial role of partnerships and knowledge recombination in promoting innovation persistence.

1. Introduction

Innovation persistence embodies a dynamic process whereby innovators continually update their local knowledge base through ongoing external learning and incremental advancements in existing technologies over successive periods [1]. This process has long been a significant research focus due to its profound implications for innovation theory and practice, strategic management, and public policy. Particularly at the enterprise level, ample evidence underscores the pivotal role of innovation sustainability as a catalyst for enhancing firm performance and fostering growth [2].

Given so many far-reaching implications, a growing body of work in the innovation economy examines the extent of persistence in innovation activities and the possible mechanisms that underlie its occurrence [3]. Innovation can be categorized into three types: process, product, and organizational innovations. These types exhibit varying degrees of persistence, with product innovation displaying the strongest persistence, while process and organizational innovation exhibit relatively weaker persistence [4,5]. Brodny et al. (2023) conducted a comparative analysis of innovation persistence among the 27 EU countries by measuring three key indicators related to supporting innovation, building stable infrastructure, and promoting sustainable industrialization [6]. This study found that between 2015 and 2020, Luxembourg, the Netherlands, Denmark, Sweden, and Germany achieved the best results, while Bulgaria and Greece achieved the worst results.

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https://doi.org/10.1016/j.heliyon.2024.e33966
Received 4 April 2024; Received in revised form 25 June 2024; Accepted 1 July 2024

Research on the mechanism underlying the emergence of innovation persistence focuses mainly on the external and internal factors of the firm. From an external perspective, a firm's innovation persistence is linked to market environments, economic policy uncertainty, and government subsidies [7,8]. In contrast, the internal perspective has emphasized that innovation persistence may result from human capital, financial constraints, R&D investment, knowledge diversity, as well as innovation strategies such as firm digital transformation and business model diversification [6,9–12]. To date, however, existing studies often overemphasize the importance of external environments and firm-level characteristics without systematically examining the inventors' innovation persistence within the firm. In fact, as practitioners, inventors' persistence in their innovation efforts is intricately linked to the firm's overall innovation persistence.

Burgeoning researchers have explored the potential benefits of collaboration networks for technology innovation. A collaboration network is a core source of innovators in achieving competitive knowledge and resources, and network relationships and structure play critical roles in strengthening their innovation capabilities. Ju & Wang (2023) proposed that strong network ties are positively associated with a firm's performance growth [13]. Drawing on the arguments of Yan & Guan (2018), a focal inventor's ego-network relational property exerts a positive effect on exploitative innovation. Still, it negatively affects exploratory innovation, and ego-network structural properties exert a positive effect on both exploratory and exploitative innovation [14]. Lin et al. (2022) also found that the stability of a focal inventor's partnerships has an inverted U-shaped effect on his/her innovation performance [15].

Although cooperation network relational and structural characteristics provide opportunities for acquiring heterogeneous knowledge and boosting innovation capabilities [14,16,17], the realization of these opportunities is also contingent upon the partners involved. Partners' network relational and structural characteristics constitute the focal inventor's second-order social capital [18]. However, there is a paucity of theoretical and empirical research on the efficacy of partners' network relations and structure concerning a focal inventor's innovation persistence. Therefore, it is worth exploring the relationship between partners' network relational and structural characteristics and the focal inventor's innovation persistence.

Moreover, innovation is a process of recombining new ideas and knowledge [19]. Innovation persistence implies that the process of focal inventors' knowledge recombination is characterized by durability. While cooperation networks provide inventors with diverse and novel knowledge and social resources, inventors still need to rely on the ability of knowledge recombination to integrate this external knowledge with their knowledge to create new valuable inventions [20,21]. Therefore, this study incorporates the diversity and novelty of knowledge recombination into our framework and discusses the transmission mechanism of partners' network characteristics for a focal inventor's innovation persistence.

Grounded in innovation network and knowledge recombination theories, this study proposes a mediation model and formulates our hypotheses. Hypotheses 1a and 1b relate to the impact of partners' network centrality and structural holes on innovation persistence. Addressing the mediating role of knowledge recombination, Hypotheses 2a and 2b concern the impact of partners' network centrality on the diversity and novelty of knowledge recombination, Hypotheses 2c and 2d concern the impact of partners' network structural holes on the diversity and novelty of knowledge recombination, while Hypotheses 3a and 3b predicts positive effects of the diversity and novelty of knowledge recombination on innovation persistence. Finally, Hypotheses 4a, 4b, 4c, and 4d propose the mediation effects of partners' network centrality and structural holes on focal inventors' innovation persistence through the diversity and novelty of knowledge recombination.

This study makes several contributions to existing literature. First, it contributes to the literature on innovation networks at the individual level by exploring the impact of the focal inventor's partners' network relationship and structure configuration on his/her innovation persistence. Second, we determine the transmission mechanism of the effect of partners' network centrality and structural holes on a foal inventor's innovation persistence, which systematically integrates the views of cooperation network and knowledge recombination and allows us to gain a deeper understanding of the mechanism of the process by which focal inventors utilize partners' network relationship and structure configuration to innovation persistence.

The following section outlines the conceptual background and hypotheses. Subsequently, it presents the study's data, methodology, and empirical findings, drawing from panel data spanning a substantial period (2000–2023). This paper concludes with a discussion and suggestions for future research.

2. Theoretical framework

2.1. Partners' network centrality and structural holes and innovation persistence

Innovation is the process by which inventors recombine the existing knowledge and resources to solve a technological problem [22,23]. Innovation persistence emphasizes that inventors maintain a certain degree of continuity in technological innovation inputs and outputs [24]. Due to the complexity and uncertainty of technological development, inventors are required to engage in continuous innovation activities within a collaborative innovation network framework [25].

According to innovation network theory, inventors can transfer information and resources through social networks and facilitate the solution of common technological problems [26]. Network relationships and structural characteristics reflect that inventors have relational and structural capital in their social networks [27]. The network relationships and structural characteristics of partners reflect the second-order relational and structural capital possessed by the focal inventor [18]. Therefore, the network relationships and structural characteristics of partners may have an impact on the innovation persistence of the focal inventor. This study uses network centrality to measure a focal inventor's partners' network relationship characteristics and structural holes to measure network structure characteristics.

Partners' network centrality has a significant impact on focal inventors' innovation activities. When partners' network centrality is low, it is difficult for focal inventors to access more potential indirect network resources through partners, thus making it difficult to carry out continuous innovation activities. As partner centrality increases, focal inventors can not only access more valuable technological resources, but also broaden the resource boundaries [20,28], which enhances the motivation and sustainability of innovation. However, when partner centrality is increased to a certain level, a further increase will be detrimental to the focal inventors' continuous innovation [18]. On the one hand, a high level of partners' network centrality generates excessive social resources, and focal inventors need to spend more time to identify and extract useful information, which increases the knowledge management cost and leads to diminishing marginal benefits of continuous innovation. On the other hand, a high level of partners' network centrality also creates the risk of knowledge path dependence and network lock-in, which reduces the motivation and continuity of focal inventors to innovate on their own [29]. Therefore, a moderate level of partner centrality is more conducive to sustained innovation than a low or high level of partner centrality.

Structural holes refer to the absence of direct connections between two or more actors (or nodes) in an inventor network, requiring other actors to serve as bridges to establish the indirect connections [17,30]. As a result, these actors, known as structural hole spanners, occupy bridging positions between unconnected actors, thereby enabling them to access more heterogeneous information from non-redundant sources. Moreover, partners' structure holes can facilitate a new round of knowledge diffusion, thereby improving the access and control of second-order network resources by focus inventors, which is conducive to the development of sustainable innovation activities [31]. On the contrary, a lower level of structural holes may lead to knowledge redundancy, which increases the cost of knowledge management for focus inventors and weakens the enthusiasm of inventors to carry out continuous innovation activities. Therefore, the increase in the number of partner structural holes can provide inventors with more heterogeneous resources, help them gain competitive advantages, and leverage them, thereby promoting their innovation sustainability [32]. Hence, the following hypotheses are proposed:

H1a. There is an inverted U-shaped relationship between the partners' network centrality and the focal inventor's innovation persistence: the focal inventor's innovation persistence first increases and then decreases as his/her partners' network centrality.

H1b. Partners' structural holes are positively associated with a focal inventor's innovation persistence.

2.2. Partners' network characteristics and the diversity and novelty of knowledge recombination

Knowledge recombination refers to the process of integrating the knowledge of different technological fields, while the knowledge recombination ability refers to the focal inventor's ability to recombine the knowledge of other inventors in the cooperative network to form diverse and novel knowledge portfolios [33,34]. The research on the functional mechanism of innovation networks shows that network relationships and structural characteristics affect the inventors' knowledge search and recombination [35]. In a co-inventor network, focal inventors directly access innovation resources in the network through their partners. Therefore, the extent to which a focal inventor benefits from knowledge recombination depends not only on its direct partnerships but also on its indirect relationships, specifically the partnerships of its partners [36]. Based on this viewpoint, this paper aims to explore the impact of the focal inventor's partners' network centrality and structural hole on the diversity and novelty of knowledge recombination.

Highly centralized partners usually have a strong knowledge base, which is conducive for focal inventors to generate new and diverse knowledge recombination. In addition, the influence and popularity of highly core partners in the co-inventor network are also increasing [37], which means they have a greater voice and access to resources throughout the cooperative network. In contrast to the peripheral inventors in the co-inventor network, highly core partners can not only gather information quickly and broadly, but also indirectly pass that information on to focal inventors [38]. In reality, a focal inventor's innovation is closely linked to their position within the co-inventor network. The focal inventors situated at the center of co-inventor networks are typically better equipped to access and comprehend the novel and diverse knowledge that flows through these networks [23]. Focal inventors with more central partners can identify and reconstruct the marginal knowledge within the co-inventor network due to their partners' strong interactions with others. Consequently, as the number of a focal inventor's core partners increases, the diversity and novelty of their knowledge recombination also improves.

However, with the further increase in the focal inventor's core partners, the over-centered partnership has the following negative effects. First, the incentive for focal inventors to seek external knowledge decreases. When working with highly central partners, focal inventors may perceive risk in the collaboration, fearing a loss of their relative advantage of network status and cooperative initiative [23]. Second, partners with high network centrality can impose disadvantages such as knowledge path dependency and knowledge redundancy [39], which limit the diversity and novelty of the knowledge reorganization [36].

Overall, for a focal inventor, choosing a partner with low centrality limits access to network resources. Although these partners may have a high motivation for knowledge recombination, their lack of network reach constrains the diversity and novelty of the focal inventor's knowledge reorganization. Conversely, selecting highly central partners enhances the ability to recombine network knowledge and resources, but the focal inventor's motivation may be lower, resulting in less diverse and novel knowledge recombination. Opting for a partner with moderate centrality strikes a balance, providing the focal inventor with both high ability and high motivation to recombine knowledge effectively, avoiding path dependency and knowledge redundancy, and thereby positively influencing the diversity and novelty of knowledge reorganization. We therefore propose:

H2a. There is an inverted U-shaped relationship between the partners' network centrality and the focal inventor's diversity of knowledge recombination: the focal inventor's diversity of knowledge recombination first increases and then decreases as his/her partners' network centrality.

H2b. There is an inverted U-shaped relationship between the partners' network centrality and the focal inventor's novelty of knowledge recombination: the focal inventor's novelty of knowledge recombination first increases and then decreases as his/her partners' network centrality.

Focal inventors leverage partnerships to access diverse and novel knowledge, significantly impacting the diversity and novelty of their knowledge recombination efforts. The collaboration network draws the attention of the focus inventor to the knowledge provided by his/her partners, and makes it prominent in knowledge recombination activities [19,40]. The partners' ability to filter and extract useful information, including their knowledge and the unique insights flowing from other inventors within the co-inventor network, becomes crucial.

Structural holes serve as a primary source of heterogeneous knowledge and facilitate the sorting out of non-redundant and useful information [17]. Exposure to unfamiliar knowledge and resources enhances the ability of inventors to recombine existing knowledge in novel and unique ways [41,42]. Consequently, partners' structural holes expand the focal inventor's capacity to access heterogeneous resources, resulting in a more diverse and novel mix of knowledge elements. Specifically, a focal inventor's partners spanning more structural holes can bridge different parts of the co-inventor network and access a broader range of resources [43].

Moreover, as the partners' structure holes increase, the motivation of focal inventors to access and recombine external knowledge also increases. The partners' structure holes increase the focal inventor's efficiency of accessing valuable heterogeneous knowledge, and reduce a large amount of knowledge redundancy cost for the focal inventor [14,17]. Meanwhile, inventors with high structural holes usually have strong innovation experience in knowledge integration and can understand the knowledge of other inventors relatively highly. Hence, the partners' increased structure holes can not only facilitate their knowledge recombination, but also positively affect the focal inventor's knowledge recombination. We therefore propose:

H2c. Partners' structural holes are positively associated with the focal inventor's diversity of knowledge recombination.

H2d. Partners' structural holes are positively associated with the focal inventor's novelty of knowledge recombination.

2.3. The diversity and novelty of knowledge recombination and innovation persistence

According to knowledge recombination theory, the generation of technological innovation largely depends on the recombination of knowledge elements, which involves establishing or altering the dependencies among these elements [44]. During the process of recombination innovation, inventors must reallocate innovation resources and knowledge, with varying knowledge recombination capabilities leading to different innovation outcomes [45]. This study, grounded in knowledge reorganization theory, explores how the diversity and novelty of the dependencies between knowledge elements impact the focal inventor's innovation persistence.

The diversity of knowledge recombination refers to the diversity of ways in which knowledge elements can be recombined, exploring their diverse interdependencies. Existing research suggests that highly diverse knowledge recombination exerts a positive impact on innovation persistence, reflected in both the potential and realization of diverse knowledge portfolios [34].

Firstly, the diversity of knowledge recombination positively impacts the combined potential of knowledge elements. Inventors can combine knowledge elements in various ways, increasing the likelihood of continuous innovation. Secondly, the diversity of knowledge reorganization enriches the inventors' cognition and thinking related to technological innovation while also broadening the innovation space [46]. From a knowledge network perspective, diverse knowledge recombination promotes interactions between knowledge elements, which focal inventors can leverage to enhance their knowledge availability and innovation capabilities [47]. Therefore, increasing the diversity of knowledge portfolios makes it more likely for inventors to improve and break through existing knowledge combination paths, leading to technological advancement and development. Furthermore, a deeper understanding of the interactions between knowledge elements enables focal inventors to better understand and utilize their partners' knowledge resources, potentially improving the efficiency of the co-inventor network [48].

The novelty of knowledge recombination involves the process of integrating previously uncombined but familiar knowledge elements, or combining new knowledge elements with familiar ones in new ways, to create high-value inventions [16]. This process encompasses the exploration, acquisition, development, and implementation of new knowledge and ideas by inventors, as well as the updating and expansion of knowledge combination relationships.

The novelty of knowledge recombination plays a crucial role in promoting innovation persistence. By exploring new dependencies between different knowledge elements, inventors can update the interaction between knowledge elements, thereby generating new knowledge portfolios. This new combination facilitates the development of new technological solutions, providing a constant impetus for innovation. Additionally, existing studies show that the novelty of knowledge recombination is key to successful innovation [49]. More novel knowledge portfolios, particularly those combining familiar elements in new ways, not only increase the potential for reusing old knowledge elements but also enhance the usefulness of new inventions and the likelihood of breakthrough technologies [50,51]. Therefore, the novelty of knowledge recombination is of great significance for improving the success rate of innovation. We therefore propose:

H3a. The focal inventor's diversity of knowledge recombination is positively associated with innovation persistence.

H3b. The focal inventor's novelty of knowledge recombination is positively associated with innovation persistence.

2.4. *The mediation effect of diversity and novelty of knowledge recombination*

According to Hypotheses H1a, H2a, and H3a, partners' network centrality affects the diversity of knowledge recombination and innovation persistence in a curvilinear way, with the diversity of knowledge recombination mediating the inverted U-shaped relationship between partners' network centrality and innovation persistence. Similarly, according to Hypotheses H1a, H2b, and H3b, the novelty of knowledge recombination mediates the inverted U-shaped relationship between partners' network centrality and innovation persistence.

According to Hypotheses H1b, H2c, and H3a, partners' structure holes positively affect the diversity of knowledge recombination and innovation persistence, and the diversity of knowledge recombination plays a mediating role in the positive relationship between partners' structure holes and innovation persistence. Similarly, Hypotheses H1b, H2d, and H3b indicate that the novelty of knowledge recombination mediates the positive relationship between partners' structure holes and innovation persistence. In other words, partners' structure holes affect innovation persistence through the positive effect of the novelty of knowledge recombination. We therefore propose:

H4a. The relationship between partners' network centrality and the focal inventor's innovation persistence is mediated by the focal inventor's diversity of knowledge recombination.

H4b. The relationship between the partners' structural holes and the focal inventor's innovation persistence is mediated by the focal inventor's diversity of knowledge recombination.

H4c. The relationship between partners' network centrality and the focal inventor's innovation persistence is mediated by the focal inventor's novelty of knowledge recombination.

H4d. The relationship between the partners' structural holes and the focal inventor's innovation persistence is mediated by the focal inventor's novelty of knowledge recombination.

Based on the above theoretical analyses and hypotheses, the research model of this study is shown in Fig. 1.

3. Methodology

3.1. *Data and sample*

This study focuses on inventors in the lithography-technology industry and examines the effects of partners' network centrality and structural holes on the focal inventor's innovation persistence. The lithography technology field is highly dynamic, characterized by technological advancements and significant interactions among multiple technological fields and inventors. Consequently, it exhibits complex co-inventor networks, numerous knowledge portfolios, and frequent instances of innovation persistence. Our main dependent, independent, and mediating variables are calculated based on lithography-technology patent data. Despite the limitations of patent-based indicators, a substantial body of research has validated their use as proxies for evaluating innovation activity [15,36,52].

We collected the lithography-technology patents data from the extensively utilized Derwent Innovation Index database (DII). This database stands as one of the most comprehensive patent databases globally, encompassing patent information from over 100 countries and 40 patent authorities, including USPTO, EPO, JPO, and so on. Therefore, lithography-technology patents sourced from this database can offer a robust reflection of the global technological development within this field.

To accurately identify and retrieve lithography-technology patents from the DII database, we developed a comprehensive search strategy using keywords and International Patent Classification (IPC) codes, as shown in Table 1. Retrieval was conducted in January 2024, focusing on patents granted between 2000 and 2023. We selected the year 2000 as the beginning year and utilized a rolling 5-year window (i.e., 2005–2009, 2006–2010, …, 2019–2023) as the observation period because there were fewer patents during 2000–2004. Following meticulous data cleaning procedures, we obtained a final dataset comprising 19,874 patents and 6820 inventors within the lithography-technology technology field."

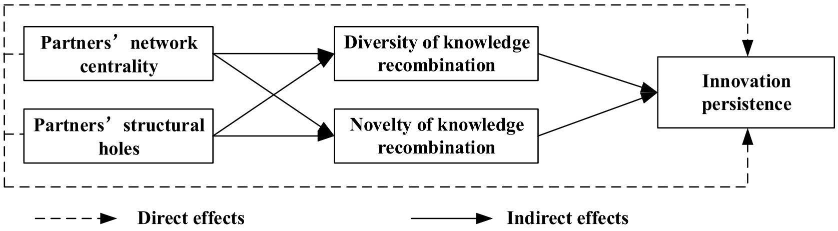

Fig. 1. Research model.

Table 1
Search strategy for lithography-technology patents.

NO	Search terms
#1 keywords search	TS= ((“lithograph” or “lithography” or “microlithograph” or “photolithograph” or “photolithography” or “stepper” or “scanner” or “step-and-repeat” or “step-and-scan”) and (“mask” or “photomask” or “lens” or “resist” or “photoresist” or “duv” or “euv” or “extreme ultraviolet”)))
#2 IPC search	IP= (“H01L*” or “G02B*” or “G03B*” or “G03F*”)
#3	#1 AND #2

3.2. Variables

3.2.1. Dependent variable

Following the procedure described in Roper & Hewitt-Dundas (2008), we calculate the focal inventor’s innovation persistence, which combines the number of lithography-technology patents filed by the focal inventor in three consecutive periods [53]. As shown in Eq. (1), $PI_{i,t}$ refers to the innovation persistence of the focal inventor i during the period t; $PN_{i,t}$, $PN_{i,t-1}$, and $PN_{i,t-2}$ represent the number of lithography-technology patents filed by the focal inventor i during the t, $t-1$, and $t-2$ periods, respectively.

$$PI_{i,t} = \frac{PN_{i,t} + PN_{i,t-1}}{PN_{i,t-1} + PN_{i,t-2}} \times \left(PN_{i,t} + PN_{i,t-1}\right) \tag{1}$$

3.2.2. Independent variables

We employed two independent variables to examine our research hypotheses. The first independent variable is the partners’ network centrality, measured as the average degree centrality of the focal inventor’s partners. Degree centrality represents the number of partners directly connected to a focal inventor within the co-inventor network [18]. As indicated in Eq. (2), N refers to the number of the focal inventor’s partners; D_j refers to the degree centrality of the focal inventor’s partner j.

$$PC_i = \frac{1}{N}\sum_{j=1}^{N} D_j \tag{2}$$

The second independent variable is the partners’ structural holes, which were assessed by the average structural holes of the focal inventor’s partners. As indicated in Eqs. (3) and (4), PS_i represents the average structural holes of the focal inventor i’s partners; S_j represents the structural hole of the focal inventor’s partner j; P_{jk} refers to the proportion of inventor j’s collaborative relationship involved in contacting the inventor j, and the formula in parentheses denotes the proportion of the actor j’s connections that are directly or indirectly involved in the linkage with the actor k, which can be seen the constraint of i.

$$S_j = 2 - \sum_k \left(P_{jk} + \sum_{q \neq j \neq k} P_{jq} P_{qk}\right)^2 \tag{3}$$

$$PS_i = \frac{1}{N}\sum_{j=1}^{N} S_j \tag{4}$$

3.2.3. Mediating variables

The mediating variables in this study were the focal inventor’s diversity and novelty of knowledge recombination. The International Patent Classification (IPC) has been established as a valid proxy for knowledge elements and has been widely utilized in previous research to represent and construct knowledge networks [15,36]. In this study, the first 4 digits of the IPC classification number are employed to represent the knowledge elements. The diversity of knowledge recombination is measured using the information entropy method [18]. The measurement of the focal inventor’s diversity of knowledge recombination is expressed as Eq. (5), where KRD_i refer to the focal inventor i’s diversity of knowledge recombination, N means the number of knowledge combination pairs among the focal inventor’s existing knowledge elements, d_p represents the proportion of the focal inventor i’s patents in knowledge combination pair p.

$$KRD_i = \sum_{p=1}^{N} d_p \ln \frac{1}{d_p} \tag{5}$$

The novelty of knowledge recombination is indicated by the new knowledge combination pairs that are advanced, explored, and innovated in a focal inventor’s patents [54]. We compared knowledge combination pairs of a focal inventor’s patents in the present period t with all patents in the preceding aggregate period from 2005 to the year before the present period t. We calculated the number of patents occupying new knowledge combination pairs as the focal inventor’s novelty of knowledge recombination. For example, to obtain the focal inventor’s novelty of knowledge recombination in the period 2006–2010, we first collected the focal inventor i’s knowledge combination pairs in the period 2006–2010. Secondly, we obtain all knowledge combination pairs involved in the focal inventor i’s all patents in the period 2000–2005. Thirdly, comparing the focal inventor i’s knowledge combination pairs in the periods 2006–2010 and 2000–2004, we considered the knowledge combination pairs as newly explored if they were absent between 2000 and 2005, but appeared in the current period 2006–2010. Finally, we measured the novelty of knowledge recombination as the number of patents containing these newly explored knowledge combination pairs.

3.2.4. Control variables

This study also incorporates the following control variables, to account for interference from other factors. The ego-network size reflects the social resources possessed by the focal inventor and is measured by the number of partners. Knowledge stock is captured and measured by the number of IPC classifications of patents filed by the focal inventor between 2000 and the observation year. Prior innovation capacity is assessed by the number of patents filed by the focal inventor between 2000 and the current period. Inventor tenure is measured by the time elapsed between the year the inventor first filed a patent and the observation year.

3.3. Model estimation

While empirical studies have explored determinants of innovation persistence, there remains a dearth of empirical literature examining the impact of partners' network characteristics on the focal inventor's innovation persistence through changes in the focal inventor's diversity and novelty of knowledge recombination. First, we employed unbalanced panel data analysis to investigate the focal inventor's innovation persistence, encompassing both cross-sectional (inventor) and time series (years) dimensions. Second, the paper applies a panel ordinary least squares (OLS) regression model on the data to yield efficient coefficient estimates. Third, according to the results of the Hausman test ($p < 0.001$), we performed the individual fixed-effect models for our panel data. Further, the bootstrap resampling approach was widely utilized to adjust for the negative impacts of some issues, like heteroscedasticity and autocorrelation [14,38]. This statistical method can provide error estimates with high variability and minimal bias by resampling with replacement from original samples. Hence, we also applied the bootstrap resampling approach to regress the panel OLS models and computed the variance of all these estimates across 2000 replications. These procedures were implemented using Stata 17.0 for our models.

The paper utilizes five OLS function's conditional models of dynamic panel estimation. Eq. (6) and Eq. (7) are designed to test the impact of partners' network centrality and structure holes on innovation persistence, as proposed by Hypotheses H1a and 1b. Eq. (8) and Eq. (9) aim to check the impact of partners' network centrality and structural holes on the focal inventor's diversity and novelty of knowledge recombination, in line with Hypotheses H2a-d. Eq. (10) is formulated to verify Hypotheses H3a and H3b, which examine the impact of diversity and novelty of knowledge recombination on innovation persistence. The combined results of Eqs. (6)–(10) are essential for verifying Hypotheses 4a-d.

$$PI_{i,t} = \beta_0 + \beta_1 PC_{i,t} + \sum \beta_k Controls_{i,t} + \mu_i + \varepsilon_{i,t} \tag{6}$$

$$PI_{i,t} = \beta_0 + \beta_1 PC_{i,t} + \beta_2 PS_{i,t} + \sum \beta_k Controls_{i,t} + \mu_i + \varepsilon_{i,t} \tag{7}$$

$$KRD_{i,t} = \beta_0 + \beta_1 PC_{i,t} + \beta_2 PS_{i,t} + \sum \beta_k Controls_{i,t} + \mu_i + \varepsilon_{i,t} \tag{8}$$

$$KRN_{i,t} = \beta_0 + \beta_1 PC_{i,t} + \beta_2 PS_{i,t} + \sum \beta_k Controls_{i,t} + \mu_i + \varepsilon_{i,t} \tag{9}$$

$$PI_{i,t} = \beta_0 + \beta_1 PC_{i,t} + \beta_2 PS_{i,t} + \beta_3 KRD_{i,t} + \beta_4 KRN_{i,t} + \sum \beta_k Controls_{i,t} + \mu_i + \varepsilon_{i,t} \tag{10}$$

where i represents focal inventors, t indicates the observation period, $PI_{i,t}$ is the degree of innovation persistence, $PC_{i,t}$ is the focal inventor i's partners' network centrality in the observation period t, $PS_{i,t}$ is the focal inventor i's partners' structure holes, $KRD_{i,t}$ and $KRN_{i,t}$ refer to the diversity and novelty of knowledge recombination, respectively. $Controls_{i,t}$ represents a series of control variables, including the focal inventor's ego-network size (ENS), knowledge stock (KS), prior innovation capacity (PIC) and the tenure of the focal inventor, $(\phi_t + \varepsilon_{i,t})$ represents composite error term.

Table 2
Descriptive statistics.

Variables	Obs	Mean	Std. Dev.	Min	Max
(1) PI	31713	13.1081	18.1013	0.6667	529
(2) PC	31713	16.8551	14.2526	1.3333	177
(3) PS	31713	1.6656	0.2113	0.2422	1.9804
(5) KRD	31713	2.5279	3.8663	0	89
(4) KRN	31713	3.9283	3.7548	0	42.1135
(6) ENS	31713	14.0565	22.3986	1	300
(7) KS	31713	6.0350	3.8439	2	46
(8) PIC	31713	3.1221	6.2112	0	118
(9) Tenure	31713	9.0786	6.0236	1	32

4. Results

4.1. Descriptive statistics

Table 2 presents the descriptive statistics for our variables. The average value of innovation persistence (PI) is 13.1081, and the standard deviation is 18.1013, indicating that the distribution of inventors' innovation persistence in the sample is greatly dispersed. The mean value of partners' network centrality (PC) is 16.8551 and the standard deviation is 14.2526. Compared to innovation persistence, the volatility of partners' network centrality is slightly lower, but it also shows great differences in partners' network centrality between focal inventors.

The average value of partners' structural holes (PS) is 1.6656, and the standard deviation is 0.2113, suggesting relatively consistent, yet still varying, structural hole positions among focal inventors. The diversity of knowledge recombination (KRD) has an average value of 2.5279 and a standard deviation of 3.8663, indicating significant variation in knowledge recombination diversity among sample inventors. The novelty of knowledge recombination (KRN) has a mean value of 3.9283 and a standard deviation of 3.7548, indicating that the novelty of knowledge recombination of the sample inventors is relatively stable, but there is still a certain degree of variability.

The mean value of ego-network size (ENS) is 14.0565, with a standard deviation of 22.3986, indicating the great differences in the ego-network size of sample inventors. The mean value of knowledge stock (KS) is 6.0350 and the standard deviation is 3.8439, reflecting slight differences in the knowledge stock among sample inventors. The mean value of prior innovation capacity (PIC) is 3.1221 and the standard deviation is 6.2112, indicating large differences in prior innovation capacity among sample inventors. The average value of the focal inventor's tenure (Tenure) is 9.0786, and the standard deviation is 6.0236, showing the differences in tenure among sample inventors.

In summary, the descriptive statistical results reveal the distribution characteristics and differences among sample inventors in terms of innovation persistence, partners' network indicators, knowledge recombination, ego-network size, knowledge stock, prior innovation capacity, and inventors' tenure. These differences provide valuable information for subsequent statistical analyses and hypothesis testing.

4.2. Correlation analysis

We calculated Pearson correlation coefficients and the variance inflation factors (VIF) for the variables of interest, as displayed in Table 3.

The correlation coefficient between partners' network centrality (PC) and partners' structural holes (PS) and innovation persistence (PI) are 0.3438 and 0.2648 respectively, both significant at the 1 % level. This indicates that partners' network centrality and structural holes positively affect the focal inventor's innovation persistence. The correlation coefficient between the diversity (KRD) and novelty (KRN) of knowledge recombination and innovation persistence (PI) are 0.3157 and 0.5870 respectively, both significant at the 1 % level. This shows that the diversity and novelty of knowledge recombination are positively related to innovation persistence.

Although some variables exhibit moderate-to-high correlations, there is no multicollinearity because the Pearson correlation coefficients do not exceed 0.7 and the VIF values for the overall model do not exceed 10.

4.3. Regression

Table 4 presents the results of panel OLS regressions with fixed effects and bootstrap standard errors from the empirical analysis. Model 1 reports the results for innovation persistence, including all control variables. Model 2 adds the partners' network centrality and its square term. Model 3 incorporates the partners' structural holes, and Model 4 adds the diversity and novelty of knowledge recombination. In model 2, the coefficient for the square term of the focal inventor's partners' network centrality is negative and significant ($\beta = -0.0223$, $p < 0.01$). This supports Hypothesis H1a, indicating that the relationship between partners' network centrality and the focal inventors' innovation persistence can be described in an inverted U-shaped function. Hypothesis 1b predicts that

Table 3
Correlation analysis and VIF value.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) PI	1								
(2) PC	0.3438*	1							
(3) PS	0.2648*	0.6635*	1						
(5) KRD	0.3157*	−0.0321*	0.0251*	1					
(4) KRN	0.5870*	0.0988*	0.1086*	0.3374*	1				
(6) ENS	0.6292*	0.4613*	0.3335*	0.4681*	0.1915*	1			
(7) KS	0.5815*	0.1632*	0.1503*	0.6508*	0.3462*	0.6325*	1		
(8) PIC	0.4276*	0.1709*	0.1233*	0.4643*	0.1852*	0.5489*	0.4635*	1	
(9) Tenure	0.2879*	0.2486*	0.1744*	0.1513*	0.0492*	0.3039*	0.2237*	0.3885*	1
VIF		2.1400	1.8000	1.1800	1.9000	2.4700	2.4000	1.7200	1.2400

Notes:*p < 0.01.

Table 4
Panel OLS regression models with fixed effects and bootstrap standard errors (N = 31713).

Variables	PI				KRD			KRN		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
ENS	0.0124***	0.0109***	0.0109***	0.0089***	0.0039	0.0019	0.0020	0.0026***	0.0021***	0.0021***
	(0.0007)	(0.0007)	(0.0007)	(0.0006)	(0.0028)	(0.0028)	(0.0029)	(0.0005)	(0.0005)	(0.0005)
KS	0.0673***	0.0679***	0.0674***	0.0440***	0.2464***	0.2460***	0.2438***	0.1199***	0.1199***	0.1195***
	(0.0028)	(0.0027)	(0.0027)	(0.0030)	(0.0167)	(0.0163)	(0.0171)	(0.0027)	(0.0027)	(0.0028)
PIC	−0.0175***	−0.0165***	−0.0164***	−0.0129***	−0.0553***	−0.0533***	−0.0529***	−0.0068***	−0.0064***	−0.0063***
	(0.0014)	(0.0013)	(0.0013)	(0.0013)	(0.0087)	(0.0089)	(0.0087)	(0.0013)	(0.0013)	(0.0013)
Tenure	−0.0041**	−0.0063***	−0.0061***	−0.0054***	−0.0730***	−0.0756***	−0.0747***	0.0125***	0.0117***	0.0119***
	(0.0018)	(0.0018)	(0.0017)	(0.0016)	(0.0116)	(0.0121)	(0.0116)	(0.0013)	(0.0014)	(0.0013)
PC		0.1149***	0.0844***	0.0904***		0.0148***	0.0043		0.0033***	0.0011
		(0.0119)	(0.0128)	(0.0119)		(0.0043)	(0.0049)		(0.0006)	(0.0007)
PC^2		−0.0223***	−0.0171***	−0.0166***		−0.0553***	−0.0297**		−0.0106***	−0.0053***
		(0.0031)	(0.0029)	(0.0027)		(0.0139)	(0.0143)		(0.0021)	(0.0020)
PS			0.2003***	0.1483***			0.9804***			0.2020***
			(0.0488)	(0.0440)			(0.2961)			(0.0416)
KRD				0.0221***						
				(0.0013)						
KRN				0.0365***						
				(0.0040)						
Constant	1.8356***	1.8917***	1.5537***	1.6139***	3.2222***	3.0755***	1.5974***	0.1349***	0.1024***	−0.2021***
	(0.0220)	(0.0227)	(0.0829)	(0.0755)	(0.1319)	(0.1330)	(0.4660)	(0.0211)	(0.0210)	(0.0636)
Year	N	N	N	N	N	N	N	N	N	N
Individual	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
R-squared	0.3667	0.3764	0.3775	0.4231	0.0592	0.0603	0.0611	0.4748	0.4767	0.4780
Wald chi2	1365.11	1987.15	2251.10	3155.92	374.61	405.42	383.32	2531.26	2734.57	2796.76

Standard errors are in parentheses ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

partners' structural holes would positively associate with the focal inventor's innovation persistence. The regressions in model 3 confirm this, showing that partners' structural holes are statistically significant and positively related to innovation persistence ($\beta = 0.2003$, $p < 0.01$). Thus, Hypothesis H1b is supported by the results displayed in Table 4.

To test Hypotheses 2a-d, Model 5 reports the results for the diversity of knowledge recombination that includes only control variables, Model 6 incorporates partners' network centrality and its square term, and Model 7 incorporates partners' structural holes. In parallel, Model 8 reports the results for the novelty of knowledge recombination that includes only control variables, Model 9 incorporates partners' network centrality and its square term, and Model 10 incorporates partners' structural holes. In Models 6 and 9, we find that partners' network centrality has an inverted U-shaped effect on the diversity and novelty of knowledge recombination (Model 6: $\beta = -0.0553$, $p < 0.01$; Model 9: $\beta = -0.0106$, $p < 0.01$). Hence, Hypotheses 2a and 2c were supported. In Models 7 and 10, we find that partners' structural holes positively affect the diversity and novelty of knowledge recombination (Model 7: $\beta = 0.9804$, $p < 0.01$; Model 10: $\beta = 0.2020$, $p < 0.01$). Hence, Hypotheses 2b and 2d were supported.

Hypotheses 3a and 3b propose that the diversity and novelty of knowledge recombination positively affect innovation persistence. In model 4, the coefficients of the focal inventor's diversity and novelty of knowledge recombination are positive and significant (KRD: $\beta = 0.0221$, $p < 0.01$; KRN: $\beta = 0.0365$, $p < 0.01$). Hence, Hypotheses 3a and 3b were supported.

To test Hypotheses 4a-4d, the study first regressed focal inventors' innovation persistence on the partners' network centrality and structural hole. Secondly, it regressed focal inventors' innovation persistence on the diversity and novelty of knowledge recombination. Thirdly, it regressed the diversity and novelty of knowledge recombination on the partners' network centrality and structural holes. In the first and second steps, the results demonstrated in models 2, 3, and 4 (Table 4) strongly support Hypotheses 1a, 1b, 3a, and 3b. In the third step, the results of models 6, 7, 9, and 10 strongly support Hypotheses 2a-2d. Moreover, compared to the results in Models 3 and 4, the absolute value of the coefficient of the square term of partners' network centrality ($\beta = -0.0166$, $p < 0.01$) is reduced by 0.0005, and the coefficient of partners' structure holes ($\beta = 0.1483$, $p < 0.01$) is decreased by 0.052. This means that the diversity and novelty of knowledge recombination partly mediate the relationship between partners' network characteristics (network centrality and structural holes) and the focal inventor's innovation persistence. Hence, our combined results support Hypotheses 4a-d.

The study further assessed the size of four indirect effects by using the bootstrap resampling method and constructing a 90 % confidential interval. Following 2000 simulations, the results are shown in Table 5. We compare the direct and indirect effects of partners' network centrality and structural holes on innovation persistence.

The indirect effects of partners' network centrality on innovation persistence through the diversity and novelty of knowledge recombination are 0.0032 and 0.0508, respectively, and the 90 % confidential interval does not contain 0. The direct effect of the partners' network centrality square term (0.2793) is stronger than its indirect effect. The indirect effects of partners' network centrality square term on innovation persistence through the diversity and novelty of knowledge recombination are −0.0031 and −0.0163, respectively, and the 90 % confidential interval does not contain 0. The direct effect of the partners' network centrality square term (−0.0284) is stronger than its indirect effect. The results indicate that the diversity and novelty of knowledge recombination play important roles in the curvilinear relationship between partners' network centrality and the focal inventor's persistence.

Similarly, the indirect effects of partners' structural holes on the focal inventor's innovation persistence through the diversity and novelty of knowledge recombination are 0.0096 and 0.1413, and the 90 % confidential interval does not contain 0. The direct effect of partners' structural holes on the focal inventor's innovation persistence (0.7215) is stronger than its indirect effect, which illustrates that the effects of partners' structural holes on innovation persistence are partly mediated by the diversity and novelty of knowledge recombination. In sum, these results indicate the effects of two types of partners' network characteristics on the focal inventor's innovation persistence are significant, and these effects are mediated by the focal inventor's diversity and novelty of knowledge recombination.

4.4. *Robustness*

We also did some robustness checks. The two-way fixed-effect model not only considers individual-fixed effects but also time-fixed effects, which can deal with the problem of missing variables that do not change over time. To make the results more meaningful and robust, we conducted the two-way fixed-effect model with a bootstrap resampling approach to test our hypotheses. As shown in Table 6, the results are consistent with the findings in Table 4, which mean that the results are robust.

Table 5

The effects of partners' network centrality and structural holes on innovation persistence.

Groups	Bootstrap 90 % Confidence Interval (CI)			
	Effects	Standard Error	LLCI	ULCI
PC→PI	0.2793	0.0045	0.2720	0.2867
PCˆ2→PI	−0.0284	0.0017	−0.0312	−0.0256
PC→KRD→PI	0.0032	0.0010	0.0016,	0.0048
PC^2→KRD→PI	−0.0031	0.0005	−0.0040	−0.0023
PC→KRN→PI	0.0508	0.0035	0.0451	0.0566
PC^2→KRN→PI	−0.0163	0.0017	−0.0191	−0.0135
PS→PI	0.7215	0.0140	0.6987	0.7444
PS→KRD→PI	0.0096	0.0020	0.0064	0.0129
PS→KRN→PI	0.1413	0.0083	0.1276	0.1551

Table 6
Results of robustness test (N = 31713).

Variables	PI				KRD			KRN		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
ENS	0.0123***	0.0108***	0.0108***	0.0087***	0.0039	0.0019	0.002	0.0029***	0.0021***	0.0021***
	(0.0006)	(0.0007)	(0.0007)	(0.0006)	(0.0027)	(0.0028)	(0.0028)	(0.0005)	(0.0005)	(0.0005)
KS	0.0658***	0.0663***	0.0659***	0.042***	0.2473***	0.2468***	0.2447***	0.1161***	0.1164***	0.116***
	(0.0027)	(0.0027)	(0.0027)	(0.0031)	(0.0167)	(0.017)	(0.0167)	(0.0025)	(0.0025)	(0.0025)
PIC	−0.0177***	−0.0167***	−0.0166***	−0.013***	−0.0551***	−0.053***	−0.0526***	−0.0069***	−0.0064***	−0.0063***
	(0.0014)	(0.0014)	(0.0014)	(0.0013)	(0.0087)	(0.0088)	(0.0088)	(0.0012)	(0.0012)	(0.0012)
Tenure	−0.0072***	−0.0088***	−0.0087***	−0.0133***	−0.0708***	−0.0728***	−0.0724***	0.0394***	0.0386***	0.0387***
	(0.0017)	(0.0017)	(0.0017)	(0.0017)	(0.011)	(0.0109)	(0.0106)	(0.0013)	(0.0014)	(0.0013)
PC		0.0082***	0.0061***	0.0063***		0.0151***	0.0044		0.0042***	0.0026***
		(0.0008)	(0.0009)	(0.0009)		(0.0044)	(0.0049)		(0.0006)	(0.0007)
PC∧2		−0.0231***	−0.018***	−0.017***		−0.0563***	−0.0302**		−0.0122***	−0.008***
		(0.0031)	(0.0031)	(0.0027)		(0.0141)	(0.0136)		(0.002)	(0.002)
PS			0.1938***	0.1487***			0.9924***			0.1568***
			(0.0494)	(0.0444)			(0.2962)			(0.0395)
KRD				0.022***						
				(0.0013)						
KRN				0.0385***						
				(0.0046)						
Constant	1.9471***	1.8636***	1.5717***	1.6219***	3.1229***	2.9719***	1.4771***	0.1872***	0.1438***	−0.0924
	(0.0217)	(0.0225)	(0.0769)	(0.0684)	(0.1499)	(0.1473)	(0.4756)	(0.021)	(0.0205)	(0.0609)
Year	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Individual	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
R-squared	0.3739	0.3839	0.3849	0.4302	0.0635	0.0646	0.0654	0.5942	0.5972	0.598
Wald chi2	1534.88	2503.27	2335.43	3577.12	492.56	498.53	564.87	6299.85	6776.20	7136.05

Standard errors are in parentheses $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

4.5. Endogeneity

The possibility may exist that innovation persistence influences the diversity and novelty of knowledge recombination as well as the diversity and novelty of knowledge recombination influences innovation persistence. We tested this by re-estimating the models with a control function approach (CFA) using instrumental variables. Firstly, we applied a Hausman test, which results found that the diversity of knowledge recombination ($\chi^2 = 1165.31$, $p < 0.01$) and the novelty of knowledge recombination ($\chi^2 = 287.65$, $p < 0.01$) has endogeneity problems. This means that the instrumental variables approach should be adopted. Secondly, the existing research has suggested that the degree centrality of focal inventors in collaboration networks and knowledge networks would influence technology innovation by influencing the diversity and novelty of knowledge recombination [21,47]. Hence, we used the focal inventor's collaboration network centrality (CNC) and knowledge network centrality (KNC) as exclusive instruments. The results of CFA model regressions are shown in Table 7.

In Table 7, Models 1 and 2 show the results of the first stage of CFA, which shows that collaboration network centrality has a positive effect on the diversity and novelty of knowledge recombination ($\beta = 0.0028$, $p < 0.01$; $\beta = 0.0066$, $p < 0.01$), while knowledge network centrality negatively affects the diversity and novelty of knowledge recombination ($\beta = -0.0017\beta$, $p < 0.01$; $\beta = -0.0059$, $p < 0.01$). In addition, the results of Models 1 and 2 also show that partners' network centrality has an inverted U-shaped effect on the diversity and novelty of knowledge recombination, and the partners' structural holes have a positive impact on the diversity and novelty of knowledge recombination. These results are consistent with our previous findings.

Models 3–5 introduce the first-stage residuals of CFA as new explanatory variables, thus obtaining the results of the second stage of CFA. The results of Models 3–5 show that the coefficients of partners' network centrality, partners' structure holes, and the diversity and novelty of knowledge recombination are consistent with the previous findings. Therefore, The CFA results further confirm the previous findings.

5. Discussion

We began this paper with the intriguing purpose of exploring the relationship between partners' network characteristics, knowledge recombination, and innovation persistence. Extensive research has highlighted the pivotal role of collaboration networks in

Table 7
Results of endogeneity test (N = 31713).

Variables	First stage		Second stage		
	KRD	KRN	PI		
	(1)	(2)	(3)	(4)	(5)
ENS	−0.002***	−0.0032***	0.0124***	0.0109***	0.0101***
	(0.0007)	(0.0004)	(0.0002)	(0.0002)	(0.0002)
KS	0.0382***	0.0776***	0.0673***	0.0674***	0.0577***
	(0.002)	(0.0013)	(0.0012)	(0.0012)	(0.0014)
PIC	−0.0079***	−0.0065***	−0.0175***	−0.0164***	−0.015***
	(0.0008)	(0.0005)	(0.0006)	(0.0006)	(0.0006)
Tenure	−0.0176***	0.0032***	−0.0041***	−0.0061***	−0.006***
	(0.0011)	(0.0007)	(0.0008)	(0.0008)	(0.0008)
PC	0.0239**	0.0116*		0.0844***	0.0871***
	(0.0093)	(0.006)		(0.007)	(0.007)
PC∧2	−0.0066***	−0.0021		−0.0171***	−0.0169***
	(0.0021)	(0.0014)		(0.0016)	(0.0016)
PS	0.0916**	0.138***		0.2003***	0.1797***
	(0.0377)	(0.0243)		(0.0282)	(0.0282)
KRD					0.0075***
					(0.0018)
KRN					0.0159***
					(0.0013)
CNC	0.0028***	0.0066***			
	(0.0006)	(0.0004)			
KNC	−0.0017***	−0.0059***			
	(0.0002)	(0.0001)			
First-stage residual(M1)			0.1161***	0.1161***	0.08***
			(0.0049)	(0.0048)	(0.0105)
First-stage residual(M2)			0.3103***	0.3103***	0.2424***
			(0.0076)	(0.0075)	(0.0094)
Constant	1.3251***	0.8523***	1.8356***	1.5537***	1.5836***
	(0.0709)	(0.0458)	(0.0091)	(0.0485)	(0.0486)
Observations	31713	31713	31713	31713	31713
R-squared	0.0828	0.5301	0.4258	0.4366	0.4404
F	7.59	5.42	5.82	5.59	5.32

Standard errors are in parentheses ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

fostering technological innovation [11,32,36]. In response, scholars have begun to probe into the influence of focal innovators' different network characteristics on their innovation performance. This study specifically focuses on partners' network centrality and structural holes, delineating their distinct and direct or indirect effects on the focal inventor's innovation persistence. In particular, we assessed the diversity and novelty of knowledge recombination as mediators of each influence.

The results of our study lead to several conclusions. First, the partners' network centrality exerts an inverted U-shaped effect on the focal inventor's diversity and novelty of knowledge recombination, as well as innovation persistence. This indicates that both excessively low or high levels of partners' network centrality impede the focal inventor's ability to achieve diverse and novel knowledge recombination and maintain innovation persistence. Conversely, a moderate level of partners' network centrality maximizes these outcomes, resulting in optimal innovation persistence. Second, partners' structural holes enhance the diversity and novelty of the focal inventor's knowledge recombination as well as innovation persistence. Third, the diversity and novelty of knowledge recombination positively influence innovation persistence and partly mediate the relationships between partners' network characteristics (network centrality and structural holes) and the focal inventor's innovation persistence.

These conclusions offer several theoretical contributions. Firstly, while prior important work has shown a relationship between the focal inventor's network relational and structural characteristics on innovation performance [14,31,37], this study provides fresh insights into the relationships between partners' network characteristics and innovation persistence. We extend these findings in two ways: First, we empirically examine the hypotheses regarding the effects of partners' network relational and structural characteristics on innovation persistence. Drawing on innovation theory, we explore how the focal inventor's innovation persistence varies based on two types of partners' network characteristics. Second, we contribute to the integration of innovation network theory and social capital theory. Partners' network relational and structural characteristics represent the focal inventor's second-order social capital [18]. This paper shows how the focal inventor can gain resources through second-order social capital, offering empirical evidence with implications for managing partnerships and enhancing innovation persistence.

Secondly, this study contributes to the theories of the effects of knowledge recombination on innovation persistence. Previous research on recombination innovation has proposed that successful innovation is the product of broader recombination as well as novelty [11,16,42,51]. However, there is a lack of literature on understanding why the diversity and novelty of knowledge recombination influence innovation persistence. To address this gap, we further innovation persistence research based on diverse and novel knowledge recombination. According to our findings, the diversity and novelty of knowledge recombination are critical antecedents of innovation persistence. This implies that researcher should carefully consider the configuration of their knowledge portfolio and pursue diverse and novel knowledge portfolios.

Thirdly, this study extends prior research by examining knowledge recombination as a mediator of the effects of partners' network characteristics on innovation persistence. According to previous knowledge recombination research, collaboration networks can be one of the drives of knowledge recombination [20,35], while empirical work to address these issues is scant. Our study is the first to explore the mediating roles of the diversity and novelty of knowledge recombination, shedding light on the mechanism by which partners' network characteristics influence innovation persistence. The innovation network theory suggests that network relational and structural characteristics represent the actor's capacity to access diverse and novel resources [14,31], which in turn influences changes in the actor's knowledge recombination. Innovation comes about by recombining knowledge components [21,45]. Our analysis results reveal the significant mediating roles of knowledge recombination, highlighting the strong indirect effects of partners' network characteristics on innovation persistence. This underscores the importance of fostering knowledge recombination for sustaining innovation.

This study provides some practical implications. Many innovators may find that merely occupying specific network relational and structural characteristics is insufficient for innovation persistence. This study demonstrates that focal inventors' innovation persistence also depends on their partners' specific network relational and structural characteristics. For example, to enhance innovation persistence, focal inventors could select partners with moderate network centrality who also span large structural holes.

Secondly, the conclusions of our study show that the benefits created by partners' network characteristics do not directly influence the focal inventor's innovation persistence. Rather, the diversity and novelty of knowledge recombination partly mediate these benefits. Inventors could adopt these insights in the innovation process by not only paying attention to network characteristics their partners possess but also emphasizing the capacity of knowledge recombination. For instance, partners' network centrality has an inverted U-shaped influence on innovation persistence, which is largely through the diversity and novelty of knowledge recombination. Thus, focal inventors should leverage their partnerships to continuously introduce diverse and novel technological knowledge, which is conducive to sustaining innovation persistence.

This paper has the following shortcomings. First, this paper constructs the co-inventor network based on patent data in the field of lithography technology. Future research should expand these findings to other industries or organizations to ensure their reliability and generalizability. Second, this paper only considers the impact of partners' network relational and structural characteristics on the focal inventor's knowledge recombination and innovation persistence. Future research should explore the impact of other factors, such as the individual ability of partners, resource allocation, social capital, and educational background, on focal inventors' innovation persistence. Third, this paper calculates innovation persistence based on the number of focal inventors' patent applications. Future studies could use other indicators, such as innovation input and scientific publications, to measure innovation persistence. Additionally, innovation persistence can be categorized into different types, such as exploitative and exploratory innovation persistence, warranting further exploration of the mechanisms underlying continuous innovation.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Jinxing Ji: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The author(s) received no specific funding for this work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e33966.

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