Complexity

Public Policy Modeling and Applications 2021

Lead Guest Editor: Miguel Fuentes
Guest Editors: Claudio Tessone and Bernardo Alves Furtado

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Editorial
Public Policy Modeling and Applications 2021

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As editors, we are glad to publish "Public Policy Modeling and Applications 2021" as an extended effort that builds upon the original Special Issue [1]. Indeed, policymakers continue to face the difficulties and intricacies of tackling complex societal issues [2]. The magnitude, heterogeneity, and idiosyncrasies of societal problems make modelling purposeful questions a hard, wicked task [3,4]. Moreover, translating quantitative and computational methodologies, along with their uncertainties and embedded assumptions, into simple—at times one-page—narratives for policymakers' consumption may prove to be challenging [5]. Besides, only trying might already be informative [6].

We look forward to contributing innovative ideas in this interdisciplinary field, which we believe is fertile for productive interaction.

This Special Issue brings together research and reviews on modelling and applications of public policy. As it might be expected, the subject matter has been diverse. This shows us that despite the highly interdisciplinary nature of the field, there is fertile ground for furthering the application of the sciences of complexity, of social systems interacting with their environment, to policy making.

There are seven papers that simultaneously comprise different disciplinary areas, focusing on their interactions and effects for policy and policymakers, using a variety of methods. The papers discuss the following: (a) how infrastructure investments and increased mobility affect sector trade heterogeneously, or how further investments at the urban scale, in turn, might attract foreign money inversions; (b) how new technologies in industry lead to firms' innovation; and (c) how widespread bases of users might help betterment of service provision. Further complex interactions permeate the debate on (d) how network structures might prove relevant to analyze contagion and public health and countermeasures; (e) how easing communication between scientists and industrialists might foster innovation; and (f) how conversation among food suppliers and administrative political bodies purchasing might prevent waste. In what follows, we will comment on each of the projects. We hope that this is another step in igniting an active and motivating field for complexity researchers.

Transport has long been studied as a driver and large effect component on spatial concentration [7] and trade and agglomeration economies [8]. Quasi-experiments and econometrics have been applied to analyze highways and railways influence on economic growth in both China and Brazil and in urban and regional contexts [9, 10]. Previous results have confirmed heterogeneity of impact due to proximity, economic sectors, and mode, with a possible gain of agriculture in detriment of industrial activities [11]. The paper by J. Zhou et al. [12] adds to those previous investigations looking at the influence of high-speed railway systems (HSRSs) [13], with an emphasis on agriculture exports specifically. The relevance of HSRS for product transportation in China is explicit by the total of 35,000 km accrued from 2008 to 2019. The authors focus on two

mechanisms of influence of HSRS in agricultural firms: market access and siphon effect. Siphon effect refers to the relative advantage that regions with access to HSRS may have gains when compared to neighboring unserviced regions, displacing trade, rather than increasing productivity. J. Zhou et al. use a multiperiod difference-in-difference model coupled with an event analysis method that introduces dummies before and after policy events, akin to the study in [14]. Having confirmed growth in agriculture-related export (consistently at about 7%), the authors investigate further the leading mechanisms delving into heterogeneity of firms' ownership, development state, and regional context. The effect is found to be constrained to a distance of 45 km from the HSRS.

Ex-post enhancement of policy evaluation in an industry-government-innovation tripod is the theme of the paper by X. Wang and C. Jiang [15]. The authors advocate for Chinese subsidy for new energy vehicles (NEVs) claiming relevant spillovers for both industrial innovation [16] and sustainability gains. The claim suggests that entering the government promotion catalogue—and thus accessing posterior subsidies—imposes a beneficial technical threshold that helps focus innovation development. The authors test two mechanisms that would influence innovation, via profit increase or via reduction of financial constraints. They apply a multistage difference-in-differences model in a quasi-natural experiment that compares industries that have entered the catalogue and those that have not. Results suggest that receiving subsidies—for the NEV Chinese promotion policy—stimulated "radical innovation" via both mechanisms tested. Fang et al. reinforce the results, specifically when observing China's anticorruption campaign that began in 2012 [17].

Interaction among a multitude of agents is at the core of complex systems analysis [18]. Within a market context, these interactions are mediated by information in the face of asymmetry, full disclosure, and regulation [19]. However, online markets do not have the "touch and feel" experience agents use to discriminate products and embedded service, quality, prices, and value [20], meanwhile having more dynamic, flexible, and pulverized consumers and sellers. Y. Yan et al. propose a game-theoretical model to investigate whether a seller decision to participate in an online retailer distribution alliance (DA)—a logistic integrated solution—might be used to signal quality of sellers [21]. Y. Yan et al. find that a high level of certification accuracy along with an application fee is necessary for the sellers' participation in a DA to effectively have a signal effect. Moreover, the authors claim that "DA is a new and good innovation in logistics and e-commerce whose organizational characteristics make it a lubricant in the traditional supply chain structure" ([21], p. 12).

Yu et al. apply another quasi-experiment DID method to study correlation between a policy smart-city program in China and the quality of foreign investment received. Longitudinal and incremental data for a range of 226 prefecture-level cities allowed the authors to run a robust model that included a placebo test [22] and a heterogeneity analysis. They found that western cities—comparatively lacking in infrastructure relative to their eastern counterparts—perceived more improvement in quality of foreign investment. Finally, the authors report that level of wages played a negative and significant impact on the quality of foreign investment.

Understanding the evolution of infectious diseases is of global importance today [23]. The highly interconnected nature of our society clearly suggests that this requires an understanding of the constantly evolving topology of social networks. X. Wang et al. review the literature on social network analysis precisely to prevent and control epidemiological events. Factors such as network structure, prevention and control measures, and their comparison are analyzed in detail. They also suggest ways to improve dynamic network simulation and the application of inputs from COVID-19 to optimize future models of epidemic spread in social networks.

The innovation system of a state has two relevant actors: industries and universities. It has been suggested that an important part of the dynamics of the innovation economy is based on a virtuous relationship between these two types of institutions [24]. H. Fang et al. analyze how technology transfer in universities (TTU) and high-tech industries development (HTID) are coupled. They conduct this study with nine years of data from China. Their findings shed light on issues that may be of interest in other states. for example, the diversity of results and their remarkable differences, depending on the different regions of China. Also notable is the relationship between the mechanisms that exist in the high-tech industries (such as technological absorptive capacity or innovation) and the impact on the promotion of coupling coordination of TTU-HTID.

One of the world's long-standing problems has been the issue of food production and distribution. The impact of COVID-19 has shown the great fragility of the food system, revealing critical points in the production and supply chain [25]. All this adds up to low efficiency of the system, with one-third of food going to waste. In their paper "Promotion Strategy of Policy against Food Waste (PAFW): The Perspective on Evolutionary Game between Local Government and Large Supermarkets," Luo and Zhao show us an interesting approach that uses evolutionary game theory to attack this problem. Their results indicate that public policies would benefit greatly from including this type of approach, which ultimately involves coordination between governance systems, production systems, actors in the supply chain, and civil society [26–28].

Conflicts of Interest

The editors declare that they have no conflicts of interest regarding the publication of this Special Issue.

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Research Article

Using Distribution Alliance to Signal the Seller's Service Quality in Online Retailing Platforms

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Signal plays a significant role in the online retailing market, especially where the service quality of sellers is unobservable. In the current study, a game-theoretical model was formulated to help examine whether the new delivery service called distribution alliance in the electronic market can serve as a superior signal in revealing online seller's service quality. Our results showed that the certification accuracy and the application fee are closely related to the signaling effect of the distribution alliance. Specifically, we found a concrete analytical boundary where a certain high level of certification accuracy is required to guarantee the existence of market equilibrium, and a corresponding application fee can convoy the signal's effectiveness. In addition, the potential extensions and limitations of this research were also discussed.

1. Introduction

For nearly two decades, e-commerce has changed the landscape of retailing worldwide. On 03 May 2021, the United Nations Conference of Trade and Development (UNCTAD) released a report announcing the global online retailing sales rise from 16% of total retail sales in 2019 to 19% in 2020 driven by COVID-19, which equals 30% of global GDP in 2019 (1 UNCTAD, "Estimates of global e-commerce 2019 and preliminary assessment of COVID-19 impact on online retail 2020," https://unctad.org/node/32767, 2021-07-27). The development of online retailing platforms provides several opportunities for small businesses to establish online storefronts to capture more potential consumers [1]. In such a marketplace, the platforms sell not only their own products but also the web pages for other sellers (i.e., the contractual sellers) to peddle commodities. In fact, allowing contractual sellers to merchandise in an online platform creates significant uncertainty about the overall level of seller's service quality at the time of purchase [2]. To improve the situation where such uncertainty of the service quality might deteriorate consumer's shopping experience, the platform introduces the distribution alliance (DA), a platform-organized logistics service, to deliver merchandise to consumers for its contractual sellers.

DA is a logistics innovation to achieve economic efficiency in delivering products through flexible capacity, benefiting the online retailing platforms at both the strategic level and the operational level. In terms of the corporate strategy, DA is one of the tentative directions of green supply chain development where green production [3, 4], protection of the environment [5, 6], and recycling process [7, 8] are the common topics to follow up with the trend of sustainability [9]. It is a feasible solution for manufacturers and retailers to increase profits by improving service quality, reducing operational costs by covering the product returns, and performing environmental-friendly by adapting to the uncertainty in the demand side, simultaneously [10]. On the other hand, the operation mechanism of DA comes from inspirations of sharing economy, which is mainly based on a two-sided market structure. Online retailing platforms initiate and organize transportation resources by recruiting social capacity such as third-party logistics to provide delivery service between online sellers and consumers. For the delivery side, the platform posts recruitment conditions and

the corresponding subsidy to attract full-time deliverers or some drivers preferring part-time tasks. For the user's side, DA is packaged as an optional delivery service, behind which is a well-integrated logistics and information flow from the platform, aiming to improve the consumer experience during the process from shopping to after-sales service [11]. Through DA, online sellers hope to collect more visits, and consumers are seeking better services, and all of these expectations ultimately conclude on whether DA can signal out the seller's private information on service quality. In this paper, we study how DA can signal the service quality of contractual sellers in the online retailing platform where consumers cannot directly identify the service quality before purchase.

We interpret service quality generally to the online seller's performance on providing after-sale support. Such performance is things like order fulfillment, logistics, and availability of after-sale service, which could be only revealed after purchase. As the storefronts share the platform's corporate image, this results in the fact that the contractual seller's service quality, in turn, would influence the platform's reputation [12] (e.g., consumers tend to expect "amazon-style" services from the contractual sellers on Amazon.com; once they experience inadequate services, they might blame it on Amazon). As a large number of literature have shown, the uncertainty caused by information asymmetry would drive some potential consumers out of the market and preclude any gain from transactions [2, 13, 14]. In addition, signals have proven to be significant to reduce information friction and help consumers learn the service quality in online retailing markets [15]; however, the current signaling strategies seem to lose efficacy in differentiating contractual seller's service quality due to the low cost of imitating the storefront setting and service descriptions from each other [16]. Therefore, the platform is using DA to differentiate its contractual sellers in their service quality. That is, what DA is trying to signal is the correspondence between the expected service quality and what is offered by the contractual sellers. The typical DA offers standard logistics service, including the details of order fulfillment and a guarantee of the delivery time. Accordingly, it requires that the sellers who intend to join DA should offer quality service at the level declared by the platform and pay a fee of application. Currently, DA has been operated by some giant online retailing platforms, such as the service of Amazon Flex called Fulfillment by Amazon (FBA), Walmart's Spark Delivery, and Alibaba's Cainiao Alliance.

Our objective is to show that DA can be a valuable signal to reveal the contractual seller's service quality. In the process, the critical issue we address is to find the market equilibrium where only the sellers with quality service will join DA. To better understand the signaling mechanism, we build a static signaling model to shape the utility of consumers and the expected profits of the sellers. On this basis, achieving such equilibrium is to determine the consumer's belief in sellers' service quality in DA and the seller's decision to apply for a given DA service. When the equilibrium is achieved, consumers believe that a separation exists among the contractual sellers where the sellers joining in DA will provide high-quality service. At the same time, those being left outside DA will offer low-quality service. Besides, the equilibrium should also be stable for any contractual seller, which indicates that each deviation of this separation turns out unprofitable. However, there exists the fact that high-quality sellers might be rejected by DA, or low-quality ones might be included in DA, which will hurt the seller's profit or compromise the consumer's perceived utility. Such misidentification might eventually lead to the DA breakdown and calls for advisable mechanisms to ensure DA functioning as a signal. The direct way to reduce misidentification is to improve the accuracy of certification. The certification accuracy refers to the probability of the platform accurately distinguishing whether the seller's service quality meets the requirements. For a given accuracy, if the certification is successful, sellers with good service quality will gain their due profit, while those with low-quality service will lose their application investment. On the contrary, if it failed, the high-quality sellers will gain nothing but bear the cost of providing quality service and applying for DA, while the low-quality ones will obtain speculative profits. It follows that the higher the accuracy is, the more the high-quality sellers prefer to join DA. As seen in practice, however, it is not easy to standardize the service quality, which makes it challenging to eliminate the misidentification. On this basis, if the application is at no cost, there will always be a part of low-quality sellers who can get positive net profits through speculation, indicating that DA is invalid as a signal. Therefore, the application fee is necessary to perfect the signaling effect of DA. The platform charges an application fee collected at the application time which is nonrefundable to each applied seller according to the certification accuracy announced by itself. Specifically, the application fee should at least keep the sellers with low service quality from profiting from pretending high-quality sellers and applying for DA; however, if the platform charges too much, DA will be abandoned as it prevents sellers from any gain in joining in DA.

Additionally, DA has the characteristic of being a signal. First, a seller joining in DA will obtain an easy-to-observe digital label that can be confidently judged by the market participants. This observability has been proved to be the essential condition of a signal in prior studies [2, 17]. Second, DA is operated by the platform, possessing the platform's reputation endorsement. When consumers are willing to purchase products on one platform, DA can inherit the consumers' trust [18]. In addition, when a seller applies for DA service, the platform must examine its service quality. Such service quality is set as the seller's private information in this study which needs to be signaled out. As [14] states that quality can be identified by a unique separating equilibrium under a certain certification accuracy (called reputation therein), it suggests that a separating equilibrium may exist when the pricing of DA is sufficient to benefit the high-quality sellers and discourage the low-quality sellers.

Some issues related to the market equilibrium where DA works effectively as a signal are also included. First, the platform's revenue should be taken seriously. Previous

researches have shed much light on our investigation of platform profitability, including the construction of the platform's payoffs and the methods of equilibrium derivation. A profit function was used to characterize the platform's revenue in this paper, which is similar to those in most studies in the field of marketing and operational management. One recent example comes from [19], which proposed an optimal decision model with an objective function to maximize an enterprise's profit in a different context. The classical solution method in game theory (i.e., backward induction) was adopted to find the market equilibrium in this article, the guidance of which can be found in [20, 21], which provided standard game-theoretical analysis process in a business environment. In our scenario about DA, if the expected equilibrium is achieved, a set of combinations of application fee and certification accuracy will be generated, resulting in pricing issues. Therefore, it is of significant meaning, both theoretically and practically, to investigate the pricing strategies for providing DA service so that the platform can achieve optimal profits while driving DA to be an effective signal.

This study belongs to the literature on the signaling theory of service quality. Signaling theory provides a framework that explains how visible features are used to transfer limited quality information to promote an interaction [22]. In transaction-based relationships, signaling theory has been applied to distinguish the signals produced by the party with private information to reduce information asymmetry [23]. Consumers often lack information to accurately assess unfamiliar sellers' service quality before purchasing [16]. Therefore, they need signals to help identify the actual quality of sellers and their services. The standard to judge a signal's performance in reducing information asymmetry is to see whether it benefits good sellers while excluding poor sellers. That is, an efficient signal can lead to a separating equilibrium [24]. In contrast, a signal will lose efficacy when failing in separating the sellers [25]. In the current study, we concentrate on the DA's signaling effect in revealing the service quality of online contractual sellers, and the signaling theory provides an available method. Unlike most of the existing literature in this field, we characterize the payoffs of the game players by constructing profit functions instead of using the traditional utility functions, which makes it more intuitive to discuss the motivations of deviating the market equilibrium when considering distribution alliances. The pattern of profit-based modeling also helps business-level discussions and discover management insights. Besides, since the classical signal results from an observable effort made by players with private information, identifying DA—one service provided by a platform—as a signal is an innovative attempt of integrated applying of the signaling theory and secondary price discrimination in the theoretical field.

In e-commerce, signal theory can offer new insight for researches into seller's service quality [26]. Signals have been widely used to convey information about the quality of sellers and their services to consumers. The prior researches focused on the signaling effect of after-sales service [27, 28], brands [29–31], labels [17, 32], and return policies [33–35]. Specifically, the "touch and feel" experience is difficult to replicate online, creating uncertainty for consumers about seller quality and service quality [36, 37]. However, the lower entry cost in online markets and similar technology used in operating online shops have incurred additional uncertainty as the current signals become less costly to produce [16]. The service quality defined in this study is such a thing that is hard to perceive before purchasing and can be disclosure via a certain signal. Compared with the related researches, our study highlights the significant role of logistics service by concluding the signaling effect of DA, which contributes to both the fields of service quality and e-commerce. For service quality, the introduction of DA as a signal provides new operational guidance for sellers to differentiate their services. It also links the seller's selection of logistics service partners to its own service levels, providing a new path of interpretation to demonstrate online sellers' service quality. For literature about e-commerce, the results of the current paper could improve the operational efficiency of the online retailing marketplace in the practical context of developing the green supply chain, and the profitability of online platforms organizing DA was also discussed.

This study also contributes to the literature on parcel delivery systems. Nowadays, online retailing platforms are launching quality delivery services to improve consumer satisfaction [38], including establishing distribution alliances to deal with the "last mile" delivery. One of the first attempts to identify distribution alliances is [39] which investigates sufficient practical enterprises of distribution platforms. Then, a game-theoretic model aiming to analyze the operational mechanism of distribution alliance is proposed [40]. The results indicate that DA can play a role in pricing regulation and platform management. Following this stream, [10] presents a series of scenario-based pricing models for the platform to design pricing strategies, which complements and refines the existing researches about DA at the operational level. Compared to these researches, our paper explores the contribution of DA in reducing information asymmetry in online retailing marketplaces from the perspective of signaling effects, which enriches the content of platform operational strategies beyond pricing governance. In addition, it also confirms that DA can serve as an effective signal to convey the service quality of online sellers under certain conditions. Besides, it has been proved that consumers will feel more satisfied when offered quality delivery services [41, 42], which indicates that DA might obtain good responses from consumers.

In summary, this paper contributes to and extends the current literature in several ways. First, it extends the application of signaling theory by recognizing DA as a new signal in online retailing markets. Second, it develops a framework to help the platform make certification accuracy selection and pricing decisions. Third, we examine the signaling effect of DA, which shows the profitability of operating DA and the potential value of the platform's reputation. Finally, we make some comments on the platforms' and DA's operation.

We organize the remainder of this paper as follows. Section 2 introduces the methodology applied in this paper

briefly and presents the model settings. Section 3 reports the principal results, and Section 4 states managerial implications and limitations of the current study. Section 5 concludes the paper. Some supplements are in the Appendix.

2. Methodology

This paper aims to formulate the decision problem of online retailing platforms that offer distribution alliance services using the mathematical modeling. The problem is described as a constrained extreme value model based on a game-theoretic framework. With concerns of examining the signaling effect, our mathematical model of the game-theoretic optimization problem includes formulas that also have been discussed in the signaling games. The equations describing prices and profits are set for helping find a purely strategic Nash equilibrium satisfying signaling constraints.

2.1. The Service Quality. We start by considering an online retailing platform operating the DA service, enabling the DA a monopoly position. Meanwhile, the platform is populated by many sellers and consumers, which creates a perfectly competitive market environment. To simplify the impact of returns on the seller's expected profit, our model setting on the product is according to [14], where the value of products to sellers is normalized to zero. Similarly, the value of the products themselves is assumed to be zero to help to concentrate on the seller's service quality. Then, the product's value to consumers depends on the seller's service quality $\theta \in \{\theta_b, \theta_g\}$, which is determined by sellers privately. For the same product, sellers can provide the service of low-quality θ_b at no cost, which is worth 0 for consumers. Alternatively, they can offer quality service worth 1 to consumers and bear an extra cost λ, which is set as the seller's private information to keep in line with the common knowledge. We refer to λ as the "type" of the sellers and assume that λ follows a uniform distribution on $[0, 1]$ to highlight their heterogeneity. Obviously, providing quality service is profitable for any seller, even if they differ in how costly they choose high quality. In a signaling theory framework, when the service quality is public information, the market turns to be full of high-quality sellers. Conversely, if service quality is private information, they have to abandon the potential profit and choose low quality irrespective of their cost. As a result, the information asymmetry obstructs the market efficiency, which calls for useful signals. This fact incentivizes us to investigate the signaling effect of DA.

2.2. The Certification Processes. When a seller applies for DA service, the platform should conduct a quality test on its service. As the Cainiao Alliance and Amazon have done in operation, if a seller is allowed to join DA, he will obtain an observed label as DA. By contrast, sellers who are not in DA can only provide third-party logistics delivery service, which might be marked as TP. Denote by q the certification accuracy of DA, which refers to the probability that a seller's service quality is correctly recognized. This gives the following conditional distributions of the seller's service quality in DA:

$$\begin{aligned} \Pr\left(\mathrm{DA}|\theta_g\right) &= \Pr\left(\mathrm{TP}|\theta_b\right) = q, \\ \Pr\left(\mathrm{DA}|\theta_b\right) &= \Pr\left(\mathrm{TP}|\theta_g\right) = 1 - q. \end{aligned} \tag{1}$$

Besides, the platform charges an application fee ϕ. In signaling theory, ϕ can be recognized as the signaling costs. As well as in practice, it is analogous to the idea of slotting fee or entry fee. We make two related assumptions on the application fee. First, we impose that the fee is only charged for sellers. This assumption catches the fact that most platforms provide free access to consumers to attract more users. That is, the consumers' decisions are only based on the expected value of products obtained in different delivery services. Second, in line with common practice, we assume that the fee should be paid upfront and not be refunded. This precludes the incentives for DA to conspire with sellers. Moreover, it increases the signaling cost and helps reduce the possibility that the seller with low quality sends a wrong signal.

2.3. The Consumer Decision. The consumers own a belief about the proportion of sellers with high service quality in DA. Denote by α this belief, and α can be verified in the market equilibrium. In such a market, the consumers can obtain products valued $\alpha * 1 + (1 - \alpha) * 0 = \alpha$ from the DA-labeled sellers and obtain zero when choosing the TP service. It indicates that consumers will choose DA as long as they have a positive belief in DA ($\alpha > 0$). We denote by $d \in \{0, 1\}$ the consumer's demand for DA, which is characterized by α such that

$$\begin{cases} d = 1, & \text{if } \alpha > 0, \\ d = 0, & \text{otherwise.} \end{cases} \tag{2}$$

2.4. The Sequence of Events. The game develops as follows:

(1) The platform publishes the application fee ϕ and claims the certification accuracy q.

(2) Privately, sellers learn their cost λ and determine the service quality θ.

(3) Sellers decide whether to join DA or not.

(4) If a seller applies for the DA service, the platform tests the seller's service quality with a certification accuracy q and produces a label in {DA, TP} observable to all participants.

(5) Consumers purchase products.

The related notations are listed in Table 1.

3. Analysis and Results

We derive the equilibrium from studying how application fee and certification accuracy affect the decisions made by all the participants, as well as the platform's profit. The solving process draws upon a backward induction method. As discussed above, the consumers' issues are evident and brief.

Table 1: Notations used in the paper.

Variables	Description
θ	The seller's service quality, $\theta \in \{\theta_b, \theta_g\}$
λ	The seller's extra cost for providing high service quality, $\lambda \in U[0,1]$
$\overline{\lambda}$	The amount of sellers applying for distribution alliance with high service quality
q	The certification accuracy of the distribution alliance
Φ	The application fee for joining distribution alliance
α	The consumer's belief about the proportion of sellers with high service quality in distribution alliance
d	The consumer's demand for distribution alliance
γ	The fraction of sellers with low service quality who apply for distribution alliance
D	The seller's demand for distribution alliance
D_T	The total market demand for distribution alliance
π	The platform's expected profit of operating distribution alliance

Besides, the certification process requires no other decision. Therefore, we start with the sellers' movements.

3.1. The Seller's Demand for DA. A seller's decision on service quality and applying for DA can be jointly acquired in equilibrium. If the seller does not use DA service, he must choose low quality since providing quality service is both of high cost and unobservable. As a result, TP-labeled sellers can only price their products at zero. It suggests that sellers with high quality always prefer DA service and get expected profit $q - \lambda - \phi$ per product. Alternatively, sellers might try to cheat the certification system by applying DA with low quality. They certainly obtain zero when the actual quality is revealed. However, if it works, they may get the expected payoff $1 - q - \phi$ per product. Indeed, the seller can also stand away and get zero. To sum up, sellers will choose to provide high-quality service when and only when

$$q - \lambda - \phi \geq \max\{0,\ 1 - q - \phi\}. \tag{3}$$

Therefore, a critical value $\overline{\lambda}$ exists satisfying that below which each seller provides high service quality and prefers to join DA, while those above $\overline{\lambda}$ provide low service quality. Whether the sellers with poor service quality soliciting DA depends on their profitability. When $1 - q - \phi \geq 0$, they will adventure sending the fake signal to gain the speculative profit. In particular, these opportunistic sellers also contribute to the purchase of DA. To identify this demand, we denote by γ the fraction of sellers with low service quality who apply for DA. γ is determined by

$$\begin{cases} \gamma = 1, & \text{if } 1 - q - \phi \geq 0, \\ \gamma = 0, & \text{otherwise.} \end{cases} \tag{4}$$

Then, the sellers' demand for DA is

$$D = \overline{\lambda} + \gamma(1 - \overline{\lambda}). \tag{5}$$

By deriving the perfect Bayesian equilibrium, we obtain Propositions 1 and 2.

Proposition 1. *For any given certification accuracy $q \leq 1/2$, a unique perfect Bayesian equilibrium exists: (1) If $\phi \leq 1 - q$, then $\overline{\lambda} = 0$, $\gamma = 1$, and $D = 1$. (2) If $\phi > 1 - q$, then $\overline{\lambda} = 0$, $\gamma = 0$, and $D = 0$.*

Proposition 1 describes the perfect Bayesian equilibrium on the condition that the certification accuracy is low ($q \leq 1/2$). It shows that when the application fee is pricey ($\phi > 1 - q$), there are no demands of sellers for the DA, which means that all kinds of sellers choose third-party logistics delivery services. By contrast, if the application for the DA is not costly ($\phi \leq 1 - q$), all sellers will burst in it ($D = 1$). From Proposition 1, we find that all sellers make the same choice between the DA and the TP according to whether the application fee is low or not if the certification accuracy of the DA is low. It means that the DA with a low certification accuracy fails as a signal in conveying service quality, which indicates the significance of the certification accuracy in operating the DA service.

Proposition 2. *For a given certification accuracy $q > 1/2$, a unique perfect Bayesian equilibrium exists: (1) If $\phi \leq 1 - q$, then $\overline{\lambda} = 2q - 1$, $\gamma = 1$, and $D = 1$. (2) If $1 - q < \phi < q$, then $\overline{\lambda} = q - \phi$, $\gamma = 0$, and $D = q - \phi$. (3) If $\phi \geq q$, then $\overline{\lambda} = 0$, $\gamma = 0$, and $D = 0$.*

Proposition 2 shows the perfect Bayesian equilibrium on the condition under a high-level certification accuracy ($q > 1/2$). When the certification fee for the DA is extremely high ($\phi \geq q$) or extremely low ($\phi \leq 1 - q$), all sellers will adopt the TP or the DA, which is similar to the situation with a low certification accuracy ($q \leq 1/2$) in Proposition 1. It is different from the situation above in that it is a market with a middle application fee for the DA, and some sellers prefer the DA while others the TP ($D = q - \phi$). In addition, sellers with low quality all abandon the DA ($\gamma = 0$). Therefore, we find that the DA serves as the signaling effect and can perfectly separate sellers with different service quality when the application fees of the DA are in the middle level ($1 - q < \phi < q$). However, the exorbitant and undervalued price will both lead to the emergence of pooling equilibrium and ruin the signaling effect of the DA. Then, we concern more about the existence of separating equilibrium, since it provides a possibility of the DA as an efficient signal. When the application fee is respectively high ($\phi > 1 - q$), sellers with low-quality service are excluded from applying the DA, since the higher cost ($\lambda > q - \phi$) precludes any gain from their speculation. Meanwhile, some high-quality sellers prefer the DA, and the number of those sellers declines with the increase

in application fee. Particularly, as ϕ increases over q, all sellers stand away due to the costly application fees.

The main conclusions in Propositions 1 and 2 are illustrated in Figures 1 and 2. Figure 1 shows the participation of sellers under the given certification accuracy (q), which clearly presents that the eligible separation equilibrium exists when and only when $q > 1/2$ and $1 - q < \phi < q$. Meanwhile, Figure 2 is formulated in an operation-friendly way to recognize the seller's demand for DA in different situations. The existing equilibriums have been divided into four areas according to q and ϕ. Specifically, Area I refers to the equilibrium where all sellers choose to join DA and provide low service quality, Area II refers to the equilibrium where all sellers use TP service while providing low-quality service, and Area IV refers to the equilibrium where all sellers will apply for DA. Still, only some will choose good service, and Area III shows the separation equilibrium where sellers with high service quality join DA, while those with low quality choose TP.

Proof of Propositions 1 and 2. The perfect Bayesian equilibrium is characterized by (λ, γ) such that

$$\overline{\lambda} = \max\{0, \min\{2q - 1, q - \phi\}\},$$
$$\begin{cases} \gamma = 1, & \text{if } 1 - q - \phi \geq 0, \\ \gamma = 0, & \text{otherwise.} \end{cases} \tag{6}$$

The consumer's belief about the proportion of sellers with high service quality in DA, α, is given by

$$\alpha = \frac{\overline{\lambda}}{D}. \tag{7}$$

We find the equilibria by solving each candidate situation obtained from equation (6) and equation (7). When $0 > 2q - 1 > q - \phi$, it implies $\phi > (1 - q) > 1/2 > q$ and hence $\overline{\lambda} = \gamma = 0$. If $\overline{\lambda} = \gamma = 0$ satisfy the requirement of one equilibrium, then everyone gains nothing in such situation, and the profit from deviating to applying for DA is $q - \lambda - \phi$ if the seller chooses high-quality service and $1 - q - \phi$ if he chooses low-quality service. The seller with a quality service who gains most from deviating is the type $\lambda = 0$, and this seller will get a payoff $q - \phi < 0$. In contrast, a seller with low quality will get $1 - q - \phi < 0$ from deviating. That is, no profitable deviation exists. Therefore, $\overline{\lambda} = \gamma = 0$ can be one equilibrium if and only if $q < 1/2$. Then we get $D(\phi, q) = 0$, and $\alpha = 0$. That is, $\overline{\lambda} = 0$, $\gamma = 0$, $D = 0$, and $\alpha = 0$ might be part of the equilibrium. We examine 16 other situations following this method and summarize the equilibrium into Proposition 1 on the condition of $q \leq 1/2$. Similarly, Proposition 2 is shaped according to the constraint that $q > 1/2$. All the details are listed in Table 2. □

3.2. The Total Demand for DA. The priority in generating the pricing strategy of the application fees is to identify the total demand of DA. In each equilibrium, by examining consumer's belief about the proportion of sellers with high-quality service in DA, we obtain Proposition 3 to describe consumer's demand for DA. It is noteworthy that $\overline{\lambda}$ always performs zero in Proposition 1, suggesting a market without high-quality sellers. Therefore, we focus on the consumer's demand for DA when $q > 1/2$.

Proposition 3. *Given $q \leq 1/2$, the consumer's demand for DA is $d = 0$. Given $q > 1/2$, the consumer's demand for DA can be recognized as follows: (1) If $\phi \leq 1 - q$, then $\alpha = 2q - 1$, and $d = 1$. (2) If $1 - q < \phi < q$, then $\alpha = 1$, and $d = 1$. (3) If $\phi \geq q$, then $\alpha = 0$, and $d = 0$.*

Proposition 3 presents customers' demand for the DA under different situations. As shown in Figure 3, with the certification accuracy (q) and the application fee for the DA (ϕ) varying, customers' beliefs for the proportion of high-quality sellers and the associating demand for DA are changing. When the certification accuracy is low ($q \leq 1/2$) or the application fee is very high ($\phi \geq q$), consumers believe there are no sellers with high service quality in DA; therefore, their demand for the DA turns to zero, as shown in Area I in Figure 3. If the certification accuracy is high ($q > 1/2$) and the application fee for the DA is moderate ($1 - q < \phi < q$), consumers believe that all sellers in the DA provide high-quality service ($\alpha = 1$). Then they all pursue the DA ($d = 1$), as shown Area II in Figure 3. As for the situation where the certification accuracy of the DA is high ($q > 1/2$) while the application fee is low ($\phi \leq 1 - q$), all consumers will choose DA ($d = 1$) even though only part of the sellers in DA might provide high service quality ($\alpha = 2q - 1$).

It is commonsense that consumers do not need the DA if its certification accuracy is low because they could not distinguish high-quality sellers from low-quality ones by the DA label. In addition, when the application fee for the DA is very high, no seller will apply for the DA, so that no consumer will need the DA service. When the DA could perfectly separate sellers with high-quality service and those with low-quality service, consumers certainly need the DA. It is surprising that although high-quality sellers cannot be perfectly distinguished from low-quality ones by the DA, consumers all prefer the DA. Because of the high certification accuracy, consumers give a high-level belief about the DA as a signal of a high-quality seller. Therefore, all consumers are willing to pay for the DA. From Proposition 3, we can find that the certification accuracy of the DA is crucial for consumers, and it largely determines whether consumers need the DA or not.

Proof of Proposition 3. The consumer's demand is described as $d = 1$ if $\alpha > 0$ and $d = 0$ in other situations. Combining this with the proof of Propositions 1 and 2, we can reformulate the conditions related to α with the expressions of d. Thus, the consumer's demand for DA can be presented as

$$\begin{cases} \text{if } \phi \leq 1 - q, & \text{then } d = 0, \\ \text{if } \phi > 1 - q, & \text{then } d = 0, \end{cases} \quad \text{when } q \leq 1/2,$$
$$\begin{cases} \text{if } \phi \leq 1 - q, & \text{then } d = 1, \\ \text{if } 1 - q < \phi < q, & \text{then } d = 1 \\ \text{if } \phi \geq q, & \text{then } d = 0 \end{cases} \quad \text{when } q > 1/2. \tag{8}$$

Then Proposition 3 is proved. □

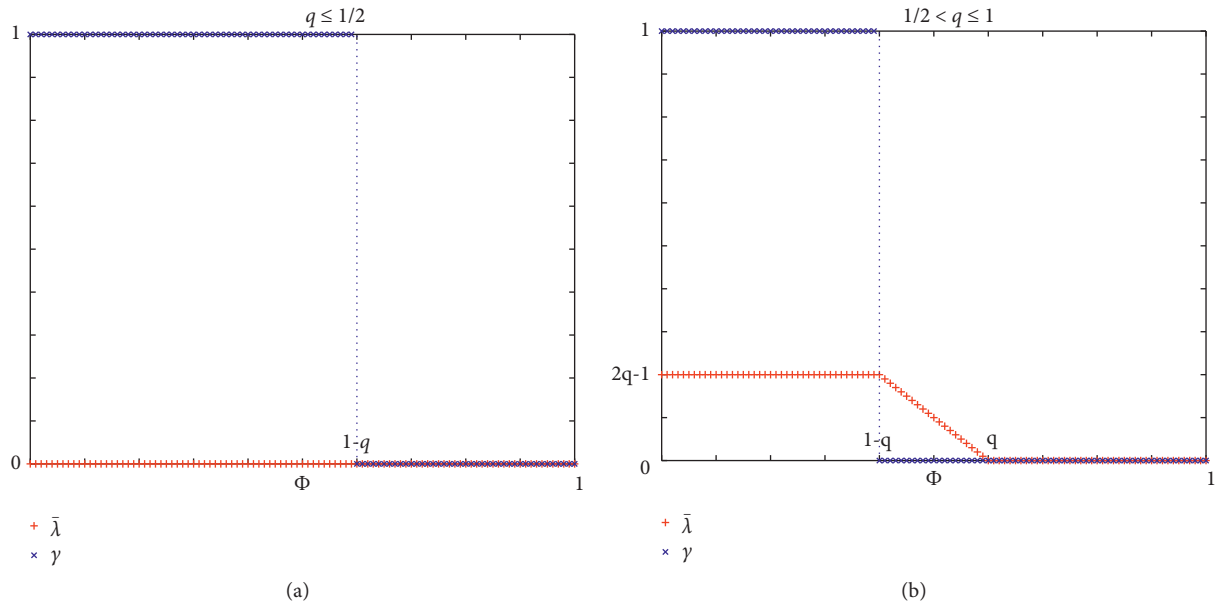

FIGURE 1: The impact of application fee on the participation of sellers under the given certification accuracy: (a) in the situation of $q = 0.4 \leq 1/2$; (b) in the situation of $1/2 < q = 0.6 \leq 1$.

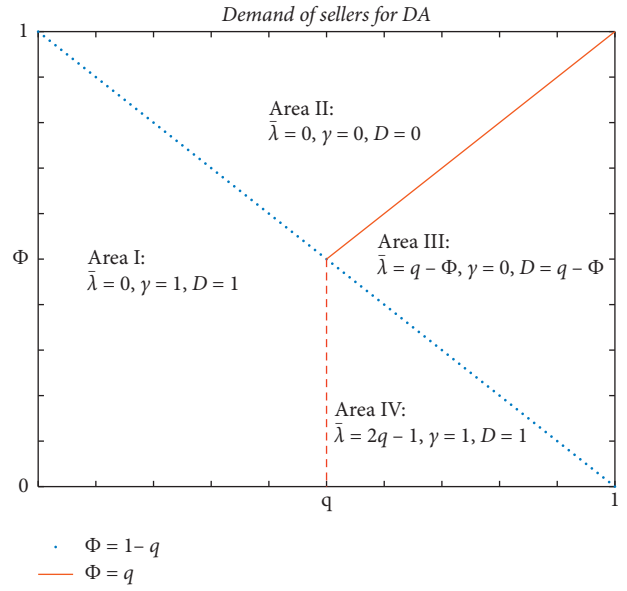

FIGURE 2: The impact of application fee and certification accuracy on the seller's demand for DA.

According to the seller's demand and consumer's demand for DA discussed above, we denote by $D_T = d \times D(\phi, q)$ the total demand for DA. The operational character $// \times //$ turns out $D_T = d * D(\phi, q)$ if and only if $d > 0, D(\phi, q) > 0$; otherwise, $D_T = 0$; and the total demand for DA then reads

$$D_T = \begin{cases} 1 & q > 1/2 \text{ and } \phi \leq 1 - q, \\ q - \phi & q > 1/2 \text{ and } 1 - q < \phi < q, \\ 0 & \text{otherwise.} \end{cases} \quad (9)$$

□

3.3. Pricing of the Application Fee. The expression of total demand for DA in equation (9) helps generate the expected profit of the platform operating DA. The profit function is presented as

$$\max \pi(\phi) = \phi D_T = \begin{cases} \phi & q > 1/2 \text{ and } \phi \leq 1 - q, \\ \phi(q - \phi) & q > 1/2 \text{ and } 1 - q < \phi < q, \\ 0 & \text{otherwise.} \end{cases} \quad (10)$$

Then we derive the optimal application fee via a standard method in the pricing decision. From equation (10), the expected profit of DA has the following properties:

(1) If $q > 1/2$ and $\phi \leq 1 - q$, a price increase raises the DA's profit, which indicates that $\phi = 1 - q$ might be a point to achieve the local maximum profit.

(2) If $q > 1/2$ and $1 - q < \phi < q$, a price increase decreases the total demand, which suggests the existence of ϕ^* to maximize the profit.

The local optimal solutions of the extremum problem in equation (10) are listed in Table 3.

We plot the optimal application fee, total market demand, and the platform's optimal profit in Figure 4 to visualize the effect of certification accuracy on such an optimal state. The decision space has been divided into four zones according to the range of q and the constraints of ϕ in (a). The relationships between ϕ and π are illustrated separately under different levels of q: (b) in the range of $1/2 < q \leq 2/3$; (c) in the range of $2/3 < q \leq 2\sqrt{2} - 2$; (d) in the range of $2\sqrt{2} - 2 < q \leq 1$.

It can be seen that the platform's decision on whether to launch DA service depends on its expected profits. According to the locally optimal results of equation (10), the maximum profit of DA can be rewritten as

Table 2: List of equilibria in all candidate situations.

Situation	Condition	Equilibrium
$0 > 2q - 1 > q - \phi$	$q < 1/2, q < (1-q) < \phi$	$\overline{\lambda} = 0, \gamma = 0, D = 0, \alpha = 0$
$0 > 2q - 1 = q - \phi$	$q < 1/2, q < (1-q) < \phi$	$\overline{\lambda} = 0, \gamma = 1, D = 1, \alpha = 0$
$0 = 2q - 1 > q - \phi$	$q < 1/2, q < (1-q) < \phi$	$\overline{\lambda} = 0, \gamma = 0, D = 0, \alpha = 0$
$0 = 2q - 1 = q - \phi$	$q < 1/2, q < (1-q) < \phi$	$\overline{\lambda} = 0, \gamma = 1, D = 1, \alpha = 0$
$0 > q - \phi > 2q - 1$	$q < 1/2,\ q < \phi < (1-q)$	$\overline{\lambda} = 0, \gamma = 1, D = 1, \alpha = 0$
$0 > q - \phi = 2q - 1$	$q < 1/2,\ q < \phi < (1-q)$	$\overline{\lambda} = 0, \gamma = 1, D = 1, \alpha = 0$
$0 = q - \phi > 2q - 1$	$q < 1/2,\ q < \phi < (1-q)$	$\overline{\lambda} = 0, \gamma = 1, D = 1, \alpha = 0$
$2q - 1 > 0 > q - \phi$	$q > 1/2, (1-q) < q < \phi$	$\overline{\lambda} = 0, \gamma = 0, D = 0, \alpha = 0$
$2q - 1 > 0 = q - \phi$	$q > 1/2, (1-q) < q < \phi$	$\overline{\lambda} = 0, \gamma = 0, D = 0, \alpha = 0$
$2q - 1 = 0 > q - \phi$	$(q = 1/2, (1-q)) = q < \phi$	$\overline{\lambda} = 0, \gamma = 0, D = 0, \alpha = 0$
$2q - 1 > q - \phi > 0$	$q > 1/2, (1-q) < q < \phi$	$\overline{\lambda} = 0, \gamma = 0, D = 0, \alpha = 0$
$2q - 1 > q - \phi = 0$	$q > 1/2, (1-q) < q < \phi$	$\overline{\lambda} = q - \phi, \gamma = 0, D = q - \phi, \alpha = 1$
$2q - 1 = q - \phi > 0$	$q > 1/2, (1-q) < q < \phi$	$\overline{\lambda} = 0, \gamma = 0, D = 0, \alpha = 0$
$q - \phi > 0 > 2q - 1$	$q < 1/2, \phi < q < (1-q)$	$\overline{\lambda} = 2q - 1, \gamma = 1, D = 1, \alpha = 2q - 1$
$q - \phi > 0 = 2q - 1$	$q < 1/2, \phi < q < (1-q)$	$\overline{\lambda} = 0, \gamma = 1, D = 1, \alpha = 0$
$q - \phi = 0 > 2q - 1$	$q < 1/2, \phi < q < (1-q)$	$\overline{\lambda} = 0, \gamma = 1, D = 1, \alpha = 0$
$q - \phi > 2q - 1 > 0$	$q > 1/2,\ \phi < (1-q) < q$	$\overline{\lambda} = 2q - 1, \gamma = 1, D = 1, \alpha = 2q - 1$
$q - \phi > 2q - 1 = 0$	$q > 1/2,\ \phi < (1-q) < q$	$\overline{\lambda} = 0, \gamma = 1, D = 1, \alpha = 0$
$q - \phi = 2q - 1 > 0$	$q > 1/2,\ \phi < (1-q) < q$	$\overline{\lambda} = 2q - 1, \gamma = 1, D = 1, \alpha = 2q - 1$

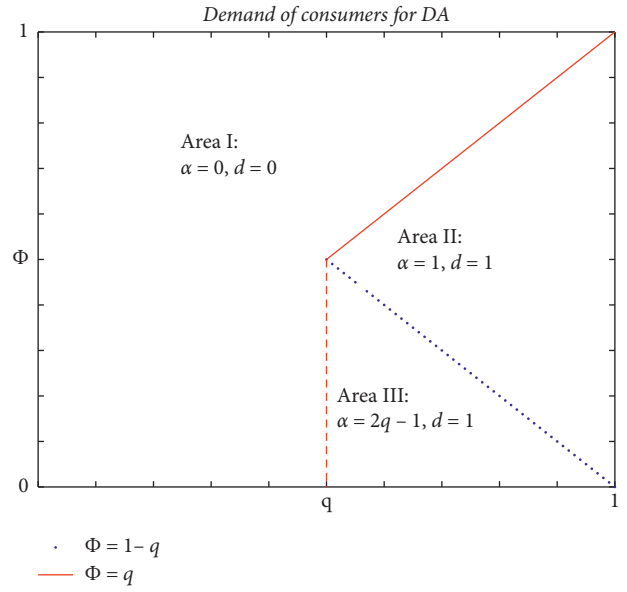

Figure 3: The impact of application fee and certification accuracy on the consumer's demand for DA.

$$\pi^*(\phi^*) = \phi^* D_T^* = \begin{cases} 1-q & q > 1/2 \text{ and } \phi \le 1-q, \\ q^2/4 & q > 1/2 \text{ and } 1-q < \phi < q, \\ 0 & \text{otherwise.} \end{cases} \tag{11}$$

By discussing the possible situations in equation (11), we summarize the global optimal pricing strategy of the application fee in Proposition 4.

Proposition 4. *The following pricing strategy ensures DA achieving the maximum profits: (1) If $q \in [0, 1/2]$, then $\phi^* = 0$, $D_T^* = 0$, and $\pi^* = 0$. (2) If $q \in (1/2, 2\sqrt{2} - 2]$, then $\phi^* = 1 - q$, $D_T^* = 1$, and $\pi^* = 1 - q$. (3) If $q \in (2\sqrt{2} - 2, 1]$, then $\phi^* = q/2$, $D_T^* = q/2$, and $\pi^* = q^2/4$.*

Proposition 4 shows the platform's optimal decisions and profits under different levels of certification accuracy of the DA. In line with Propositions 1 and 2, the low accuracy ($q \in [0, 1/2]$) demotivates sellers to provide quality service and shrinks the demand of DA ($D_T^* = 0$), which results in the incapacitation of the platform ($\pi^* = 0$). However, the increase of certification accuracy does not indicate that the DA can convey the information of service quality precisely. When the certification accuracy is not high enough ($q \in (1/2, 2\sqrt{2} - 2)$), the platform can obtain a certain profit by the DA ($\pi^* = 1 - q$), but it still hinders identifying the seller's types ($\gamma = 1$). Therefore, a more accurate certification process is required to guarantee that the DA works efficiently as a signal. We have proven that the high-level certification accuracy of the DA ($q \in (2\sqrt{2} - 2, 1]$) can help the platform get a sufficient signal ($\gamma = 0$) and the highest profits at the same time ($\pi^* = q^2 > 4 - 4q$).

The main results of Proposition 4 are illustrated in Figure 5.

In Figure 5, we present the optimal application fee for the DA, and corresponding demand and maximal profit vary with the certification accuracy (q). We can find that the platform can get the highest profit by pricing the DA application highly when the accuracy remains in a middle level. In addition, with a middle-level certification accuracy, the optimal application fee for the DA drops down with the increasing certification accuracy of the DA, as well as the optimal profit, while the demand remains at a high level ($D_T^* = 1$). However, when the accuracy reaches a pretty high level, the optimal application fee for the DA and corresponding demand and profit all improve with the increasing accuracy of the DA. It is interesting that, from Figure 5, we can see that a high-level certification accuracy does not mean a high profit for the platform. When the accuracy is very

Table 3: The local optimal application fee, total market demand, and profits under different levels of certification accuracy.

	Constraints	The range of certification accuracy			
		$q < 1/2$	$1/2 < q \le 2/3$	$2/3 < q \le 2\sqrt{2} - 2$	$q \ge 2\sqrt{2} - 2$
Φ^*	$\phi \le 1 - q$	0	$1 - q$	$1 - q$	$1 - q$
	$1 - q < \phi < q$	0	$1 - q$	$q/2$	$q/2$
	$\phi \ge q$	0	0	0	0
D_T^*	$\phi \le 1 - q$	0	1	1	1
	$1 - q < \phi < q$	0	$2q - 1$	$q/2$	$q/2$
	$\phi \ge q$	0	0	0	0
π^*	$\phi \le 1 - q$	0	$1 - q$	$1 - q$	$1 - q$
	$1 - q < \phi < q$	0	$(1 - q)(2q - 1)$	$q^2/4$	$q^2/4$
	$\phi \ge q$	0	0	0	0

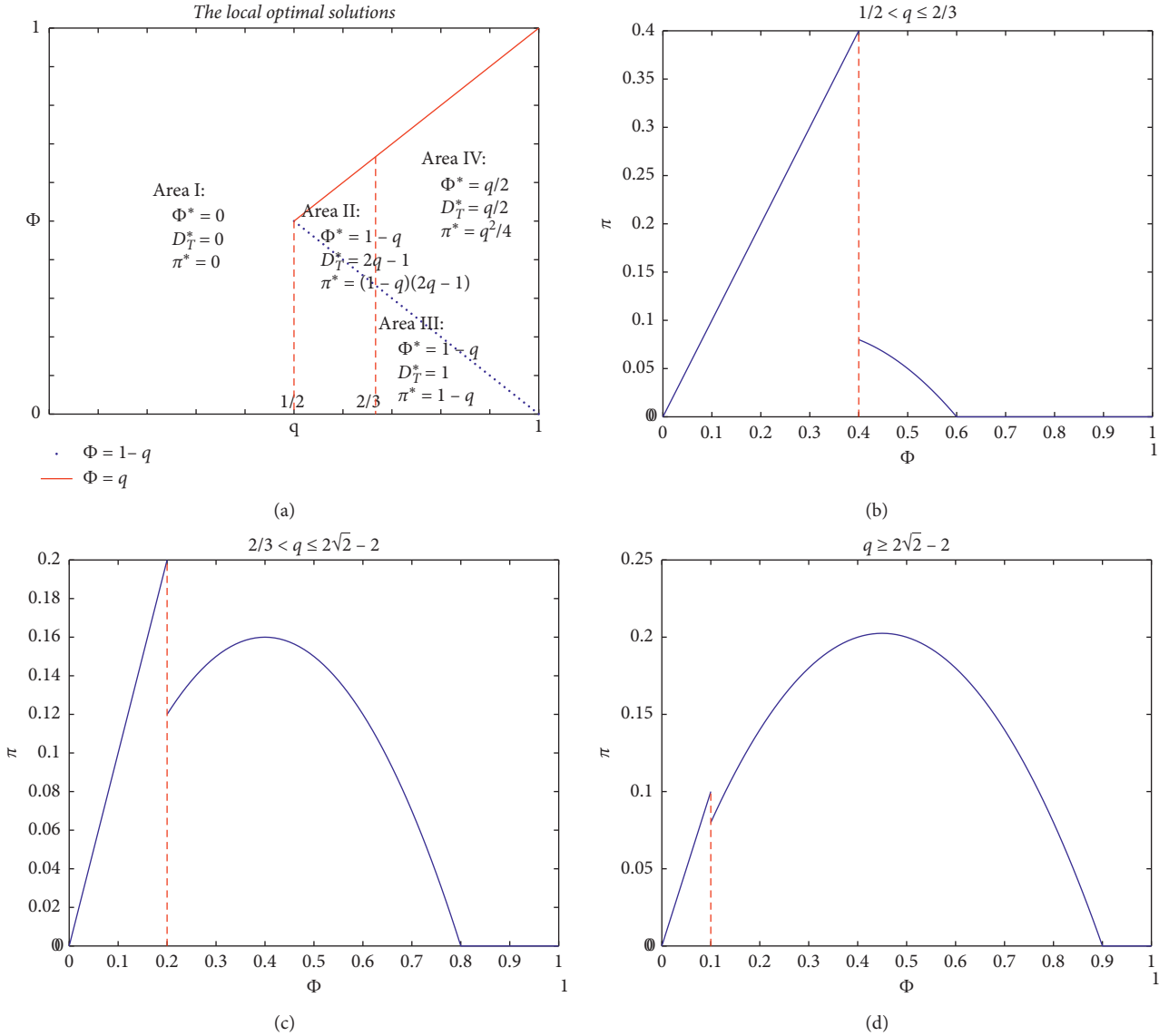

Figure 4: The local optimal solutions in different situations of certification accuracy: (a) details of decision space; (b) in the situation of $1/2 < q = 0.6 \le 2/3$; (c) in the situation of $2/3 < q = 0.8 \le 2\sqrt{2} - 2$; (d) in the situation of $2\sqrt{2} - 2 < q = 0.9 \le 1$.

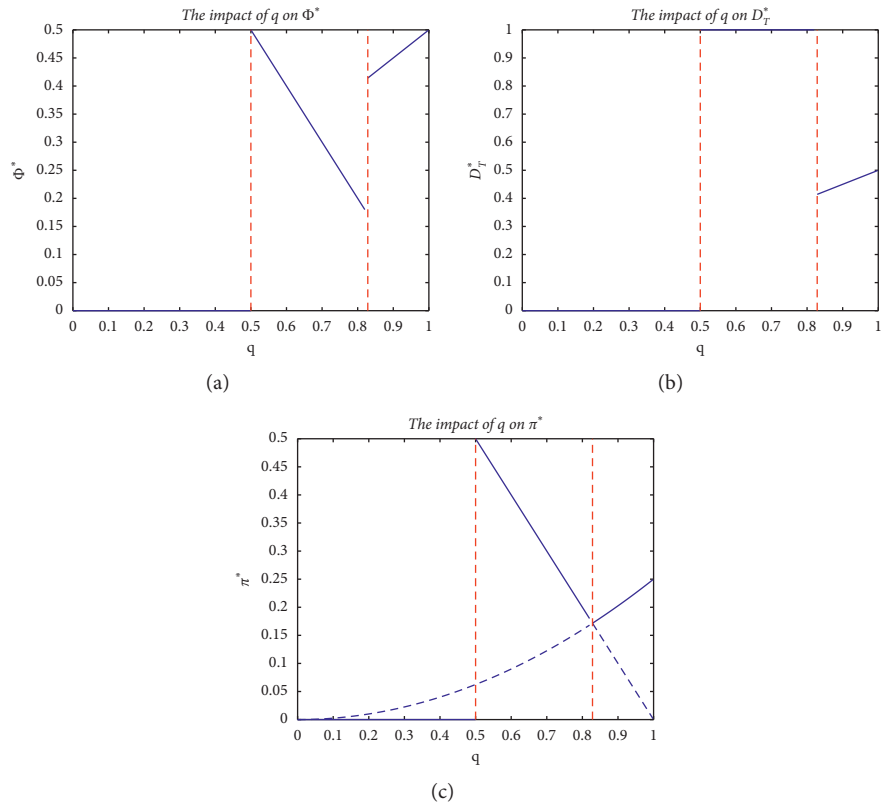

FIGURE 5: The impact of certification accuracy on (a) the global optimal application fee, (b) the total market demand, and (c) the platform's optimal profits.

high, the demand decrease results in the DA service being less profitable than that in a middle-level accuracy for the platform. This result clarifies the fact that not all sellers in DA provide high-quality service on a platform.

Proof of Proposition 4. When $q \in [0, 1/2]$, it is evident that $\pi^* = 0$ because there is no demand for DA. Assume that $f(q) = q^2/4 - (1-q)$. Let $f(q) = 0$. We obtain that $q = -2 - 2\sqrt{2}$ and $q = -2 + 2\sqrt{2}$. The former does not satisfy the set of q. Then, it shows that $q^2/4 \leq (1-q)$ when $q \in (1/2, 2\sqrt{2} - 2]$, and $q^2/4 > (1-q)$ when $q \in (2\sqrt{2} - 2, 1]$. It suggests that the platform should price $\phi \leq 1 - q$ when claiming $q \in (1/2, 2\sqrt{2} - 2]$, the optimal price is $\phi^* = 1 - q$, and the optimal profit is $\pi^* = 1 - q$. Alternatively, the platform can price $1 - q < \phi < q$ when claiming $q \in (2\sqrt{2} - 2, 1]$, and then the maximal profit $\pi^* = q^2/4$ can be reached at $\phi^* = q/2$.

Then Proposition 4 is proved. □

4. Discussion

4.1. Managerial Implications. This study provides both theoretical and practical contributions. In the academic aspect, the examination of DA's signaling effect can contribute to our understanding of how the platform's certification accuracy can influence both sellers' and consumers' participating in DA and inform us about the pricing strategies to regularize the DA's operation. In the practical aspect, our findings can help inform online enterprises (both sellers and platforms) about the effect of DA on the consumer's perceptions.

For platform enterprises, while it has been proven that DA can help consumers differentiate the service quality of sellers and improve the welfare of society, profitability is the primary concern to launch DA services. Therefore, our investigation has been devoted to showing that platforms can be profitable through DA for given different market equilibrium. From an operational viewpoint, if a platform plans to implement DA service, it still needs to accumulate enough sellers and consumers to maintain the user volume and reserve enough quality capacity resources to ensure that DA is competent. According to the network externality of the two-sided market structure, more consumers will attract more sellers and vice versa. When the delivery service is promoted, a new similar market structure led by DA emerges. In this marketplace, DA links high- quality-service sellers and delivery resources, and the numbers of such sellers and deliverers are in line with the basic law of network externality. Hence, more high-quality deliverers can bring more sellers with high service quality, which attracts more consumers; the new joining consumers can help the platform attract more high-quality sellers and then quality deliverers to join DA.

Besides the operational implications for online retailing platforms, there are still two issues that can be discussed in

depth. The first one is how the platforms price DA service. Given that both sellers and consumers accept DA service, the platform should provide appropriate pricing contracts to promote the healthy development of the DA system. In practice, the platform generally charges only sellers and offers free options to consumers to maintain market share. Considering the context in which we are operating, things might change so that the platform should be charging consumers rather than sellers. As DA conveys private information about the service quality of sellers while providing new delivery service, it adds value to products sold on the platform, which allows for charging to the consumers. Meanwhile, the platform also has options to adopt types of pricing strategies for consumers, such as membership projects, transaction-based prices, or two-part tariff prices. The other issue that deserves to be discussed is how to regulate the pricing behavior of the platform to consolidate the target equilibrium. A separated equilibrium where DA can signal the different service quality sellers is expected. However, in our results, the platform seems to gain more profit in some other equilibriums. In order to prevent the platform from making undue profits at the expense of service quality, market oversights (i.e., reputational mechanisms) and government actions (i.e., regulatory mechanisms) should be introduced. As we state that DA possesses the platform's reputation endorsement, if the low precision cannot identify service quality but ensures the platform gets a certain potential profit, this might motivate the platform to deviate from its claimed certification accuracy, which results in a moral hazard. When it is true, the reputation mechanism is required to regulate the platform's operation. The reputation of the platform eventually turns out to be the signal, whose efficiency can only be examined via the proportion of quality sellers in DA. The regulatory mechanism operates on similar logic to the reputational mechanism, except that, at a technical level, it moves from a goal to be achieved by the platform to a constraint that must be obeyed.

For logistics service providers, how to develop a cooperation plan with the platform is the most significant issue. As a logistics manager, determining whether the signal of DA works efficiently is a priority, which could be guided by the current paper. The next step is how to allocate the available capacity resources to make the logistics enterprise operate most efficiently. Here we give three basic principles for participating in DA. First, distribution alliances that rely on the platform for customer acquisition can provide sufficient orders to ensure profitability; second, the profit level of participating in distribution alliances can cover the costs associated with developing new capacity resources (procurement costs, human resources costs, etc.); third, according to the daily situation, when the trucks are not fully loaded, they can take orders from distribution alliances to reduce the average cost. These three problems correspond to the market assessment problem, the return-on-investment problem, and the project selection problem which can be solved by referring to the literature and experience in related fields.

In addition, the methodology in this paper provides effective tools for examining new potential signals which can be explored further. For example, online reviews and repeat purchase rates are emerging as new factors influencing consumers' online purchasing behavior. Our approach should be evaluated further to determine whether they can serve as signals to convey private information about sellers and platforms and whether their signaling effects in an online marketplace can be validated.

4.2. Limitations. The first limitation of our model is the setting of the game period. The results of static gaming analysis can only present the short-term profits; that is, the platform obtains certain profit from the process of turning the distribution alliance into an adequate signal. When it comes to long-term consideration, the potential motivation of deviating from our target separation equilibrium appears due to the fact that the expected profits outside the equilibrium path are larger than the optimal ones in a period. Specifically, with the reputational concerns in a finite-stage repeated game, the platform might deviate the equilibrium via choosing a lower certification accuracy, and the corresponding application fee at the last stage (extremely like the situation where q is slightly more than 1/2, $\phi^* = 1 - q$, $\pi^* = 1 - q$) or a new equilibrium will be found to guide the platform's decision. To overcome the limitations of the proposed model, we encourage future researchers to consider two-stage game-theoretical models and (or) infinite-horizon evolutionary gaming models, both of which will benefit understanding and analyzing the decision behaviors of platform firms in the medium-to-long term. Regardless of which recommended model is adapted, it is necessary to design a reputation mechanism for platforms which allows consumers and sellers to update their beliefs about the announced certification accuracy when joining DA as the game goes on. The key point of making DA a signal here is to introduce the unobservable effort invested by the platform in certification accuracy.

The other limitation of our model lies in the model setting about the cost. The cost of the certification process has been omitted for the purpose of simplification. The certification accuracy is assumed to be cost-free by now, which suggests that the platform can provide the highest precision, $q = 1$, to create a frictionless market where service quality is public information. In practice, it is rare because the platform should bear the related cost of quality detection. Our model can explain this situation to some extent. As presented in Proposition 2 that a more accurate certification is associated with a higher application fee, covering the cost of quality testing can be thought of. However, in other situations, this cost might grow even faster as the certification accuracy increases. We recommend an alternative method for future researches to catch this fact, in which a cost function in a quadratic form related to the certification accuracy is introduced (i.e., $c = kq^2$, where c represents the cost of the certification process and k is a parameter). The consideration of

certification cost requires the platform to make decisions on q and ϕ simultaneously, which increases the designing complexity of DA. In this situation, the market equilibrium in our model might be broken, and the platform must balance the certification cost and the expected profit in operating DA service.

Some other future directions of the current study are listed as follows. First, the signal design of DA could be more complex. For the concerns of abstract representation, only two levels of service quality, high and low, are presented in our model. In fact, when combined with other information, DA can signal more types of seller's service quality. For instance, a product on Amazon.com might be labeled as "sold by and ships from Amazon" or "ships from Amazon" or might have no label, which might help identify three kinds of sellers. Another similar example comes from Jingdong.com, one of the most popular e-commerce platforms in China, whose labels also include "sold by Jingdong," "only ships from Jingdong," and "sold by third-party sellers." Second, the applications of some studies in the field of certification can be introduced into the signaling mechanism of DA, such as credit ratings, scoring systems, and recommendation mechanisms.

5. Conclusions

In this study, we proposed a game-theoretical model to examine the signaling effect of DA in an online platform marketplace where online sellers have their private information on the service quality. Considering the operability of the potential results, we introduced profit functions to describe the game players' payoffs. In the discussed market equilibriums, the certification accuracy and application fees are two key factors influencing each participant's behavior. Theoretically, the certification accuracy should be set high enough to preclude sellers with low service quality from applying DA speculatively. Meanwhile, a proper setting of the application fee also ensures the validity of DA's signal effect; it should be neither too low to allow low-service-quality sellers to realize undue profits nor too high to prevent any gain from transactions. Based on the model settings, the boundary conditions of the target equilibrium have been presented in our results.

The major contribution of the paper is to launch a game-theoretical model to identify the signaling effect of distribution alliance. DA is a new and good innovation in logistics and e-commerce whose organizational characteristics make it a lubricant in the traditional supply chain structure. Meanwhile, DA becomes a signal conveying the service quality of online sellers and complements the existing signal theory and marketing theory, indicating that new signals belonging to the new consumption have emerged. In addition, the methodology in this paper can be applied to the identification of other potential signals in similar situations, which enriches the application scenarios of mathematical modeling method, signal theory, and game-theoretical methods.

We also recommended some directions for future researches. The current static finite-period game-theoretical model could be promoted to a dynamic infinite repeated gaming to help illustrate the platform's long-term decisions while considering a certification cost. Also, it could be developed in a complex situation where there are three or more types of sellers needed to be identified.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

Promotion Strategy of Policy against Food Waste (PAFW): The Perspective on Evolutionary Game between Local Government and Large Supermarkets

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The implementation of PAFW is an important way to reduce food waste. Discussing how to more successfully implement PAFW to reduce food waste is of great significance in achieving sustainable development. Different from the previous literature, this paper uses evolutionary game theory to establish a strategic interaction income matrix between local governments and large supermarkets and analyzes the strategic interaction between local governments and large supermarkets by copying dynamic equations, revealing the strategic choice between the two parties evolution process. A simulation-based approach is used to validate the theoretical results and analyze the influence of key parameters on the evolutionary trajectory. The study found the following: (1) to promote the system to an optimal evolutionarily stable strategy (ESS), it is necessary to strengthen policy publicity, increase the willingness of large supermarkets to implement the PAFW, and increase the enthusiasm of the public or third-party organizations to monitor system; (2) stakeholders' initial willingness will influence the evolutionary trajectory; and (3) it is important to strengthen the institutional development of local government regulators, improve the local government's achievements, reduce the local government's regulatory costs, improve policies to support large supermarkets' implementation of the PAFW, and reduce the cost of implementing the PAFW for large supermarkets.

1. Introduction

One of the most challenging issues currently facing societies around the world is the issue of food waste [1, 2]. Item 12 of the sustainable development goals set by the United Nations in 2015, "Ensure sustainable consumption and production patterns," sets out to achieve a reduction in food waste [3]. Currently, the efficiency of the food system is extremely low. One-third of the food produced in the world every year is wasted, amounting to a total of 1.3 billion tons [4, 5]. In the United States, approximately 63 million tons of food is discarded into landfills each year without being eaten. Supermarkets and restaurants contribute 40% of the total food waste. Moreover, the waste produced by supermarkets is much higher than that produced by restaurants. It can be seen that supermarkets account for a large proportion of the food waste [6]. Promoting the PAFW is an important way to reduce food waste from supermarkets [7].

China, a country with a population base of 1.4 billion, also has a serious food waste problem. The value of the food thrown away in the country each year is $28 billion [8], helping make the issue of food waste a very important political and social issue in China [9]. In August 2020, Chinese President Xi Jinping highlighted the problem: "The phenomenon of food waste is shocking and heartbreaking, and despite our successive bumper harvests, we must always be aware of the crisis in food security, and the impact of this year's global novel coronavirus pneumonia is a wake-up call [10]." In this political context, various departments of the Chinese government are formulating and planning policies

and raising awareness about food waste [11]. At the same time, the introduction of foreign advanced management techniques has played an important role in alleviating the current situation of food waste in China. France has developed the most advanced management approaches. Since 2013, the French government has introduced several bills to restrict food waste, the most effective of which is the NRDC's 2015 "France Moves Toward a National Policy Against Food Waste," which directly requires that major supermarkets be prohibited from directly discarding unsold but edible foods and that they be forced to sign agreements with charitable organizations to donate these foods to charitable organizations. Then, in the same period, it was proposed that large supermarkets over 400 square meters must sign agreements with charitable organizations before July of the following year [12]. The bill has had a positive impact since its implementation, curbing food waste to a certain extent and producing a significant increase in the number of meals distributed to charities for the poor. Countries such as Italy, Peru, and Finland have followed France's lead in adopting similar measures [13].

Under the current political system with strong enforcement, China will achieve good results if it adopts the French model of management and develops timely policies to address food waste. The prerequisite for such effectiveness is that the policies are widely implemented. When a specific policy is promoted, it may also encounter some resistance and large supermarkets may not implement the policy because of the high cost, immature incentives, and a lack of political impetus. Therefore, in the absence of regulation, a large supermarket will not voluntarily sacrifice its own interests to implement the policy. Given the interplay between local government and large supermarkets, there will be a conflict of interest between the local government pushing for the PAFW and large supermarkets in policy implementation. Game theory can be used to study the mutual strategic decisions in the interest of both parties [14].

This paper first analyzes the conflicts of interest between large supermarkets and the local government in implementing the PAFW in China and constructs an evolutionary game model for the local government and large supermarkets to weigh their respective strategies to be optimized for the corresponding dynamic evolutionary trends. Second, a simulation analysis is conducted to examine how the initial proportion of each stakeholder's strategy affects the evolutionary trend and the influence of key parameters on the final trend in the evolutionary game system toward the ideal stable direction. Currently, from the perspective of evolutionary game, there are relatively few studies on the PAFW, and the new research clearly reveals the complex dynamic evolution game model in the case of the limited rationality, and for the analysis of dynamic game between local government and large supermarket, the process provides a qualitative and quantitative simulation platform, which provides effective theoretical support for the decision-makers.

The paper is structured as follows: Section 2 reviews the related literature and highlights the contributions of the paper. Section 3 describes the conflicts between the participants and the assumptions required in the game. In Section 4, the results of the model are analyzed, and the relevant parameters are simulated and sensitivity analyzed. Finally, Section 5 draws a conclusion and provides policy suggestion.

2. Literature Review

Recently, scholars conducted extensive research on "against food waste management." Thyberg and Tonjes explored the social, demographic, cultural, political, and economic drivers of food waste and highlighted how perceptions of food waste differ globally, suggesting the importance of policies to prevent food waste for sustainable development [15]. Heikkilae et al. studied the causes of food waste in restaurants and catering establishments and determined the diversity of food waste management in the food service sector and how a comprehensive approach can be taken to prevent and reduce it. This analysis revealed that food waste is controllable and should be controlled through management tools [16]. These two studies demonstrated the importance of policy and management approaches to prevent food waste. Lunkes et al. used structural equation modeling to analyze the relationship between management control systems, food waste information, and restaurant financial and nonfinancial performance to examine how a broad information system can support restaurant managers in making decisions about food waste [17]. Muriana discussed the importance of supply chain strategies in the fight against food waste and examined techniques to reduce food waste and management systems to identify factors that lead to food waste and promote food waste minimization [18]. They began by considering the information system and supply chain to provide a decision-making basis for the policy against food waste management. Schneider summarized the evolution of food donation activities; examined the political, legal, social, and logistical barriers to incentivizing food donation; proposed the concept of food donation networks; and discussed their ecological, economic, and social impact [19]. Dolnicar et al. proposed a game to promote the reduction of food waste in hotels in tourist areas by exchanging a "clear your plate" campaign for stamp collection and demonstrated its effectiveness [20]. These studies suggested practical ways to reduce food waste from different perspectives.

The current research confirms that management interventions and policy facilitation are indispensable if food waste is to be reduced and suggests a number of ways to reduce food waste from management and practice perspectives, respectively. However, less literature focused on the issue of PAFW facilitation from a microeconomic point of view. The adoption mechanism of PAFW must be analyzed at the microlevel of interaction between local governments and the large supermarkets. Game theory has been used in the study of conflict coordination and interaction models among different target stakeholders [21]. Game theory can fulfill the expectation of maximizing stakeholder interests by predicting the behavior of others to determine the most advantageous strategy [22]. The classical static

game argues that the stakeholders not only are completely rational but also have overall information; however, it is the opposite of the actual situation [23]. Evolutionary game theory improves on the traditional game by treating the participants' strategy selection as a dynamic adjustment process based on the premise of limited rationality [24].

Scholars' applications of evolutionary game theory between government and enterprises bring inspirations to this study. Sheng et al. developed a tripartite evolutionary game model for the implementation of environmental regulatory policies in China between the national government, local governments, and enterprises; studied the stability of various evolutionary strategies and the influence of parameter changes on these strategies through numerical simulations; and concluded that increasing penalties for noncompliance and compliance incentives can encourage local governments to enforce environmental regulations more effectively, thereby alleviating the burden on various stakeholders and the conflicts of interest between them [25]. Zhang and Xi studied the dynamic evolution of local government regulatory strategies and enterprises' nitrogen emission reduction strategies under static and dynamic subsidy policies using the evolutionary game method and found that the choice of enterprises' emission reduction strategies depends mainly on the comparison of nitrogen emission costs and benefits, and whether the government implements regulations depends on the comparison of public opinion costs and monitoring costs, subsidy costs, and other factors [26]. Song et al. analyzed the strategic interaction benefit matrix between management and chemical companies by establishing a strategic interaction between the two parties and replicating the dynamic equation, revealing the evolutionary process of behavioral strategy choice between management and companies, and providing a basis and recommendations for the safety management of chemical engineering [27]. By reviewing these studies, we learn that fines for violations and compliance incentives are the main factors that influence firms' strategic choices.

Evolutionary game theory has also been applied in other fields, which also offers some inspiration. Liu et al., through the in-depth study of a proprietary evolutionary game model between doctors and patients and a numerical simulation, found that the doctor-patient relationship will eventually form a zero-sum game or win-win situation; as to which case is stable, this is closely related to the initial probability and parameter settings of the evolutionary game model [28]. Feng and Ma constructed an asymmetric model of service-based manufacturing firms and service providers based on an evolutionary game, and through stability analysis and numerical simulation, they found that the cooperation between manufacturing firms and service providers is related to the initial choice of initial probability and different parameter settings of the two strategies [29]. The above study leads us to find that the choice of initial probability and different parameter changes of the participants affect their initial state and thus the evolutionary trend if there are two different stability points in the evolutionary process.

3. Model

3.1. Problem Description and Conflicts among the Participants. China accounts for 7% of the world's arable land and 20% of the world's population, which have made food issues a key social concern of the Chinese government [30]. In the current context of increasing food waste, Chinese President Xi Jinping's directive on this issue indicates that the Chinese government attaches great importance to the issue of food waste and has attempted to implement policies to alleviate the situation. In this context, in addition to restricting food waste in the restaurant industry, restricting discarded food in large supermarkets should also be included in sustainable development strategies. However, large supermarkets are reluctant to bear the costs of implementing policies, including contacting charities and logistics. Large supermarkets have to make a choice between maximizing their own profit and implementing policies, and while making this choice, it is more important for the local government to actively guide their support and commitment to environmental protection and provide some regulatory function.

Laws and regulations are an important influencing factor in promoting the PAFW. In 2020, due to COVID-19, international food production will decrease by more than 20%, and the international community is facing a food shortage crisis, which also affects China, making it urgent to promote the implementation of the PAFW [31, 32]. However, because the implementation of regulations will consume many human, material, and financial resources, the local government is also faced with many dilemmas regarding the implementation of regulations.

In summary, policymakers are faced with the challenge of how to help large supermarkets to implement the PAFW; large supermarket policymakers need to consider whether to implement these policies. They are some of the most important stakeholders in the promotion of the PAFW.

3.2. Assumptions of the Evolutionary Game. Before conducting the evolutionary game between local government and large supermarkets, we need to point out several important assumptions. In general, we establish the following 5 assumptions by referencing the relevant studies in the literature [33, 34].

Assumption 1. The subjects of the game in the model are the local government and the large supermarkets, both of whom are finite rational.

Assumption 2. Participants can learn from each other and correct their mistakes to continuously improve their strategies because it is difficult for them to choose the ideal strategy to maximize the benefits at the beginning.

Assumption 3. The local government has two strategies—" positive regulation" and "negative regulation"—with probabilities $x(0 < x < 1)$ and 1-x, respectively.

Assumption 4. Large supermarkets have two strategies—"implementation policy" and " nonimplementation policy"—with probabilities y($0 < y < 1$) and 1-y, respectively.

Assumption 5. The probability of a large supermarket not enforcing its policy under negative regulation and exposure to the public or a third-party agency is ω ($0 < \omega < 1$). When large supermarkets do not enforce the policy, a local government that chooses the "positive regulation" strategy will earn political success and a fine, while a local government that chooses "negative regulation" will be negatively affected and will not receive a fine, which will be enforced by a higher authority.

4. Evolutionary Game between the Local Government and Large Supermarkets

4.1. Evolutionary Game Models and Parameters. Based on the above description of the problem and the conflict between the local government of China and the large supermarkets, the parameters of the game model are defined. When the local government chooses the "positive regulation" strategy and the large supermarkets choose the strategy of "implementation policy," the local government will alleviate the problem of food waste and gain great political success, set to N. At the same time, the local government will incur regulatory costs, denoted as Cr. When large supermarkets are found not to implement the policy, a certain penalty is imposed on them, which is denoted by P.

When large supermarkets choose the "nonimplementation policy," no matter what policy the local government chooses, the benefit is denoted by Rt. When large supermarkets choose "implementation policy," no matter what policy the local government chooses, the large supermarkets will incur additional costs to enforce the policy, denoted by Ca, including the transportation costs of donating food to charities. At the same time, the large supermarket will gain a good corporate image and a hidden benefit, set to Ra. When the local government chooses "negative regulation" and the large supermarket chooses "nonimplementation policy," there is a risk of public or third-party exposure. The probability is recorded as ω; at this point, the local government receives a negative impact, recorded as F. The large supermarket will be penalized by the higher government, which is also P, but the local government will not receive this fine.

Thus, the meaning of the parameters and the matrix of benefits for the local government and the large supermarkets are shown in Tables 1 and 2.

4.2. Systematic Stability Analysis. Initially, U_{g1} and U_{g2} signify the expected earnings when the local government selects the "positive regulation" and "negative regulation" strategies, respectively, and $\overline{U_g}$ signifies the average earnings for local government, described as follows:

$$\begin{aligned} U_{g1} &= y(N - Cr) + (1 - y)(P - Cr), \\ U_{g2} &= -(1 - y)\omega F, \\ \overline{U_g} &= xU_{g1} + (1 - x)U_{g2}. \end{aligned} \tag{1}$$

Similarly, let U_{s1} and U_{s2} denote the expected returns of the large supermarkets when they choose the "implementation policy" and "nonimplementation policy" strategies, respectively, and $\overline{U_s}$ denotes the average returns for large supermarkets, described as follows:

$$\begin{aligned} U_{s1} &= x(Rt + Ra - Ca) + (1 - x)(Rt + Ra - Ca), \\ U_{s2} &= x(Rt - P) + (1 - x)(Rt - \omega P), \\ \overline{U_s} &= yU_{s1} + (1 - y)U_{s2}. \end{aligned} \tag{2}$$

Accordingly, the replication dynamic equation [35] of the local government's "positive regulation" strategy and the large supermarket's "implementation policy" strategy is

$$\begin{aligned} F(x) = \frac{dx}{dt} &= x\left(U_{g1} - \overline{U_g}\right) \\ &= x(1 - x)[y(N - P - \omega F) + P - Cr + \omega F], \end{aligned} \tag{3}$$

$$\begin{aligned} F(y) = \frac{dy}{dt} &= y\left(U_{s1} - \overline{U_s}\right) \\ &= y(1 - y)[x(P - \omega P) + Ra - Ca + \omega P]. \end{aligned} \tag{4}$$

The result is that the replicated dynamic state can be obtained, by making equations (3) and (4), and local equilibrium points (LEPs) also can be obtained by making equations (3) and (4) equal to 0. Therefore, the five LEPs in the system are (0, 0), (0, 1), (1, 0), (1, 1), and (x^*, y^*), in which $x^* \in [0, 1]$ and $y^* \in [0, 1]$, where $x^* = (Ca - Ra - \omega P)/(P - \omega P)$ and $y^* = (Cr - P - \omega F)/(N - P - \omega F)$. Friedman [36] proposed describing the group dynamics by means of differential equations, and the stability of its equilibrium point can be obtained from the local stability analysis of the Jacobian matrix of the system, which is as follows:

$$J = \begin{bmatrix} \dfrac{df(x)}{dx} & \dfrac{df(x)}{dy} \\ \dfrac{df(y)}{dx} & \dfrac{df(y)}{dy} \end{bmatrix} = \begin{bmatrix} (1 - 2x)[y(N - P - \omega F) + P - Cr + \omega F] & x(1 - x)(N - P - \omega F) \\ y(1 - y)(P - \omega P) & (1 - 2y)[x(P - \omega P) + Ra - Ca + \omega P] \end{bmatrix}. \tag{5}$$

Table 1: Parameters symbol descriptions.

Parameters	Stakeholders	Descriptions
Cr	Local governments	The costs of positive regulation
P		The large supermarket is punished if it does not implement the policy
N		The political achievements from positive regulation
F		Under negative supervision, the problems are exposed by third-party supervision or the public, and the local government is negatively affected
ω		The probability of problems being exposed by third-party supervision or the public under passive supervision
Rt	Large supermarkets	Large supermarkets will be fined if they do not implement the policy
Ca		Extra cost of implementing the PAFW
Ra		Additional earnings

Table 2: Payoff matrix.

		Large supermarket	
		Implementation policy	Nonimplementation policy
Local governments	Positive regulation	N–Cr, Rt + Ra–Ca	P–Cr, Rt-P
	Negative regulation	0, Rt + Ra–Ca	$-\omega$F, Rt-ωP

The LEP of the replicated dynamic system is judged as an ESS if it satisfies the following conditions: det $J > 0$, tr $J < 0$. Det J and tr J for each LEPs are shown in Table 3.

To simplify the analysis, it is first necessary to construct a hypothesis. $N - \omega F > P$, that is, under active local government regulation, large supermarkets will increase the political performance of the local government when they choose the "implementation policy" strategy, and under negative regulation, large supermarkets will increase their political performance when they choose the "nonimplementation policy" strategy if a third party is involved. The difference between institutional or public exposure, which can have a negative effect on the local government, should be greater than the fine the local government receives for negative regulation. Otherwise, the local government has no incentive to regulate aggressively.

As seen from Table 3, to determine the symbols of det J and tr J for different LEPs, the symbols of $P - Cr + \omega F$, $N - Cr$, $Ra + P - Ca$, and $Ra + \omega P - Ca$ should be discussed, where ω is the probability that the problem will be exposed to third-party regulation or public exposure under negative regulation ($0 < \omega < 1$), $\omega P < P$.

As shown in Table 4, there are six evolution states to be analyzed, and we express the regional ABCD as the mixed strategy space of this evolutionary game:

(1) In Scenario 1, Scenario 2, and Scenario 4: as shown in Table 4, point A (0, 0) is the ESS of the system, namely, {negative regulation, nonimplementation policy}, and the evolutionary path is shown in Figures 1(a), 1(b), and 1(d). This scenario is not conducive to policy diffusion. For large supermarkets, the high cost of implementing the policy discourages them from implementing the policy. For the local government, being exposed causes little negative impact, and the penalties for large supermarkets that fail to implement the policy are too light to compensate for the huge cost of local government regulation, and local government incentives to regulate will be greatly discouraged.

(2) In Scenario 3: as shown in Table 4, point B (0, 1) is the ESS of the system, namely, {positive regulation, nonimplementation policy}, and the evolutionary path is shown in Figure 1(c). For the large supermarkets, the high fines make them enforce the policy. The small negative impact of being exposed and the low fines will make the local government choose the "negative regulation" strategy.

(3) In Scenario 5: as shown in Table 4, point A (0, 0) and point D (1, 1) are both the system ESS {negative regulation, nonimplementation policy} and the optimal policy {positive regulation, implementation policy}, respectively, with evolutionary paths shown in Figure 1(e). In this context, when the local government is actively regulating, the cost to the large supermarket of enforcing the policy is less than the amount of the fine imposed for nonimplementation but greater than the expected value of the fine due to public or third-party exposure when the local government is negatively regulating. The cost of local government regulation is still higher than the sum of the fines imposed on large supermarkets that do not enforce the policy and the negative impact of being exposed. As shown in Figure 1(e), the final ESS depends not only on the saddle point (x, y) but also on the participants' initial choice of proportions. Specifically, if a participant's initial state is in the ABEC region and when the participant's initial state converges to A (0, 0), the final choice is the {negative supervision, nonimplementation policy} strategy. If the participant's initial state is in the BECD region and when the participant's initial state converges to D (1, 1), the final choice is the {positive regulation, implementation policy} strategy.

Table 3: The det J and tr J at each LEP.

LEP	det J	tr J
A(0,0)	$(P - Cr + \omega F)(Ra - Ca + \omega P)$	$P - Cr + \omega F + Ra - Ca + \omega P$
B(0,1)	$(N - Cr)(Ca - Ra - \omega P)$	$N - Cr + Ca - Ra - \omega P$
C(1,0)	$(Cr - P - \omega F)(P + Ra - Ca)$	$Cr - P - \omega F + P + Ra - Ca$
D(1,1)	$(N - Cr)(P + Ra - Ca)$	$Cr - N - P - Ra + Ca$
E(x^*, y^*)	$[(P - Cr + \omega F)(Ca - Ra - \omega P)(N - Cr)(P + Ra - Ca)]/[(N - P - \omega F)(P - \omega P)]$	0

Table 4: The evolutionary stability of each LEP.

Scenarios	LEP	det J	tr J	State
Scenario 1: $Cr > N > P + \omega F$	A(0,0)	+	−	ESS
	B(0,1)	−	Uncertain	Saddle point
$Ca > Ra + P$	C(1,0)	−	Uncertain	Saddle point
	D(1,1)	+	+	Unstable
Scenario 2: $Cr > N > P + \omega F$	A(0,0)	+	−	ESS
	B(0,1)	−	Uncertain	Saddle point
$Ra + \omega P < Ca < Ra + P$	C(1,0)	+	+	Unstable
	D(1,1)	−	Uncertain	Saddle point
Scenario 3: $Cr > N > P + \omega F$	A(0,0)	−	Uncertain	Saddle point
	B(0,1)	+	−	ESS
$Ca < Ra + \omega P$	C(1,0)	+	+	Unstable
	D(1,1)	−	Uncertain	Saddle point
Scenario 4: $N > Cr > P + \omega F$	A(0,0)	+	−	ESS
	B(0,1)	+	+	Unstable
$Ca > Ra + P$	C(1,0)	−	Uncertain	Saddle point
	D(1,1)	−	Uncertain	Saddle point
Scenario 5: $N > Cr > P + \omega F$	A(0,0)	+	−	ESS
	B(0,1)	+	+	Unstable
$Ra + \omega P < Ca < Ra + P$	C(1,0)	+	+	Unstable
	D(1,1)	+	−	ESS
Scenario 6: $N > Cr > P + \omega F$	A(0,0)	−	Uncertain	Saddle point
	B(0,1)	−	Uncertain	Saddle point
$Ca < Ra + \omega P$	C(1,0)	+	+	Unstable
	D(1,1)	+	−	ESS
Scenario 7: $N > P + \omega F > Cr$	A(0,0)	−	Uncertain	Saddle point
	B(0,1)	+	+	Unstable
$Ca > Ra + P$	C(1,0)	+	−	ESS
	D(1,1)	−	Uncertain	Saddle point
Scenario 8: $N > P + \omega F > Cr$	A(0,0)	−	Uncertain	Saddle point
	B(0,1)	+	+	Unstable
$Ra + \omega P < Ca < Ra + P$	C(1,0)	−	Uncertain	Saddle point
	D(1,1)	+	−	ESS
Scenario 9: $N > P + \omega F > Cr$	A(0,0)	+	+	Unstable
	B(0,1)	−	Uncertain	Saddle point
$Ca < Ra + \omega P$	C(1,0)	−	Uncertain	Saddle point
	D(1,1)	+	−	ESS

(4) In Scenario 7: as shown in Table 4, point C (1, 0) is the ESS of the system, namely, {positive regulation, nonimplementation policy}, and the evolutionary path is shown in Figure 1(g). In this scenario, the local government will choose the "negative regulation" strategy because of the high fine, while the large supermarkets will not choose the "implementation policy" strategy because the cost is higher than the fine.

(5) In Scenario 6, Scenario 8, and Scenario 9: as shown in Table 4, point D (1, 1) is the ESS of the system, namely, {positive regulation, implementation policy}, and the evolutionary path is shown in Figures 1(f), 1(h), and 1(i). In this scenario, the local government will choose the "positive regulation" strategy due to the high fine. However, large supermarkets will be fined so much when choosing the "nonimplementation policy" strategy in the positive regulation scenario that they can only choose the "implementation policy" in the positive regulation. However, because of the existence of discretion, local governments can choose their own fines within the

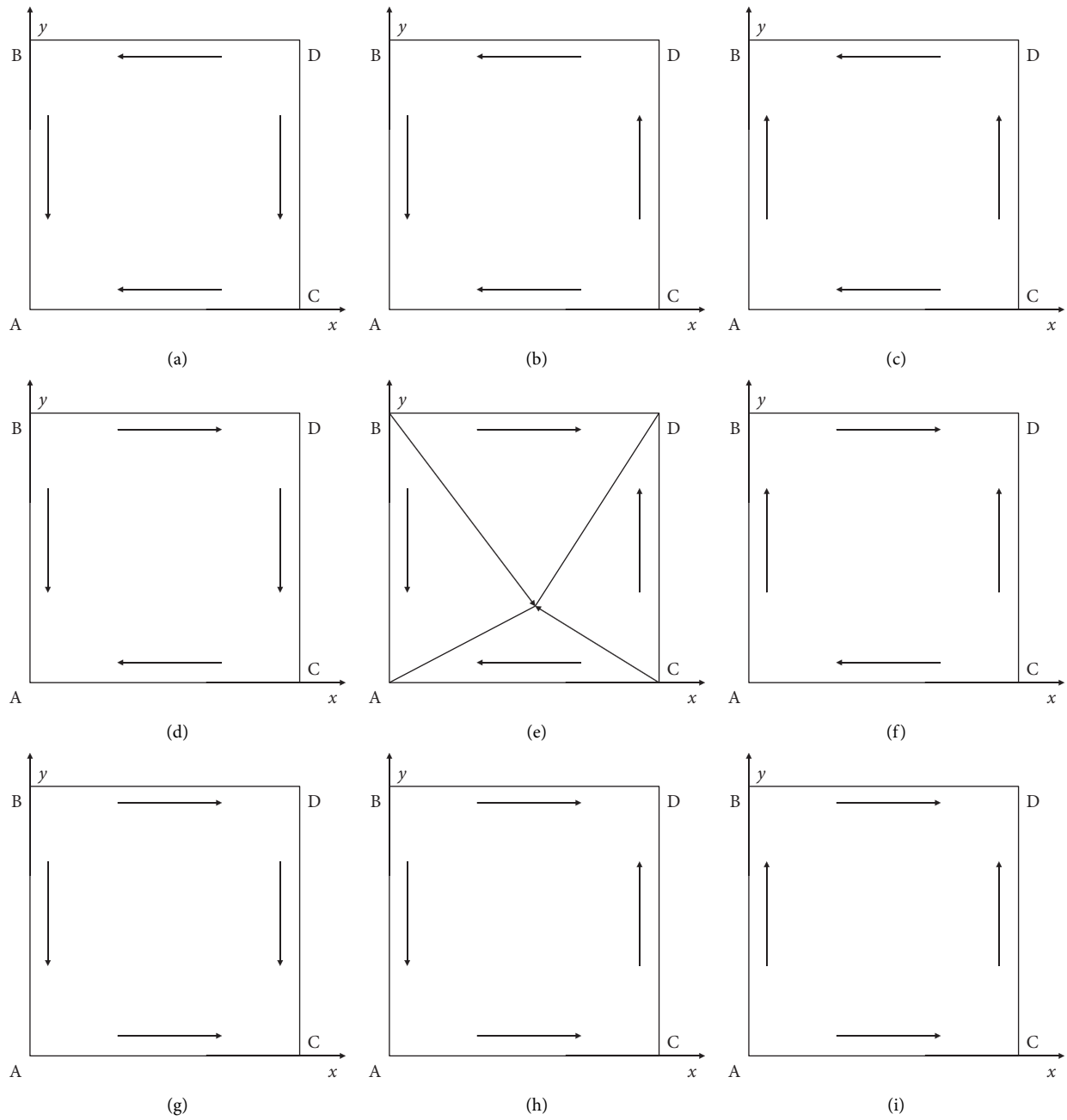

Figure 1: Evolution phase diagram of the system.

standard range. Therefore, to facilitate the development of local enterprises, local governments generally do not implement fines that are too severe.

4.3. System Simulation Analysis. In order to verify the accuracy of the model results and make the dynamic evolution trend clearer and more vivid, we use MATLAB 2020a software to simulate the dynamic evolution trajectory of the evolutionary system. The parameter settings for the different situations are as follows:

(1) In Scenario 1, $N = 16$ Cr = 22 Ca = 17 Ra = 8 $P = 6$, $F = 6$ $\omega = 0.5$, as shown in Figure 2(a), the track of evolution will be eventually inclined to ESS A (0, 0) that is consistent with the analysis of the model.

(2) In Scenario 2, $N = 16$ Cr = 22 Ca = 17 Ra = 8 $P = 12$, $F = 6$ $\omega = 0.5$, as shown in Figure 2(b), the track of evolution will be eventually inclined to ESS A (0, 0) that is consistent with the analysis of the model.

(3) In Scenario 3, $N = 16$ Cr = 22 Ca = 17 Ra = 8 $P = 20$, $F = 6$ $\omega = 0.5$, as shown in Figure 2(c), the track of evolution will be eventually inclined to ESS B (0, 1) that is consistent with the analysis of the model.

(4) In Scenario 4, $N = 28$ Cr = 22 Ca = 17 Ra = 8 $P = 6$, $F = 6$ $\omega = 0.5$, as shown in Figure 2(d), the track of evolution will be eventually inclined to ESS A

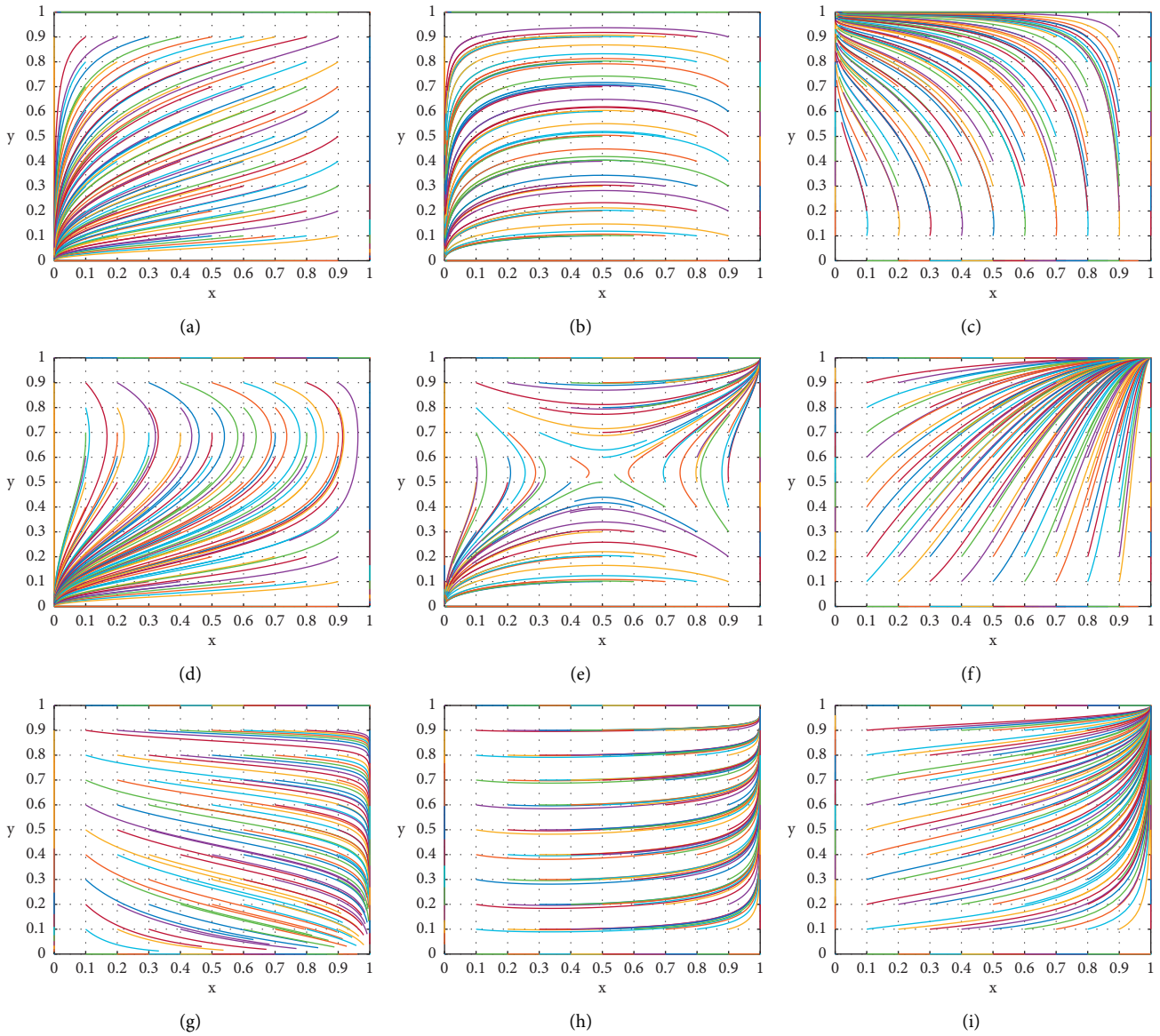

Figure 2: System evolution phase diagram.

(0, 0) that is consistent with the analysis of the model.

(5) In Scenario 5, $N = 28$ Cr = 22 Ca = 17 Ra = 8 $P = 12$, $F = 6$ $\omega = 0.5$, as shown in Figure 2(e), the track of evolution will be eventually inclined to ESS A (0, 0) and D (1, 1) that is consistent with the analysis of the model.

(6) In Scenario 6, $N = 28$ Cr = 22 Ca = 17 Ra = 8 $P = 20$, $F = 6$ $\omega = 0.5$, as shown in Figure 2(f), the track of evolution will be eventually inclined to ESS D (1, 1) that is consistent with the analysis of the model.

(7) In Scenario 7, $N = 16$ Cr = 3 Ca = 12 Ra = 8 $P = 3$, $F = 2$ $\omega = 0.5$, as shown in Figure 2(g), the track of evolution will be eventually inclined to ESS C (1, 0) that is consistent with the analysis of the model.

(8) In Scenario 8, $N = 16$ Cr = 3 Ca = 12 Ra = 8 $P = 6$, $F = 2$ $\omega = 0.5$, as shown in Figure 2(h), the track of evolution will be eventually inclined to ESS D (1, 1) that is consistent with the analysis of the model.

(9) In Scenario 9, $N = 16$ Cr = 3 Ca = 12 Ra = 8 $P = 10$, $F = 2$ $\omega = 0.5$, as shown in Figure 2(i), the track of evolution will be eventually inclined to ESS D (1, 1) that is consistent with the analysis of the model.

4.4. System Sensitivity Analysis. According to the above analysis, the evolutionary game systems of Scenario 1, Scenario 2, Scenario 3, Scenario 4, Scenario 6, Scenario 7, Scenario 8, and Scenario 9 all have only one ESS. Scenario 5 ESS will be {negative regulation, nonimplementation policy} and the perfect one, {positive regulation, implementation policy}. Due to the position of the saddle point (x^*, y^*) and the initial selection probability of each participant, the

evolutionary game system tends to have different stable points [37]. Hence, it has great significance to study which factors will influence the system.

It can be seen from Figure 1(e), when the initial state is in the ABEC region, point A (0, 0) is the ESS. Similarly, when the initial state is at BECD, then point D (1, 1) will be the ESS. In order to reach the probability that the evolutionary game system will tend toward the optimal strategy {positive regulation, implementation policy}, the location of point E should be inclined to the direction of point A to reduce the area of ABEC, which can be calculated as follows:

$$S_{ABEC} = \frac{1}{2}\left(x^* + y^*\right) = \frac{1}{2}\left(\frac{Ca - Ra - \omega P}{P - \omega P} + \frac{Cr - P - \omega F}{N - P - \omega F}\right). \tag{6}$$

Equation (6) shows that the area of SABEC changes with the change in x^* and y^*, and the change in x^* and y^* changes with the change in seven parameters: Ca, Cr, Ra, N, P, F, and ω. Intuitively, Ca and Cr are positively correlated with SABEC, and Ra, F, and ω being negatively correlated. However, the effect of the remaining parameters on the SABEC is uncertain. Therefore, in order to facilitate the analysis, the method of numerical simulation is used in Scenario 5, the initial selection of participants and the change in various parameters affect the evolutionary trajectory.

4.4.1. Sensitivity Analysis of the Initial Probability of Strategies. First, it discusses the influence of the initial strategy choice probability of local governments and large supermarkets on the ESS is discussed. The probabilities of choosing X and Y are (0.5, 0.5) and (0.8, 0.8), respectively. The simulation results are shown in Figure 3. It can be known that the different selection probabilities will make the evolutionary game system have different evolutionary directions. The simulation results show that the method can effectively improve the performance of the system. The initial probability that the local government chooses the "positive regulation" strategy and the large supermarket chooses the "implementation policy" strategy is 0.5, and the ESS is {negative regulation, nonimplementation policy}, as shown in Figure 3(a). However, when the initial probability rises to 0.8 and 0.8, the ESS is {positive regulation, implementation policy}, and it is shown in Figure 3(b). This finding proves that the initial state of both participants will immediately impact the final ESS. Hence, it is a must to establish clear guidance measures to improve the probability of local government choosing positive regulation and the probability of the large supermarket initially choosing to implement the policy, which has important guiding significance for the promotion of the PAFW.

4.4.2. Sensitivity Analysis of the Parameters. In this section, the parameter sensitivities of the participants in Scenario 5 are examined, that is, the additional cost to the large supermarket from implementing the policy (Ca), the additional profit (Ra), the penalty to the large supermarket for not implementing the policy (P), the monitoring expenditure (Cr), and the political achievement from active monitoring (N). Under negative supervision, the problems are exposed by third-party supervision or the public, the government is negatively affected (F), and problems can be exposed by third-party supervision or the public under passive supervision (ω). We assume that when simulating the sensitivity of one parameter, the values of the other parameters are held constant in Scenario 5, where the initial choice probabilities of the stakeholders are 0.5 [38]:

(1) Figure 4 shows the sensitivity of stakeholders to the expenditure cost (Ca) of large supermarkets when implementing policies by setting Ca to 15, 17, and 19. When the expenditure cost of large supermarkets implementing policies is low (Ca = 15), the ESS will tend toward {positive regulation, implementation policy}. When Ca increases to 17 and 19, the ESS will tend toward {negative regulation, nonimplementation policy}, and when Ca increases from 17 to 19, the rate of evolution increases, indicating that supermarkets will choose the "nonimplementation policy" strategy when the cost of enforcing the policy is higher than a certain level.

(2) Figure 5 shows the sensitivity of stakeholders to political achievement (N) when the local government is actively enforcing regulations, setting N to 28, 30, and 32. When the political achievement that the local government receives as a result of active regulation is too low ($N = 28$), the ESS will tend toward {negative regulation, nonimplementation policy}. As N increases to 30 and 32, the ESS will tend toward {positive regulation, implementation policy}, and when Ca increases from 30 to 32, the rate of evolution increases, indicating that when the local government's political achievement from positive regulation is below a certain level, the local government will choose the "negative regulation" strategy.

(3) Figure 6 shows the sensitivity of stakeholders to the additional gains (Ra) that large supermarkets make from choosing to implement the policy, setting Ra to 6, 8, and 10. When the local government's political success from active regulation is too low (Ra = 6, 8), the ESS will tend toward {negative regulation, nonimplementation policy}. When $r = 6$, the evolution is faster. When Ra increases to 10, the ESS will tend toward {positive regulation, nonimplementation policy}. When Ra rises to 10, the ESS will tend toward {positive regulation, implementation policy}, indicating that large supermarkets will choose the "implementation policy" strategy when the additional gains from enforcing the policy are above a certain level.

(4) Figure 7 shows the sensitivity of stakeholders to the cost of local government regulation (Cr), setting Cr to 22, 24, and 26. The ESS will evolve toward

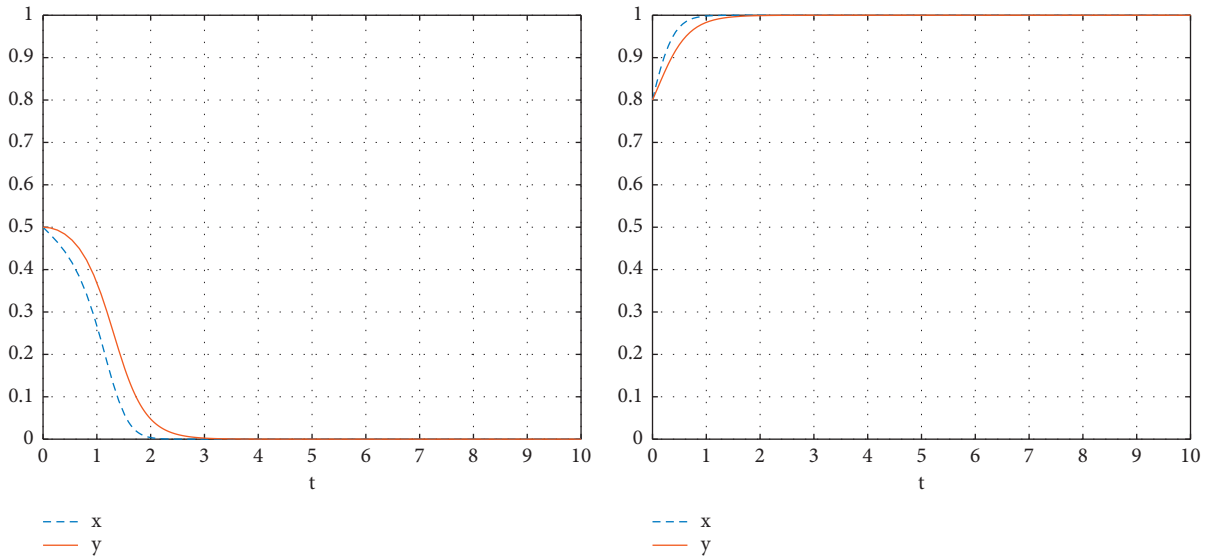

Figure 3: Dynamic evolution path of various initial probabilities.

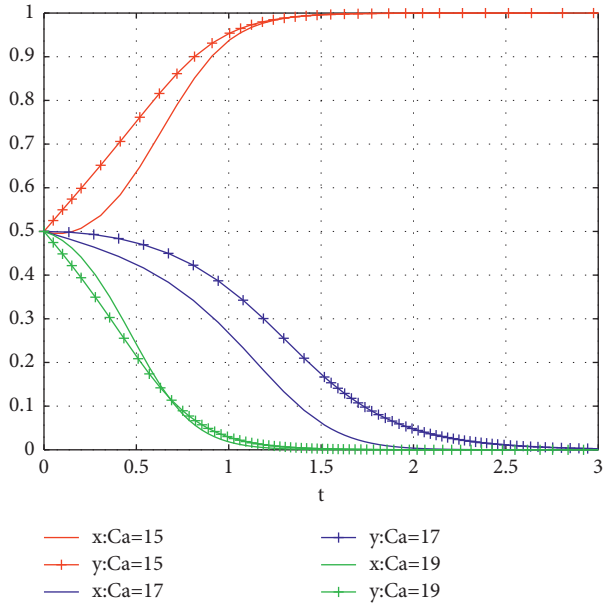

Figure 4: The sensitivity of Ca.

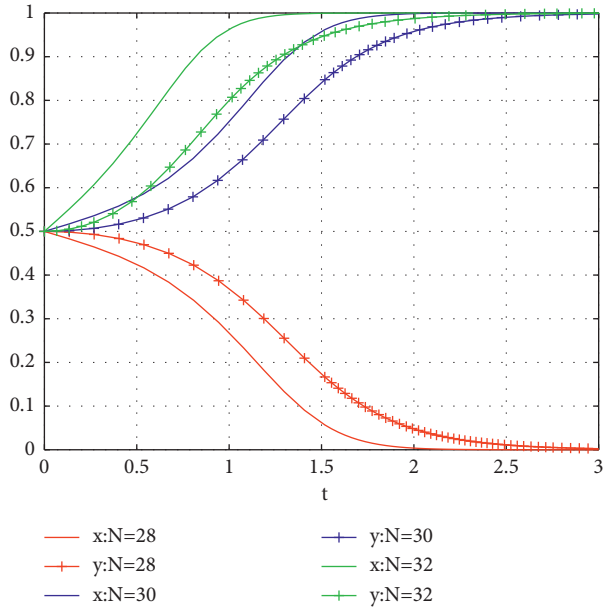

Figure 5: The sensitivity of N.

{negative regulation, nonimplementation policy}, and it evolves more quickly as Cr increases, which further suggests that measures should be taken to reduce the cost of local government regulation.

(5) Figure 8 shows the sensitivity of stakeholders to a penalty on large supermarket (P), setting P to 12, 14, and 16. When the local government imposes a lower penalty on large supermarkets ($P = 12$), the ESS will be {negative regulation, nonimplementation policy}. When P increases to 14 and 16, the ESS will be {positive regulation, implementation policy}, and as P increases from 14 to 16, the speed of evolution increases, indicating that large supermarkets tend to choose the "implementation policy" strategy when the large supermarket penalty (P) is higher.

(6) Figure 9 shows the sensitivity of stakeholders to the negative impact (F) on the local government when issues are exposed to third-party agencies or the public under negative regulation, setting F to 5, 6, and 7. The ESS evolves toward {negative regulation, nonimplementation policy}, and this evolution slows as F increases, suggesting that the smaller the negative impact is, the more the government tends to regulate negatively.

(7) Figure 10 shows the sensitivity of stakeholders to the probability (ω) that a local government issue will be

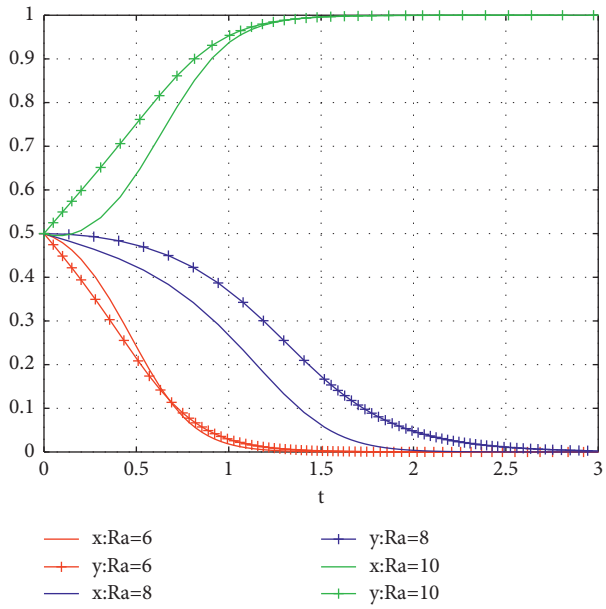

Figure 6: The sensitivity of Ra.

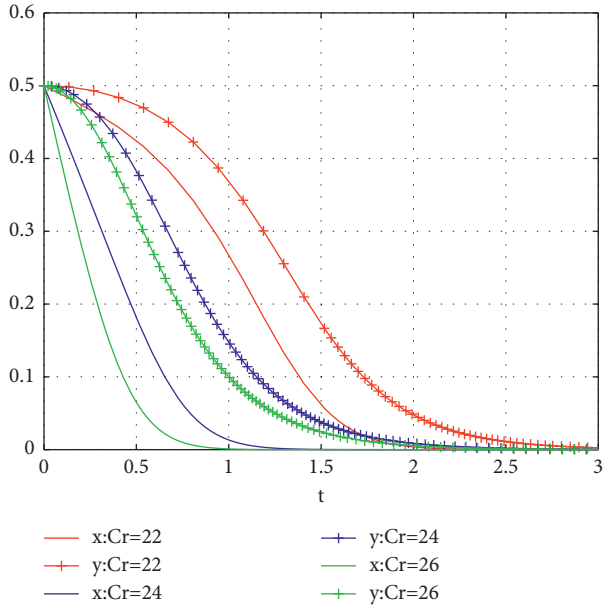

Figure 7: The sensitivity of Cr.

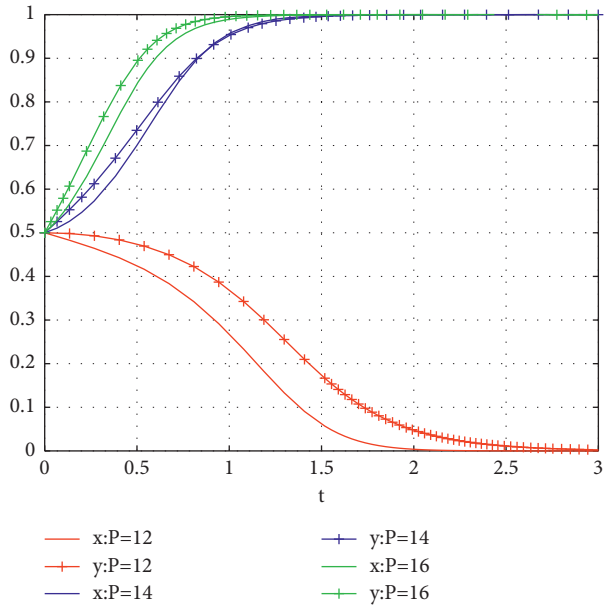

Figure 8: The sensitivity of P.

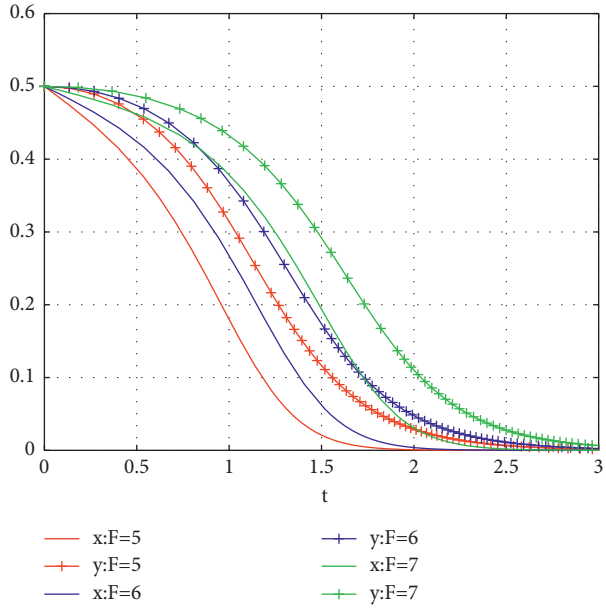

Figure 9: The sensitivity of F.

exposed to a third-party agency or the public under negative regulation, setting ω to 0.3, 0.5, and 0.7. When the probability of exposure is too low ($\omega = 0.3, 0.5$), the ESS will evolve toward {negative regulation, nonimplementation policy}, and when the probability of exposure rises to 0.7, the ESS will evolve toward {positive regulation, nonimplementation policy}. This further demonstrates the need for measures to increase the publicity and public awareness of environmental protection so that they have a higher probability of exposing large supermarkets that do not enforce their policies.

4.5. Simulation Results' Discussion. From the above simulation results, it can be concluded that the local government plays a key role in promoting the effective implementation of the PAFW in large supermarkets, and the effective and positive regulation of the PAFW is the key issue. The ESS is {negative regulation, nonimplementation policy} if the local government spends huge regulatory costs and very light penalties for large supermarkets that do not enforce the policy. Thus, local governments can use regulation by the public, NGOs, the press, and the Internet to reduce regulatory costs while gaining a good reputation and political success. In the scenario of large supermarkets, the strategy

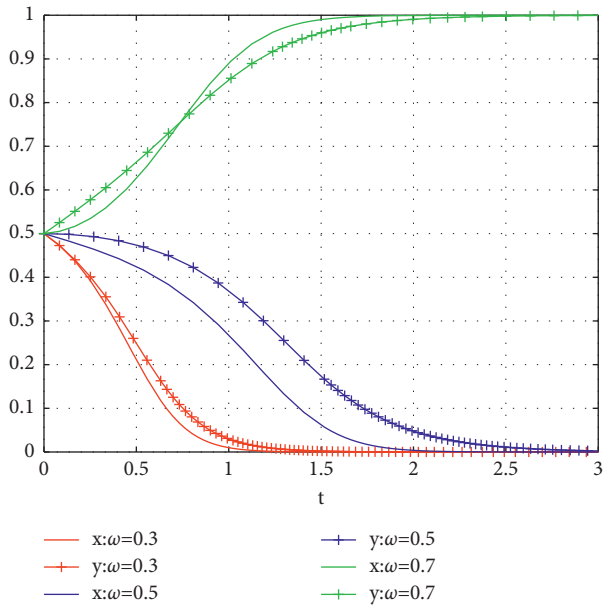

Figure 10: The sensitivity of ω.

depends on the degree of local government regulation, the cost of implementing the PAFW, and the additional benefits gained. It is therefore necessary for local governments to increase the penalties for large supermarkets that choose the "nonimplementation policy" strategy beyond what is already in place. In addition, greater awareness of the dangers of food waste and the importance of the PAFW will increase the public regulation of large supermarkets and the additional benefits that large supermarkets gain from implementing them.

5. Conclusions and Policy Implications

5.1. Conclusions. Food waste not only causes economic losses but also seriously endangers the natural resources on which human beings depend for survival. Therefore, the implementation of the PAFW is necessary. In this paper, the local government-large supermarket game model is established to explore how to promote the PAFW among large supermarkets in China from a micro perspective. The results show that to achieve the most effective strategy of active local government regulation and large supermarket policy implementation, China should adopt the following three measures: (1) strengthen local government regulation, including improving the local government's political performance and reducing regulatory costs; (2) enhance the willingness of large supermarkets to implement the PAFW, including reducing the cost of implementing the policy and increasing the benefits of implementation policy, such as the local government giving large supermarkets a certain amount of tax exemption due to the implementation of the policy and establishing a good image, and the public welcoming and promoting change; (3) facilitate the public's and third parties' exposure of large supermarkets' failure to implement the policy. Through numerical simulation, we find that increasing the initial probability of the local government and the large supermarket choosing the active regulation and implementation strategy will have guiding significance for the research. In addition, to obtain a greater probability of achieving the optimal strategy {positive regulation, implementation policy}, the key is to reduce the local government's regulatory costs, improve the implementation of the large supermarket policy to obtain additional benefits, reduce the cost of implementing the policy, and improve the public's and third parties' exposure of large supermarkets' failure to implement the policy and the negative impact on the local government after exposure.

5.2. Policy Implications.

(1) The local government should increase public awareness about saving food so that large supermarkets and the public grasp the need to save food; it should also highlight the importance of the PAFW and the related policies in France, Italy, Finland, and other countries in terms of economic benefits, social benefits, and environmental benefits. Relevant departments should strengthen the legislative work in this regard, developing laws against food waste as well as the corresponding specific standards, and it is necessary to strengthen the efficiency of local government supervision of large supermarkets. At the same time, through supervision by NGOs, the Internet, the news media, the public, and large supermarkets' implementation policy, the policy will lead to a good corporate image. In contrast, when a large supermarket does not implement the policy and is exposed by these parties, the large supermarket is fined, and the reputation of the local government is affected and severely punished by the higher-level government; this will promote the local government to strengthen its supervision of supermarkets.

(2) Because the implementation of the policy may involve high costs and lower income, large supermarkets may not be willing to choose the "implement the policy" strategy, and the local government must give some preferential policies, such as a certain amount of tax exemptions, to encourage the large supermarkets to implement the policy; it should also encourage nonprofit organizations to actively cooperate with large supermarkets, reducing the costs of implementing the policy for large supermarkets. To strengthen the implementation of the policy and improve large supermarkets' publicity, other large supermarkets should choose the "implementation policy" strategy to inject new momentum.

(3) The local government should strengthen the construction of the regulatory system, optimize the structure, and reduce the cost of supervision. First, management should be strengthened by establishing and improving the regulatory authorities at the level of laws and regulations and establishing financial

standards. The basic principles and system of the regulatory authorities should be established; work requirements should be clarified, the regulatory authorities should carry out regulatory activities according to the established principles, the implementation of the system should be implemented, and the standards should be enforced to further improve the level of standardization and institutionalization. Additionally, to obtain the maximum management and service benefits, logistics service resources should be used; administrative expenses, energy consumption, and the operating costs of regulatory authorities should be reduced; human, financial, and material resources should be allocated and used reasonably; and as few as possible resources should be consumed.

In general, promoting the regulations on the PAFW relies on the collaborations among government, companies, and the public society. In particular, it can indirectly increase the food supply in China and smooth the trend of rapid growth in the import rate, which benefits the issues on food safety in China. Furthermore, it will release the pressure from the increase in food prices in China, which makes certain contributions in controlling inflation.

5.3. Limitations. This study contends with several limitations. First, the promotion of the PAFW involves many stakeholders, including the local government, large supermarkets, higher authorities, NGOs, and the news media. The game between the local government and large supermarkets is established under the premise of ignoring other game models. Second, this paper only uses the scenario for simulation because of the lack of real data. In future research, it is hoped that the real data can be used to test the interest coordination of stakeholders in the policy promotion process. Third, the parametric assumptions used in our game model are static. In addition to static scenarios, dynamic parameters can enrich the content of this article. Fourth, in addition to the evolutionary game, data-driven approaches could provide useful solutions in addressing the problem of the donation intention of supermarkets and the implementation cost for different policies [39, 40].

Data Availability

No data were used to support the findings of this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Research Article

The Impact of Smart City Construction on the Quality of Foreign Direct Investment in China

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As a new model of urban development, it is important to scientifically analyze the impact of smart cities on the quality of foreign direct investment (FDI). This article constructs a difference in differences' model to test the impact of foreign direct investment quality in smart city construction based on panel data of 226 prefecture-level cities from 2006–2017. Study shows the following. (1) The construction of smart cities has significantly improved the quality of FDI utilized in pilot cities. (2) Heterogeneity analysis shows that smart city construction significantly contributes to the quality of FDI in the western city subsample and a subsample of cities with low natural resource dependence. After a series of robustness tests and placebo tests, the above conclusions still hold. The results of the study suggest that China should further promote the construction of smart cities to optimize the quality of foreign direct investment and promote high-quality economic growth. The findings of the study also provide theoretical and practical references for the construction of smart cities in China and other countries around the world.

1. Introduction

In 2008, the International Business Machines Corporation (IBM) puts forward the concept of smart city, China's smart city development in the concept of the introduction period; at this time, local enterprises are in the fumbling stage. The market is also dominated by international software system integrator. In 2012, with the increasing level of urbanization in China, the Ministry of Housing and Construction issued the "Interim Measures on National Smart City Pilot," and the construction of smart cities in China started to get on track driven by the development of information technology. In 2016, as China's 5G, big data, artificial intelligence (AI), and other technology levels become increasingly mature, China's smart city construction towards digital and intelligent development enters a new stage of development. As of early April 2020, the number of three batches of smart city pilot lists announced by the Ministry of Housing and Construction in China has reached 290. China's smart city construction has shown the trend of provincial-level cities leading, prefecture-level cities following, and county-level cities and city clusters starting, with emerging applications and models emerging in the development process.

Since China's accession to the World Trade Organization in 2001, the amount of foreign investment in China has shown an overall growth trend, with the actual amount of foreign investment utilized in China increasing from US$ 53.505 billion in 2003 to US$163 billion in 2020 (see Figure 1).As a result of the new crown epidemic, global FDI will total about $859 billion in 2020, a significant contraction of 42% compared to 2019, but China will absorb foreign investment against the trend of 4% growth, surpassing the United States to become the world's largest foreign investment inflow country. In the difficult time of global foreign investment flow, China achieves the "three improvements" in the total amount of attracted capital, growth rate, and global share. Global R&D centers, headquarters projects, and supply chain operation centers have become hotspots for foreign investment in China. As a smart city in the first echelon of Shanghai, in January 15, 2021, 62 foreign investment projects concentrated in Shanghai, with a total investment of $ 11.85 billion. And, the signed projects cover a number of fields such as artificial intelligence, integrated

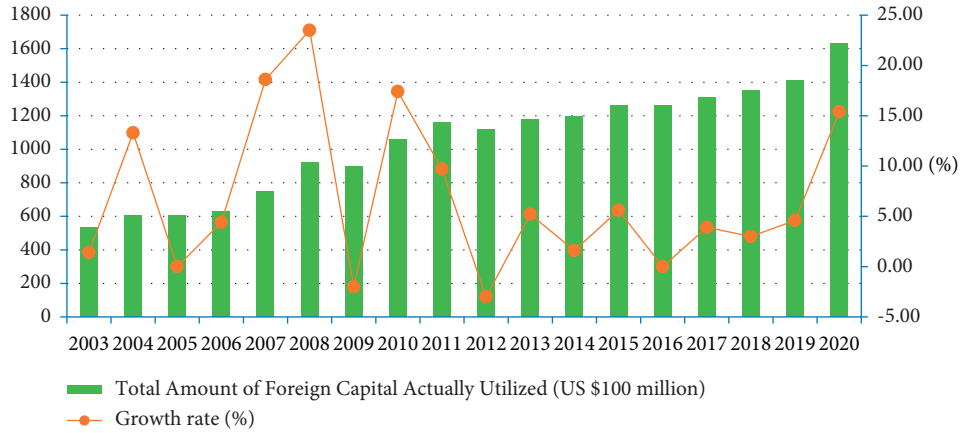

Figure 1: Total amount of foreign capital actually utilized in China from 2003 to 2020.

circuits, and digital economy, with the characteristics of high capacity of the investment body, key functional area projects, leading industry technology tip, and wide distribution of key industries. The comprehensive promotion of *s* related to smart city innovation and reform trials will help promote the digital and intelligent transformation of industries in pilot cities and maintain the rapid development momentum of strategic emerging industries.

Although smart city construction has moved into the 2.0 era of data interconnection, there is little literature on the study of smart city pilots on the quality of foreign investment. In the context of the innovation-driven development strategy, the utility of specific applications of smart city construction is extensive and far reaching, especially in terms of transforming the city's economic development and thus improving the performance of attracting foreign investment. Only an in-depth investigation into the impact of China's smart city pilot construction on the quality of attracting foreign investment can provide targeted guidance for China's smart city construction practice on the use of foreign investment in cities under economic opening.

2. Literature Review

The research in this article is mainly related to the literature on three aspects: the significance of smart city construction, the mechanism of the role of smart city construction on China's high-quality development, and the study of factors influencing the quality of foreign investment.

2.1. The Significance of Smart City Construction. At present, scholars are mostly positive about the construction of smart cities. Alcaide Muñoz and Rodríguez Bolívar argue that smart city building can empower people in public decision-making and facilitate access to knowledge and innovation-based solutions for sustainable development [1]. Algorithms based on deep learning and clustering techniques, such as those of Parlina et al., argue that smart cities can be built in six dimensions of smart sustainability: technology, energy, environment, transportation, e-governance, human capital, and welfare [2]. Linde et al. argue that, in the smart city building environment, the requirements of technological development, digitization, and sustainability have led to an increasing dynamism of businesses and created new opportunities for innovation in urban systems [3]. Shi et al., using China as a case study, argue that the potential mechanism of smart city development inhibited the New Crown Pneumonia epidemic and that the epidemic has, to some extent, instead accelerate the construction of smart cities in China [4]. Interventionary studies involving animals or humans and other studies that require ethical approval must list the authority that provides approval and the corresponding ethical approval code.

2.2. Mechanism of the Role of Smart City Construction on China's High-Quality Development. The essence of a smart city is to use the Internet, big data, and other technical means to promote the organic coordination of urban service elements and residents' needs and to improve people's quality of life. At present, numerous scholars have focused on the research aspect of the effects of smart city construction. According to Zhou and Li, smart cities have a significant boosting effect on economic growth that increases with the level of urban human capital, higher levels of financial development, and lower levels of government intervention [5]. Tang empirically analyzed smart city construction as a proxy variable for the digital economy and concluded that it can promote high-quality urban development [6]. Shi and Zhang construct a PSM-DID model to empirically analyze a sample of 224 cities in China and find that smart city construction can significantly promote the development of the financial industry [7]. Nie reveals the logic of the "binary margin" expansion of smart city construction and foreign investment through empirical evidence from a panel of 186 prefecture-level cities and argues that the expansion effect of foreign investment in smart city pilots is achieved mainly by reducing inputs and enhancing infrastructure construction [8].

2.3. Study on the Influencing Factors of Foreign Investment Quality. The earliest scholar to focus on the quality of foreign investment was the British economist Dunning.

Dunning argues that the investment motives of multinational firms and the location advantages of the host country determine the quality of foreign investment [9]. Jin et al. further argue that the competitiveness stage of the host country plays a decisive role in the quality of international investment [10]. In addition, some scholars have explored the factors influencing the quality of foreign investment in terms of infrastructure level, technology level and competitiveness, and preferential policies, respectively [11]. In recent years, as the scale of foreign investment attracted by China has been expanding (see Figure 2), scholars have begun to pay attention to the quality of foreign investment utilized in China and come to different conclusions. Fu conducted an empirical study based on the average size of the project, the proportion of large and medium-sized enterprises, and other indicators and concluded that the quality of China's use of foreign investment is at a low level [12]. Nei and Liu, on the contrary, combined panel data from 2003–2015 in China for an empirical analysis and concluded that the productivity improvement of local firms significantly improved the quality of foreign investment in China [13].

In summary, the relevant literature on the impact of new city construction on the quality of foreign investment is still scarce, and scholars have not yet focused on the impact of smart cities on the quality of attracting foreign investment in China. As an important national "policy experiment," the smart city construction pilot is a remedy for the bottleneck of urbanization development. The pilot policy will lead to changes in the institutional environment, releasing dividends through the policy and thus attracting large-scale FDI inflows. As a reflection of China's institutional innovation, the smart city pilot can effectively improve the efficiency of urban management and enhance the supply of urban industries and services, promote the upgrading of urban industrial structure, and thus create a first-class business environment and expand the attractiveness to foreign enterprises. Therefore, based on the above literature review, this article proposes the core theoretical hypothesis to be tested: the construction of smart city pilot cities can improve the quality of foreign investment.

3. Materials and Methods

3.1. Measurement Methods. Taking into account the variability of economic agents before and after the smart city pilot policy, the variability of the provinces to which different cities belong and their own scale of attracting FDI, and the variability of being influenced by different levels of economic development, this article uses the smart city pilot in China as a quasi-natural experiment to analyze the impact of the smart city pilot on the quality of FDI using a difference-in-difference (DID) model. The DID model can effectively correct for "policy endogenous" and "selectivity bias" in the policy evaluation process. Among them, the double difference mainly comes from two levels, city and year, comparing the quality of foreign investment in pilot cities and nonpilot cities before and after the pilot. Under the model setting, this article sets the following DID model based on the study of Gehrsitz [14].

FDI_{ct} denotes FDI quality, and the subscripts c and t denote city as well as time, respectively. Smart_{ct} indicates whether city c is a pilot city in period t after the start of the smart city pilot. If $\mathrm{Smart}_{ct} = 1$, then it means that city c is a smart city pilot city in period t. Conversely, if $\mathrm{Smart}_{ct} = 0$ means that city c is not a smart city pilot city in period t. D_{ct} denotes a set of control variables. W_t and W_c denote the time fixed effect as well as the city fixed effect, respectively. ϑ_{ct} denotes the error term:

$$\mathrm{FDI}_{ct} = \alpha_0 + \alpha_1 \mathrm{Smart}_{ct} + \alpha_2 D_{ct} + W_t + W_c + \vartheta_{ct}. \quad (1)$$

3.2. Samples and Variables. China's Ministry of Housing and Urban-Rural Development and Ministry of Science and Technology announced three batches of smart city pilot lists in 2012, 2013, and 2014, respectively. For the purpose of model construction, after considering the consistency and availability of data, the prefecture-level cities with serious data deficiencies were excluded from this article, and data from 226 prefecture-level cities from 2006–2017 were selected to assess the impact of smart city pilots on the quality of FDI. Among them, the pilot cities of smart cities belong to the processing group, and the pilot cities not included in the "smart cities" belong to the control group. The data in this article are obtained from official statistical sources such as China City Yearbook and China Statistical Yearbook. Table 1 indicates that the variables selected in this article do not have serious autocorrelation.

3.2.1. Explained Variable: Quality of FDI. Currently, there is no unified standard in the academic community for measuring the quality of foreign investment. In this article, the average size of FDI enterprises and the foreign investment performance index are used to refer to the quality of FDI after referring to the studies of scholars such as Zhong and Chen and Sun and Zhou, respectively [15, 16]. ① Average size of foreign-invested enterprises (fdi_1): they are calculated using the ratio of actual FDI to the number of foreign-invested enterprises in each prefecture-level city. ② Foreign investment performance index: this was calculated using the following equation:

$$\mathrm{fdi}_2 = \frac{(\mathrm{fdi}_{ct}/\mathrm{cnfdi}_t)}{(\mathrm{gdp}_{ct}/\mathrm{cngdp}_t)}, \quad (2)$$

where fdi_{ct} denotes the amount of actual FDI acquired by city c in year t, cnfdi_t denotes the actual FDI acquired by China in year t, gdp_{ct}denotes the gross regional product of city c in year t, and cngdp_t denotes the GDP of China in year t.

3.2.2. Explanatory Variable: Whether It Is a "Smart Pilot" City. The core variable interpretation of a smart city pilot (smart) is defined as taking a value of 1 for the year of pilot and subsequent years if the city implements a smart city pilot effort, and 0 otherwise. Since the smart city pilots were

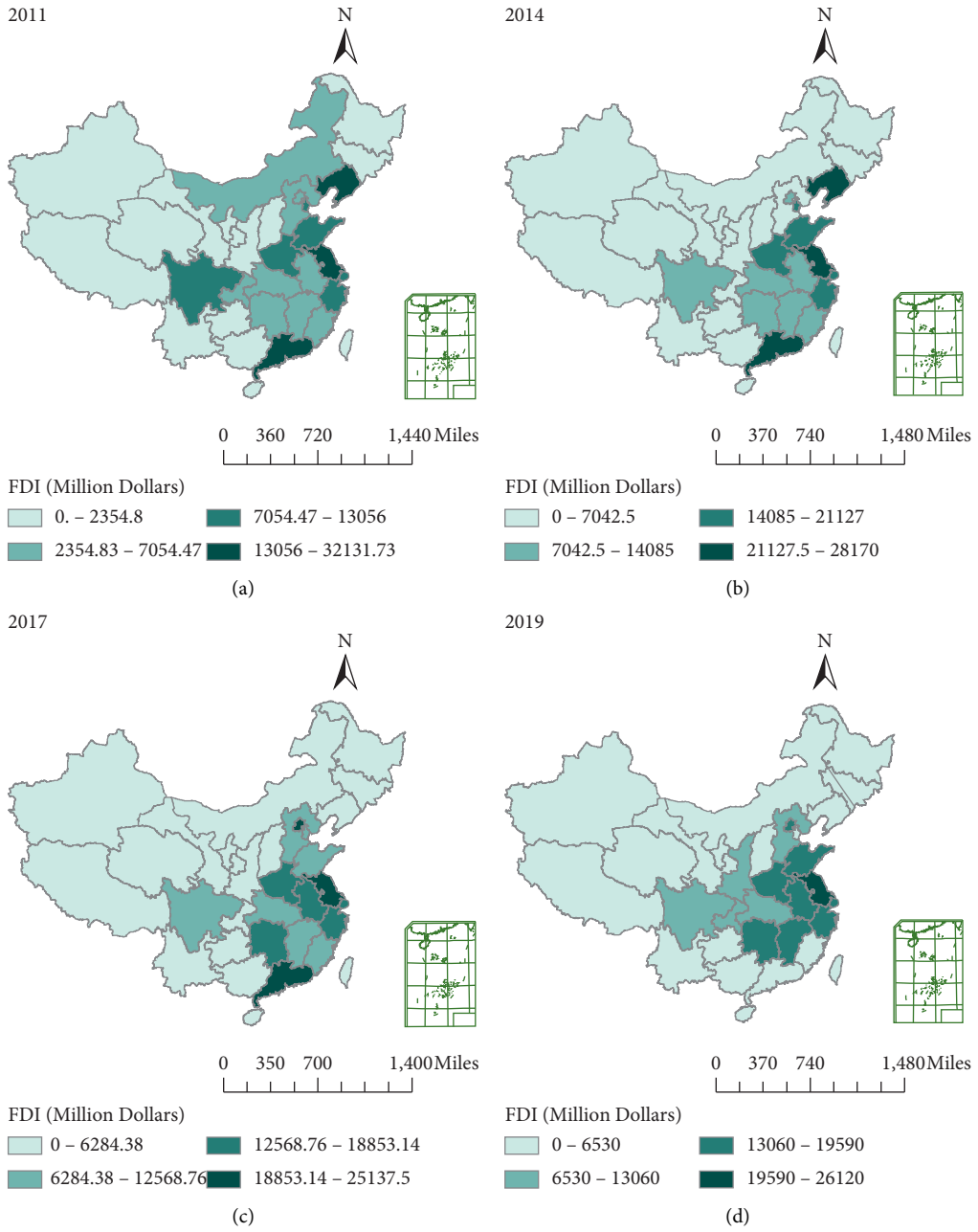

Figure 2: Changes in trends in attracting foreign investment by province (missing data for individual provinces). (a) 2011. (b) 2014. (c) 2017. (d) 2019.

Table 1: Correlation coefficient matrix.

	LNGDP	RPOP	LNJOB	LNROAD	LNEDU	SAVERATE	LNSO2	CTCH	LNGFDI	LNTAX	LIFE
LNGDP	1										
RPOP	0.247	1									
LNJOB	0.459	0.136	1								
LNROAD	0.834	0.473	0.418	1							
LNEDU	0.731	−0.04	0.418	0.610	1						
SAVERATE	0.266	0.412	0.344	0.385	0.295	1					
LNSO2	0.293	−0.05	0.148	0.239	0.294	−0.02	1				
CTCH	0.388	0.385	0.197	0.379	0.312	0.383	0.037	1			
LNGFDI	0.803	0.327	0.359	0.760	0.524	0.270	0.257	0.328	1		
LNTA	0.848	0.135	0.308	0.666	0.561	0.064	0.305	0.254	0.723	1	
LIFE	0.328	0.161	0.104	0.288	0.058	0.052	0.017	0.106	0.265	0.302	1

conducted a total of three times from 2012–2014, the sample in this paper covers all batches of the smart city pilots.

3.2.3. Control Variables. In this article, based on the studies of Moraghen et al., Nie, Ang-Tan and Ang, and Doytch and Eren, the following control variables were selected [8, 17–19]. The logarithm of the gross regional product is used to measure the level of economic development (LNGDP). The level of urbanization (RPOP) is measured using the ratio of the total year-end population of a city's municipal area (CPOP) to the total year-end population of the city (POP). The logarithm of the average number of workers on the job is used to measure the size of the labor force (LNJOB). The logarithm of the actual paved road area at the end of the year is used to measure the level of infrastructure development (LNROAD). The logarithm of the number of educational practitioners is used to measure the level of human capital (LNEDU). The savings' rate (SAVERATE) is measured using the ratio of the balance of various RMB deposits in financial institutions (SAVE) to GDP at the end of the year. The logarithm of industrial SO2 emissions is used to measure the urban environment (LNSO2). The level of science, technology, and innovation (CTCH) is measured using the ratio of the total number of personnel in the research integrated technical services' sector (TCH) to the total urban population. The logarithm of the total industrial output value of foreign-invested industrial enterprises above the scale (Annual revenue from main business greater than $3.08 million) is used to measure the degree of openness to the outside world (LNGFDI). Business environment is measured by the logarithm of total profit tax (LNTAX). Environmental governance capacity is measured by the ratio of household waste disposal without harm (LIFE).

4. Results and Discussion

4.1. Parallel Trend Test. When using DID, an important prerequisite is to satisfy that the treatment and control groups are trending in parallel [20]. Since China's smart city pilot is conducted in batches, this article uses fdi_{2ct} as the explanatory variable and selects the first batch of smart city pilot list in 2012 for parallel trend testing, excluding the pilot cities in 2013 and 2014. In this article, we refer to Beck et al. and set up the following model for parallel trend testing [21]:

$$\begin{aligned}\mathrm{fdi}_{2ct} = {} & \alpha + \beta_1 \mathrm{smart}_{t-5} + \beta_2 \mathrm{smart}_{t-4} + \beta_3 \mathrm{smart}_{t-3} + \cdots + \beta_8 \mathrm{smart}_{t+2} \\ & + \beta_9 \mathrm{smart}_{t+3} + \gamma D_{ct} + W_t + W_c + \vartheta_{ct}.\end{aligned} \tag{3}$$

In equation (3), $\mathrm{smart}_{t\pm n}$ denotes the dummy variables for n years before and after the launch of the smart city pilot, respectively. Using the year 2012 as the boundary for the first batch of pilot work, we examined the trend of fdi_2 in the first five years and the last three years of the pilot. If the coefficient of smart_{t-n} is not significant and the coefficient of smart_{t+n} is significant, it indicates that the treatment group has a parallel trend with the control group and the driving effect of the smart city pilot work is obvious. The results of the parallel trend test are shown in Figure 3. The coefficient of $\mathrm{smart}_{t-n}$was not significant before the smart city pilot was launched, and the coefficient was only significantly positive after the smart city pilot was launched, which indicates that the model passed the parallel trend test and the policy effect of the smart city pilot has a certain degree of persistence.

4.2. Baseline Regression Results. Table 2 shows the regression results of smart city pilot on the quality of FDI. Among them, (1) and (2) are the regression results with the scale of foreign-invested enterprises (fdi_1) and the performance index of foreign investment (fdi_2) as the explanatory variables, respectively, (3) and (4) are the regression results with the control variables added. We find that the estimated coefficients for the smart city pilots are significantly positive after controlling city fixed effects as well as time fixed effects, regardless of the inclusion or exclusion of control variables. Exploring columns (3) and (4) reveals that the estimated coefficients of smart_{ct} are 0.249 and 0.178, respectively, which indicate that compared to nonpilot cities, the average size of foreign-invested enterprises and the foreign investment performance index of smart cities are on average 0.249 units and 0.178 units higher, respectively. Therefore, this indicates that the smart city pilot has indeed helped to improve the quality of FDI and played the expected promotional role.

For the estimation results of the control variables, we analyze them in columns (3) and (4). In column (3), the coefficient of LNGFDI is significantly positive at the 5% level, which indicates that foreign-invested enterprises prefer to invest in cities with higher levels of openness to the outside world and thus expand their enterprises. In column (4), the coefficient of LNGDP is significantly negative at the 10% level, indicating that the level of urban economic development significantly and negatively affects the level of performance of foreign-invested enterprises. The possible reason is that, in the more economically developed cities, there are more local enterprises of the same type as foreign-invested enterprises, which intensifies the competitive behavior among enterprises and does not help foreign enterprises to improve their performance level. The LNROAD is significantly positive in both column (3) and column (4), indicating that the level of infrastructure development significantly and positively affects the quality of foreign investment, which is consistent with the findings of He et al. [22].

4.3. Robustness Tests. Based on the studies of Cheng et al. and Liang, this article uses fdi_2 as the explanatory variable for robustness testing [23, 24]. Three methods are used:

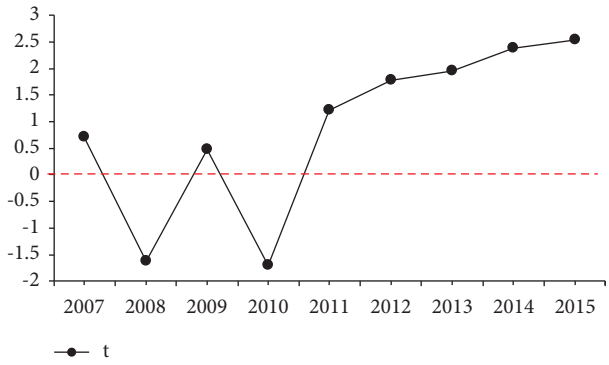

Figure 3: Parallel trend check chart.

Table 2: Estimated results of the baseline regression.

Variables	(1)	(2)	(3)	(4)
SMART	0.168**	0.134**	0.249***	0.178**
	(2.10)	(2.25)	(2.73)	(2.57)
LNGDP			−0.288	−0.492**
			(−0.94)	(−2.11)
RPOP			−0.0494	−0.0372
			(−0.16)	(−0.15)
LNJOB			−0.104	−0.104
			(−0.68)	(−0.90)
LNROAD			0.260**	0.236**
			(2.13)	(2.54)
LNEDU			−0.250	0.0390
			(−0.78)	(0.16)
SAVERATE			0.0874	0.0373
			(0.83)	(0.47)
LNSO2			0.00916	−0.0500
			(0.18)	(−1.29)
CTCH			−0.778	−0.782
			(−0.10)	(−0.14)
LNGFDI			0.171***	0.0102
			(2.82)	(0.22)
LNTAX			0.0716	0.0224
			(1.43)	(0.59)
LIFE			−0.000502	−0.000185
			(−0.40)	(−0.20)
Cons_	0.0631	0.153***	6.971	6.320*
	−0.88	(2.86)	(1.38)	(1.65)
City fe	YES	YES	YES	YES
Year fe	YES	YES	YES	YES
N	2712	2712	2712	2712
R^2	0.022	0.048	0.029	0.050

Notes: T statistics are in parentheses; $^{*}p < 0.10$; $^{**}p < 0.05$; $^{***}p < 0.01$.

front-loading the smart city pilot to 2011, excluding extreme values and lagging the smart city pilot variable, and all control variables by one period.

4.3.1. Front-Loading Smart City Pilot to 2011. To ensure randomness in the enactment of the three batches of smart city pilot policies from 2012–2014, a counterfactual test was conducted by changing the timing of the implementation of the smart city pilots. For the quality of FDI, apart from the smart city pilot work, other policies such as the "low carbon city" pilot policy and consequent factors may cause differences in the quality of FDI that are not generated by the implementation of the smart city pilot work, which would lead to the previous conclusion not being valid. Therefore, in this article, all three batches of smart city pilots are front loaded to 2011 for regression, and if the coefficient of smart_{ct} estimation is still significantly positive, it indicates that the variation in the quality of FDI may originate from the influence of other policies or random factors. If the coefficient of smart_{ct} is insignificant or significantly negative, it proves that the enactment of the smart city pilot is random. The results are shown in (1) in Table 3, where the coefficient of smart_{ct} is insignificant, which indicates that the estimation results of this article possess good robustness.

4.3.2. Excluding Extreme Values. As shown in Table 4, the standard deviation data between the explanatory variables indicate that the samples differ significantly between the variables and that there are extreme end outliers. Therefore, this article adopts the "tailing method" to deal with extreme outliers, in which the highest and lowest 1% of all the control variables are reduced, and the reduced samples are regressed. The results are shown in (2) in Table 3, where the coefficient on smart_{ct} remains significantly positive, proving that smart city pilots significantly and positively contribute to the quality of FDI.

4.3.3. Lagging the Smart City Pilot Variable and All Control Variables by One Period. Considering the time lag of the smart city pilot, this article treats smart_{ct} with a one-period lag, while all control variables are also treated with a one-period lag to avoid joint cubic equation bias. The treated regression results are shown in (3) in Table 3. The coefficient of smart_{ct} is still significantly positive, proving that the findings of this article are robust.

4.4. Placebo Test. For the DID model constructed in this article, there may be differences in the characteristics of the treatment group and the control group other than whether they are smart city pilot cities before the smart city pilot work is carried out. For equation (1), although it has controlled most of the city characteristics variables, it is not sufficient to control all city characteristics. Therefore, in this article, we refer to Yu et al. and adopt the following method of placebo testing with fdi_2 as the explanatory variable to observe whether omitted characteristics may have an effect on the results [25]. First, the expression for the fdi_2 coefficient is derived based on equation (1):

$$\alpha_{1r} = \alpha_1 + \delta * \frac{\text{cov}\left(\text{smart}_{ct}, \vartheta_{ct} | D\right)}{\text{var}\left(\text{smart}_{ct}, D\right)}. \tag{4}$$

If a variable can be found to replace smart_{ct}, this variable does not theoretically affect the corresponding (i.e. $\alpha_1 = 0$); after estimating $\alpha_{1r} = 0$, it can be proved that $\delta = 0$; i.e., the omitted feature does not affect the estimation result.

Table 3: Robustness tests.

Variables	(1)	(2)	(3)
Smart	0.182	0.156*	0.188*
	(1.86)	(2.24)	(2.45)
Control variables	YES	YES	YES
City fe	YES	YES	YES
Year fe	YES	YES	YES
R^2	0.0589	0.0521	0.0529

Notes: T statistics are in parentheses; $^{*}p < 0.10$; $^{**}p < 0.05$; $^{***}p < 0.01$.

Table 4: Summary statistics.

Variables	Units	Mean	Sd	Min	Max
FDI1	100,000,000	0.239	1.151	0	33.33
FDI2	1	0.272	0.864	0	19.82
SMART	1	0.209	0.406	0	1
LNGDP	10,000	16.27	0.926	13.91	19.55
RPOP	1	0.34	0.23	0.43	1
LNJOB	10,000	3.164	1.521	−2.74	6.625
LNROAD	10,000	6.986	0.92	4.127	9.975
LNEDU	1	10.71	0.652	8.455	13.13
SAVERATE	1	1.024	0.76	0.214	9.054
LNSO2	1,000	10.56	1.137	0.693	14.15
CTCH	1	0.002	0.004	0	0.145
LNGFDI	10,000	13.64	1.859	7.324	18.82
LNTAX	10,000	13.77	1.35	6.56	17.77
LIFE	1	0.86	0.23	0	3.62

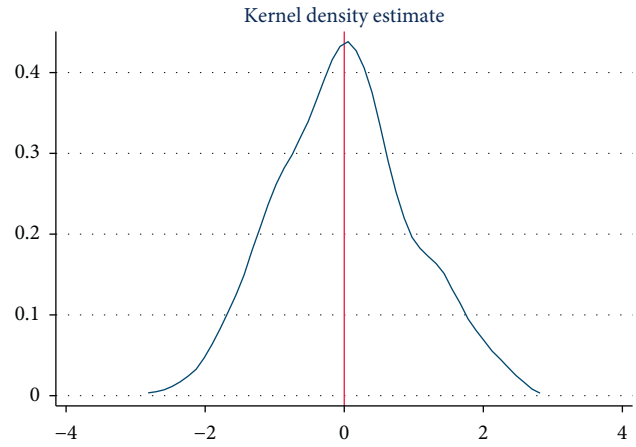

Figure 4: Placebo test.

Therefore, this article regresses the shock of the smart city pilot after becoming random and repeats this random regression process 1000 times so that fdi_{2ct} will not be affected (i.e., $\alpha_{1r}^{\text{random}} = 0$).The results are shown in Figure 4, and we find that the distributions of $\alpha_{1r}^{\text{random}}$ are all around $x = 0$ and normally distributed after 1000 estimations, which indicates that $\delta = 0$ holds, i.e., the estimation results in this article are reasonable.

4.5. Heterogeneity Analysis. Different cities have certain differences in economic structure, policy implementation, and natural endowment degrees, and these differences may lead to different effects of smart city pilot policies on different cities, which in turn affects the quality of FDI. Therefore, this article draws on Doytch et al and Li and Li to further test regional differences in the quality of foreign investment affected by smart city pilot policies, using fdi_2 as the explained variable [26, 27].① Divide cities into three equal parts based on 2016 GDP per capita. Cities with low economic development have GDP per capital in the 0%–33% range. Medium economic development level cities have GDP per capital in the 33%–66% range. Cities with high economic development have GDP per capital in the 66% or higher range. ② Heterogeneity analysis was performed by two methods based on the geographic location of the city and divided into three subsamples: eastern, central, and western. ③ The degree of urban natural resource dependence was determined based on the proportion of mining employment to total urban employment in 2016 and was categorized into three levels: cities with low natural resource dependency are in the 0%–33% range, cities with medium natural resource dependency are in the 33%–66% range, and cities with high natural resource dependency are in the 66% range.

As can be seen from Table 5, the improvement in the quality of FDI in the smart city pilot is more significant in the subsample of western cities. This may be due to the fact that the economic conditions and FDI levels of western cities are relatively backward compared to those of eastern and central cities. When the smart city pilot policy is implemented, the level of infrastructure development within the region can be improved, which can attract a large amount of foreign capital and high-quality foreign enterprises, thus improving the quality of FDI in western cities. Meanwhile, the enhancement of quality of FDI by smart city pilot is more significant in the subsample of cities with low natural endowment dependence. This is because the reduction of natural resource dependence will increase the level of physical investment, education, and R&D in the region, which is more in line with the trend of foreign-invested enterprises moving from resource-seeking to market-seeking, efficiency-seeking, and system-seeking, which enables foreign-invested enterprises to utilize the agglomeration effect and better play the promotion effect of smart city construction on the quality improvement of FDI.

Table 5: Heterogeneity.

Variables	Geographical position			Economic development			Natural resource dependency		
	(1) East	(2) Middle	(3) West	(4) Low	(5) Medium	(6) High	(7) Low	(8) Medium	(9) High
Smart	0.0968	0.216	0.0742**	−0.0947	0.172	0.190	0.386**	0.0278	0.103
	(0.103)	(1.50)	(2.66)	(−0.54)	(1.77)	(1.95)	(3.00)	(0.31)	(0.76)
Control variables	YES	YES	YES	YES	YES	YES	YES	YES	YES
City Fe	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year Fe	YES	YES	YES	YES	YES	YES	YES	YES	YES
R2	0.0986	0.0634	0.1105	0.932	0.1035	0.0482	0.0976	0.0704	0.0540

Notes: T statistics are in parentheses; $^{*}p < 0.10$; $^{**}p < 0.05$; $^{***}p < 0.01$.

5. Conclusions

Based on data from 226 prefecture-level cities from 2006–2017, this article explores whether smart city pilots, which were gradually introduced in 2012 as a quasi-natural experiment, have improved the quality of foreign investment in China using a DID model after controlling fixed effects at both the time and city levels. The results show that the core explanatory variable smart city pilot has a significant positive effect on the quality of foreign investment as indicated by the average size of foreign-invested enterprises and the foreign investment performance index at two levels, while the level of infrastructure development among the control variables has a significant positive effect on the quality of foreign investment and the level of wages has a significant negative effect on the quality of foreign investment. After parallel trend tests, a series of robustness tests, and placebo tests, the results are still held. In addition, heterogeneity analysis shows that smart city pilot has a significant contribution to improve the quality of FDI in western cities and cities with low natural resource dependence.

Although the pilot work on smart cities has significantly improved the quality of attracting foreign investment in China, China and other countries around the world should continue to rationalise and improve the construction of smart cities in the following 3 areas to meet the optimisation and sustainable development of foreign investment in the postepidemic era.

First, China should further liberalise the market access conditions for infrastructure in smart city pilot cities in western cities of China, treating foreign investment equally. The empirical results show that the smart city construction has improved the quality of foreign investment in western cities, more significantly compared to eastern and central cities. Therefore, for the western cities whose economic development level is still at a low level, they should further liberalise the market access in the field of infrastructure investment, expand the channels for foreign enterprises to participate in construction investment with the help of smart city construction, give full play to the decisive role of the market for resource allocation, promote the healthy and orderly operation of the market, and promote the high-quality development of the region's urban economy.

Second, governments should regulate and promote PPP financing models to bring in foreign investment and pay attention to scientific planning and step-by-step implementation. Currently, smart city construction focuses on seven important areas of new infrastructure: 5G base stations, data centers, industrial Internet, artificial intelligence, charging piles, extrahigh voltage, and high-speed rail and urban rail transit. In terms of the investment scale, the market size of the seven new infrastructure areas still has room to rise and will still need strong capital as support in the future. The government can only introduce high-quality foreign investment to improve efficiency by standardizing and continuously developing the PPP financing model.

Third, countries around the world should strengthen data management and security to break information silos and reduce network risks. In the construction of smart city, the phenomenon of fragmentation is very common, the massive amount of data failed to achieve effective integration, and network security risks are increasing. Optimizing the foreign investment environment requires not only hard new infrastructure but also soft new infrastructure, the most urgent of which is the construction of urban data. Only to carry out a comprehensive evaluation of urban big data, realize the standardized management of the whole procedure from data collection to data capitalization, and implement basic systems such as grade protection and security measurement, can we effectively guarantee the security of foreign investment in the process of sharing and using urban data and reduce network risks?

Data Availability

The processed data used to reproduce the findings of the study cannot be shared at this time as the data also form part of an ongoing study.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

C.Y., Z.Z., and J.C. conceptualized the study; C.Y. and Z.Z. developed the methodology; Z.Z. helped with software; C.Y., Z.Z., and J.C. validated the study; C.Y., Z.Z., and J.C. carried out formal analysis; C.Y. investigated the study; Z.Z. helped with the resources; Z.Z. curated the data; Z.Z. and J.C. wrote and prepared the original draft; C.Y., Z.Z., and J.C. reviewed and edited the article; C.Y. visualized the study; C.Y.

supervised the study; C.Y. administrated the project; C.Y. carried out funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Research Article

The Impact of High-Speed Railway Accession on Agricultural Exports: Evidence from Chinese Agriculture-Related Enterprises

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Although many studies have analyzed the transportation infrastructure effects on economic and trade development, little is known about the relationship between transportation infrastructure and trade in the agricultural sector. We take the opening of China's high-speed railway (HSR) as a quasi-natural experiment and use multiperiod DID model to explore the impact and mechanism of HSR on agriculture-related enterprises' exports. The results show that HSR can promote export growth of agriculture-related enterprises by 6.9%, and it will reach 10% in 5 years. However, the effect of HSR on the export of agriculture-related enterprises only exists within 45 km around HSR stations. HSR can reduce information barriers and costs for enterprises to enter the international market by providing transportation convenience and improving market access levels. HSR also offers local areas more transportation advantage compared to other surrounding areas, which in turn makes a siphon effect on export activities. Both these mechanisms are significant within 45 km, and it is extremely obvious for poor transportation areas and enterprises with higher productivity, and the siphon effect is even stronger than market access. Heterogeneity analysis results demonstrate that HSR has different effects for different types of enterprises.

1. Introduction

Agriculture is the foundation of the economy for a country, and the export of agricultural products is an important manifestation of the agricultural international competitiveness. Since the 21st century, Chinese agricultural exports have shown a gradually increasing trend, making China become the world fifth largest agricultural exporter (Chinese agricultural exports from 15.449 billion dollars in 2001 increase to 76.989 billion dollars in 2019. The data comes from the UN Comtrade database). However, Chinese agricultural exports lack international competitiveness with a lower market share compared to other countries (in 2019, it accounted for only 4.89% of the world's agricultural exports, which was lower than the EU (39.13%), USA (9.00%), ASEAN (8.54%), and Brazil (4.97%). The data comes from the UN Comtrade database and has been sorted and calculated). In China, agricultural products have also shown a trend of marginalization in the export structure. Their share of total exports has gradually decreased from 5.81% in 2001 to 3.08% in 2019, while the EU, USA, ASEAN, and Brazil have maintained their share of agricultural exports stable and rising trend, keeping an important position in its export structure (the share of EU agricultural exports in total exports has gradually increased from 8.12% in 2001 to 9.83% in 2019, the USA has increased from 7.67% to 8.61%, ASEAN has risen from 7.69% to 9.10%, and Brazil has increased from 27.90% to 34.93%. The data comes from the UN Comtrade database). The export influence of Chinese agricultural products is far less than that of developed countries. And, there is still a considerable gap compared with some developing countries such as Brazil and ASEAN. More importantly, compared with industrial enterprises, China's agricultural enterprises are generally small in scale and low in technology intensity, in addition to China's vast territory, poor traffic, and information conditions in counties and townships, imposing the export of agricultural products under high restrictions and barriers to enter the

international market. In 2017, the Chinese government proposed a rural revitalization strategy to revitalize the declining agriculture and rural areas and clearly requested to promote the prosperity of agricultural and rural industries. Therefore, we need to support the development of agricultural enterprises and encourage agricultural enterprises to expand the market scope to enter the international trade market. It can facilitate the export of Chinese agricultural products and revitalize Chinese agricultural and rural areas. How to break through geographic restrictions and market information barriers and lower the thresholds to enter the international market so that more agricultural enterprises participate in the export has become a critical issue for China's agriculture. The emergence of high-speed railway (HSR) offers possibilities to solve this problem.

HSR has brought a new growth engine for Chinese economy, and it also has a huge impact on Chinese agricultural trade. HSR has gone through a fast development in China since the construction of its first high-speed railway in 2008. By the end of 2019, Chinese HSR operating mileage has reached 35,000 km, becoming the largest HSR's country in the world (the data comes from the 2019 China Statistical Yearbook). At the same time, the "eight horizontal and eight vertical" network pattern and trunk lines have basically been formed, and a series of branch HSR lines have been extended from trunk lines, further improving Chinese HSR's network. As a result, the coverage of HSR in small- and medium-sized cities and even county areas rather than just large cities has greatly improved the convenience of transportation in those areas and stimulated the vitality of local industry. The downward extension of HSR's network takes charge of the agricultural and rural economy within the scope of HSR. Its space-time compression has greatly narrowed the barriers and obstacles to communicate with the outside world and brought huge development opportunities to the agricultural enterprises in these areas. In county-level and township areas, agriculture and agricultural product processing industries account for a large proportion of the industry, which play a crucial role in the growth of local employment and income. Under the dual background of Chinese promotion of rural revitalization strategy and the improvement of HSR's construction, will HSR become an important force for agriculture-related enterprises to break through the time-space limitation and enhance the participation of export? If HSR can promote the export of agriculture-related enterprises, it will raise a series of theoretical and practical questions: should we explore the degree of HSR's effect on the export of enterprises and the impact's mechanism? Will the effect of HSR on the exports be affected by the distance between enterprises and HSR's stations? Will the policy effects of HSR on different enterprises be heterogeneous? The discussion of the above questions will enrich and improve the relevant theories of HSR's economy and also expand the application research in Chinese agricultural trade.

In this paper, we take the opening of Chinese HSR as a quasi-natural experiment to explore the impact and mechanisms of HSR on export of agriculture-related enterprises. Then, we group the distance between enterprises and HSR stations to further discuss the role of distance threshold in determining HSR's effect on enterprises. We use instrumental variables to deal with endogenous problems and adopt robustness and placebo tests to verify the reliability of the results. Furthermore, we examine the mechanisms from two aspects: market access and siphon effect. Finally, we analyze the heterogeneous impact of HSR on different enterprises. To sum up, the research in this paper will contribute to and further supplement the existing literature. First of all, although there are many literature confirming the positive impact of roads, highways, railways, and other transportation infrastructure on economic growth and international trade, because HSR is an emerging transportation infrastructure, there is a lack of literature on the impact of HSR on international trade. Our paper will focus on HSR and supplement this part; second, we are concerned about the development of China's agriculture and the impact of China's HSR in agricultural development. There are few literature in this part, but this has very important practical significance for China's agricultural development; finally, we discuss the mechanism of the impact of HSR on trade and make up for the lack of previous literature on mechanism research. Then, the rest of the thesis is organized as follows. Section 2 provides a literature review. Section 3 offers a theoretical analysis. Section 4 presents empirical strategy and data. Section 5 presents estimation results, solution of endogenous problems, robustness checks, and placebo test. Section 6 discusses the mechanisms and heterogeneous effects. Section 7 concludes and offers policy suggestions.

2. Literature Review

Transport improvements can be regarded as a key component of regional economic competitiveness. "If you want to get rich, build roads first" shows the importance of transportation infrastructure construction for the local economy [1]. Most studies have fully confirmed the positive role of transportation infrastructure in regional economic growth [2–5]. As a fast-reaching transportation, HSR can operate at a speed of more than 200 km/h, up to and can reach a maximum of 350 km/h. It significantly breaks the time-space constraints and has an obvious impact on economic activities. Zou et al. explored the impact of the HSR network on the economic growth of 110 major cities in China and found that the start of HSR has an apparent positive effect [6]. Diao et al., respectively, verified the positive effects of HSR on regional economic growth according to the changes in fixed asset investment and the intensity of night light before and after the opening of HSR [7, 8].

With the deepening of globalization and trade liberalization, the impact of transportation infrastructure on international trade has gradually received greater attention from researchers. Many studies have shown that the transportation infrastructure plays a crucial role in reducing transportation costs and facilitating the growth of trading activities [9–11]. Countries with large trade value in the world usually have relatively better domestic transportation

conditions [12–14], and low-level domestic transportation infrastructure has a restraining effect on the international trade [15, 16]. In the research on transportation infrastructure and trade, the traffic objects such as roads and railways are mainly studied, with relatively less focus on HSR. The main reason is that HSR is an emerging transportation infrastructure. Only a few countries in the world, such as China, have a complete HSR's network. Therefore, the impact of HSR on export has been rarely studied, which is far from enough and requires further improvement. Xu et al. provided some research evidences in this field, showing that the construction of HSR can help promote the growth of local export [17–19].

Many scholars have discussed how transportation infrastructure affects export. The most intuitive conclusion is that the construction of transportation infrastructure can reduce the transportation cost of enterprises, and enterprises can conduct export activities at lower costs, thereby promoting the growth of export [20–23]. However, it is worth noting that China's HSR cannot directly reduce transportation costs because it does not directly transport goods. It enables scholars to explore the mechanism of HSR on trade from other aspects. Some scholars think that trade relations depend on the interaction of producers, intermediate traders, and foreign buyers. Therefore, close communication between trading partners plays a key role in information sharing and identification of trade opportunities [24, 25]. A good transportation infrastructure can increase the frequency of external contacts. It has created an efficient information communication mechanism to reduce information barriers and improve trade efficiency. Cosar and Demir pointed out that the construction of highways has reduced access barriers to international markets [26]. Some scholars also believe that HSR plays a very important role in increasing the frequency of communication between enterprises and reducing information costs and barriers. However, there are not many direct research studies on trade, most of which are focused on the business activities of enterprises. Faber pointed out that constructing transportation facilities would connect the central and surrounding cities and reduce trade cost by strengthening communication and exchanges between regions [27]. This kind of communication is reflected in improving commuting efficiency between regions and exchanging information between corporate headquarters and branches [28]. And, it enables enterprises to strengthen their ties with the outside areas and reduce their market search and business outsourcing costs by enhancing their matching efficiency with suppliers, thereby improving the business performance of enterprises along the route [29].

This paper mainly contributes to the literature in the following ways. Firstly, more and more literature have confirmed the positive effects of transportation infrastructure such as road, highway, and railway on economic growth and international trade. But there is still lack of research on HSR in the trade field. So, we will use the export data of Chinese enterprises to further improve from a micro-perspective. Secondly, this paper studies the impact of HSR on the export of agriculture-related enterprises. Previous studies have rarely involved research on the application of HSR in the agricultural field. With the improvement of Chinese HSR's network and the implementation of rural revitalization strategy, it is necessary and worthwhile to study the impact of HSR on agricultural-related industries. Thirdly, we have discussed the impact of the distance between enterprises and HSR's station on the export and confirmed that the opening of HSR can only affect the export of enterprises within 45 km, with no significant effect beyond 45 km. This is a novel point of view compared to previous studies. Finally, the previous literature has not sufficiently discussed the mechanism of HSR on trade. We have considered the mechanism of HSR on trade from two aspects: market access and siphonic effect, which have effectively made up for the deficiencies of the previous literature on the mechanism. China's vast territory provides extremely rich agricultural resources, and plenty of agriculture-related enterprises use agricultural products as their main raw materials or final products, which provide rich samples for this research. This paper is significant for China to attach great importance to agriculture and rural areas, and it also has significant referential effects for other developing countries with the attempt to establish rapid transportation infrastructure similar to HSR to promote agricultural export.

3. Theoretical Background and Analysis Framework

We explore the effect of HSR on export under the following theoretical background. With reference to the methods of Grossman et al. [30, 31], we assume that the export products of agriculture-related enterprises need to be made by several manufacturers in multiple regions, from raw material acquisition, product processing, and transportation to external sales. This process is restricted by the cost of information such as communication between the two regions. The substantial improvement of transportation infrastructure made by HSR can greatly improve the local market access level. Local agriculture-related enterprises, especially those around HSR's stations, can take full advantage of the transportation superiorities brought by HSR, quickly reach other regions, and establish more frequent contacts with producers, middlemen, and traders in other regions. It can help agriculture-related enterprises fully understand the market information and find more production orders and trade opportunities. Therefore, this passenger-oriented transportation mainly improves the market access level and lowers the threshold of entering the local market. It is conductive to the frequent face-to-face communication between local enterprises and the outside world to drive the growth of economic and trade activities.

HSR can improve the local market access level and then guide economic and trade activities in surrounding regions without HSR flow to HSR's location. It is easy to cause trade competition between different regions, resulting in a siphonic effect. Krugman [12] used "center-periphery" model to analyze economical activities' spatial location and believed that economic activities tend to gather from periphery to central area, which has a siphonic effect on

economic and trade activities in peripheral areas. HSR will increase spatial mobility of the resources and the clustering from non-HSR regions to HSR's regions and enable local agriculture-related enterprises to gain benefits in trade competition among similar enterprises in surrounding areas. Since agriculture-related enterprises mainly export low-end and homogenized products, export trade activities have strong regional substitutability. HSR helps local enterprises to compete for more trade opportunities and export orders, forming a siphonic effect for enterprises in surrounding regions. While promoting the export growth of agriculture-related enterprises in HSR's regions, it has also led to a decrease in exports of enterprises without HSR.

Furthermore, we take the mechanism of market access as an example for the theoretical derivation of export. In international trade, we treat all countries as our own country and foreign countries. Our country is composed of N regions, and each has a lot of agriculture-related enterprises. There is also a trade relationship between agriculture-related enterprises in each region and foreign countries. For easy distinction, we mark the starting point of the export as region a and all destination countries of export as country b.

3.1. Consumer Preferences. We assume that consumers in country b consume a series of differentiated products i and have a standard CES preference for product i. The utility function is

$$U_b = \left(\int_0^{\Omega} x_b(i)^{(\sigma-1)/\sigma} \mathrm{d}i \right)^{\sigma/(\sigma-1)}. \tag{1}$$

In formula (1), Ω represents the set of products available for consumers in country b, σ represents the elasticity of mutual substitution between products, and $\sigma > 0$, and $x_k(i)$ represents the consumption of product i by consumers in country b, which is constrained by the income level of consumers in country b:

$$y_b = \int_0^{\Omega} p_b(i) x_b(i) \mathrm{d}i. \tag{2}$$

In formula (2), $p_b(i)$ represents price of product i in country b and y_b represents the per capita income level of country b.

3.2. Production Technology Level. We assume that production factors of each region include land (L), labor (H), and capital (K). The production function is in the form of Cobb–Douglas:

$$X_a(i) = z_a(i) L_a(i)^{\alpha} H_a(i)^{\gamma} K_a(i)^{1-\alpha-\gamma}, \tag{3}$$

$$\mathrm{MC}_a(i) = \frac{q_a^{\alpha} w_a^{\gamma} r_a^{1-\alpha-\gamma}}{z_a(i)}. \tag{4}$$

In formula (3), $z_a(i)$ represents average productivity, $\mathrm{MC}_a(i)$ represents marginal cost of product i in the region a, q_a, w_a, and r_a, respectively, indicate the factor return rates of land, labor, and capital, and average productivity $z_a(i)$ obeys following distribution:

$$F_a(z) = \Pr(Z_a \le z) = \exp\left(-A_a z^{-\theta}\right). \tag{5}$$

In formula (5), θ represents the change in productivity within region a and A_a represents the technological level of region a.

At the enterprise level, we learn from Melitz and assume that the production of agriculture-related enterprises has increasing returns to scale, the products produced have subtle differences, and there is heterogeneity among enterprises [32]. Therefore, productivity φ of agriculture-related enterprises obeys following distribution:

$$G(\varphi) = 1 - \varphi^{\gamma}. \tag{6}$$

In formula (6), $\varphi \ge 1$ for an agriculture-related enterprise m with a productivity of φ, the marginal cost of production is (mc_s/φ), and mc_s represents marginal cost of lowest-productivity firm s, so the higher a company's productivity is, the lower marginal cost it will face.

3.3. Trade Cost and Enterprise Export. We use a simple "iceberg cost" to describe trade cost, assuming that the trade cost between a and b is τ_{ab}, and the trade cost between a and b is symmetrical, that is, $\tau_{ab} = \tau_{ba}$, $\tau_{ab} = \tau_{ba} > 1$. If product i is produced in region a and directly supplied to region a, the price of product i is $p_{aa}(i)$. But if product i is produced in region a and then sold to country b through international trade, the price of the product i is $p_{ab}(i)$; these two prices satisfy the following relationship:

$$p_{ab}(i) = \tau_{ab} \times p_{aa}(i) = \tau_{ab} \times \mathrm{MC}_a(i) = \tau_{ab} \times \frac{q_a^{\alpha} w_a^{\gamma} r_a^{1-\alpha-\gamma}}{z_a(i)}. \tag{7}$$

For ordinary consumers, when they make a commodity purchase decision, they are sensitive to its price, and they usually choose commodity with the lowest price, so goods' price is often affected by productivity distribution.

From Eaton and Kortum, we can get two important conclusions [33]. Firstly, the price index of trade destination country b satisfies

$$(P_b)^{-\theta} = \kappa_1 \sum_a \left[A_a \left(q_a^{\alpha} w_a^{\gamma} r_a^{1-\alpha-\gamma} \right)^{-\theta} \tau_{ab}^{-\theta} \right] \equiv \mathrm{CMA}_b. \tag{8}$$

In formula (8), we define CMA_b as the market access of consumers in country b, which reflects low-priced products' availability in market for consumers in country b. The other important conclusion is the total value of products sold from region a to country b, as shown below:

$$X_{ab} = \kappa_1 A_a \left(q_a^{\alpha} w_a^{\gamma} r_a^{1-\alpha-\gamma} \right) Y_b \tau_{ab}^{-\theta} \mathrm{CMA}_b^{-1}. \tag{9}$$

In formula (9), we can see that the total value of products X_{ab} sold by region a to country b is a standard gravitational equation. When the target country's trade cost decreases, the export trade from region a to country b will increase; otherwise, export trade will decrease.

3.4. Market Access and Enterprise Export. Since we treat all export trading countries as country b, we can sum up formula (9) to get

$$X_a = \sum_b X_{ab} = \kappa_1 A_a \left(q_a^{\alpha} w_a^{\gamma} r_a^{1-\alpha-\gamma}\right)^{-\theta} \sum_b \left(\tau_{ab}^{-\theta} \mathrm{CMA}_b^{-1} Y_b\right). \tag{10}$$

In formula (10), X_a is the total income of region a representing whole exports to all foreign countries, that is, the total amount of exports. We define the enterprise market access level of region a as follows:

$$\mathrm{FMA}_a \equiv \sum_b \tau_{ab}^{-\theta} \mathrm{CMA}_b^{-1} Y_b. \tag{11}$$

In formula (11), enterprise's market access is composed of the market size Y_b, the consumer market access CMA_b of the destination country, and trade cost τ_{ab} between region a and country b. Market size and level of market competition in country b are often not affected by region a, so the market access level of enterprises in region a largely depends on trade cost τ_{ab} between these two places.

Because the trade cost between a and b is symmetrical, that is, $\tau_{ab} = \tau_{ba}$, according to Donaldson and Hornbeck, it can be obtained $\mathrm{FMA}_a = \lambda \mathrm{CMA}_a$ and $\mathrm{FMA}_b = \lambda \mathrm{CMA}_b$, $\lambda > 0$. It shows that, for the same region, there is a linear correlation between the enterprise market access and the consumer market access, and this linear correlation feature λ will not affect the analysis, so we can get

$$\mathrm{FMA}_a = \lambda \mathrm{CMA}_a = \mathrm{MA}_a, \tag{12}$$

$$\mathrm{MA}_a = \lambda \sum_b \tau_{ab}^{-\theta} \mathrm{MA}_b^{-1} Y_b. \tag{13}$$

We put formula (13) into (10), and we can get

$$X_a = \kappa_2 A_a \left(q_a^{\alpha} w_a^{\gamma} r_a^{1-\alpha-\gamma}\right)^{-\theta} \mathrm{MA}_a. \tag{14}$$

Substituting the factor income of land, labor, and capital into formula (14), we can get

$$X_a = \left(\kappa_3 A_a\right)^{1/(1+\theta\alpha+\theta\gamma)} \left(\frac{\alpha}{L_a}\right)^{-(\theta\alpha/1+\theta\alpha+\theta\gamma)} \left(\frac{\gamma}{H_a}\right)^{-(\gamma\alpha/1+\theta\alpha+\theta\gamma)} \left(\frac{1-\alpha-\gamma}{K_a}\right)^{-((1-\alpha-\gamma)\alpha/1+\theta\alpha+\theta\gamma)} \mathrm{MA}_a^{(1+\theta(1+\alpha+\gamma))/\theta(1+\theta\alpha+\theta\gamma)}. \tag{15}$$

In formulas (13)–(15), we can see that when the cost of trade between a and b decreases, the market access level of region a can be greatly improved, further increasing the income level brought by export trade. With the size of the destination market and the degree of market competition unchanged, reducing trade cost between these two places is a crucial way to ameliorate market access and promote export trade.

4. Methods and Materials

4.1. Empirical Model Setting. Considering that different regions open HSR in different times, we learn from the methods of Lin and Qin and use a multiperiod DID model to examine the effect of HSR on export of agriculture-related enterprises [34, 35]. In the DID model, we take the regions where the HSR has not been opened as the control group and the regions where the HSR has been opened as the experimental group and obtain the policy effect of the HSR's opening through two differences. The benchmark model adopts following settings:

$$\ln \mathrm{export}_{ict} = \beta_1 \mathrm{HSR}_{ct} + \beta_2 E_{ict} + \beta_3 C_{ct} + \xi_i + \xi_{pt} + \xi_{nt} + \mu_{ict}. \tag{16}$$

In formula (16), $\ln \mathrm{export}_{ict}$ represents agriculture-related enterprise's export value and HSR_{ct} indicates whether this region c has opened HSR. When HSR is opened, $\mathrm{HSR}_{ct} = 1$; otherwise, $\mathrm{HSR}_{ct} = 0$. β_1 is the estimated coefficient of HSR. In order to obtain the net effect of HSR's opening on the export of enterprises, we need to control other factors that affect the export of enterprises. It mainly comes from two aspects: on the one hand, it comes from the enterprise itself, and some enterprise's own factors will also affect the export. E_{ict} are control variables at the enterprise level, including variables that measure individual characteristics of agriculture-related enterprises to control their impact on exports such as the size of enterprise (lnsize); the larger the enterprise scale, the stronger the export capacity. The operating time of enterprise (lnage): as the operating time has become longer, the business and trade relationships of the enterprise have gradually stabilized, and the enterprise has also passed the dangerous period of survival. It is more likely to explore the higher risk international market, which will help the enterprise's export growth. The labor productivity (lnlarborate): Melitz points out that enterprises with higher productivity are more likely to engage in export activities. Therefore, enterprise productivity has a significant positive impact on exports. Other factors that affect the export of enterprise are the external trade dependence (open) and financial liquidity (finance). On the other hand, some region characteristics will also affect the export activities of enterprises. C_{ct} are control variables at the regional level that affect export such as the level of road traffic (lnroad); good road conditions are conducive to product transportation, reduce transportation and trade costs, and then promote enterprise exports. The gross domestic product of agriculture (lnagriculture): a region with a higher agricultural production value will make the agricultural enterprises in that region more likely to export. In addition, economic development (lnpgdp), total population (lnpopulation), and Internet development (lninternet) will also affect the exports of enterprise. Therefore, we need to add these control variables to the empirical model. For some

fixed effect choices, we use a fixed effect model to analyze the impact of HSR on enterprise exports, so we need to control the fixed effects at the enterprise level. ξ_i is a enterprise's fixed effect, which is used to control factors that enterprise does not change over time. Since enterprise's location is fixed, when we control enterprise's fixed effect, regional fixed effect will be controlled accordingly. Finally, in the industry and provincial level, there are some unobservable time trends, which will also affect the export of enterprises. For example, if some industries develop rapidly, the export of enterprises in these industries will be significantly faster than that of enterprises in other industries. Therefore, we control the industry-time fixed effect and province-time fixed effect in the model setting. ξ_{nt} represents industry-time fixed effect, ξ_{pt} represents province-time fixed effect, which is used to control time trend at the industry and provincial level, and μ_{ict} represents the random disturbance item.

4.2. Parallel Trend Test. Due to the inconsistency of HSR's opening time in different regions, it is impossible to directly obtain a parallel trend of policy effects. Therefore, we learn the event analysis method from Beck et al. [36] and add dummy variables before and after the policy on the basis of formula (16):

$$\ln \text{export}_{ict} = \sum_{m=1}^{10} \beta_m \text{BFHSR}_{c,t-m} + \sum_{n=0}^{6} \beta_n \text{AFHSR}_{c,t+n} + \beta_2 E_{ict} + \beta_3 C_{ct} + \xi_i + \xi_{pt} + \xi_{nt} + \mu_{ict}. \quad (17)$$

In formula (17), $\text{BFHSR}_{c,t-m}$ represents the m years before HSR's opening and $\text{AFHSR}_{c,t+n}$ represents the n years after HSR's opening. When the coefficient β_m is close to 0, it indicates that, before the opening of HSR, there is no significant difference in exports of agriculture-related enterprises between the experimental and control group. When the coefficient β_n is significantly different from 0, it is means policy effect is very obvious. The results are shown in Figure 1: HSR has brought a significant and continuous increasing for agriculture-related enterprises' export.

4.3. The Distance between Agriculture-Related Enterprises and HSR Stations. The reason why the problem of distance is introduced to the analysis of this article is mainly due to the differences in city form and geographic location of enterprises, which are rarely considered in previous studies. They treat different cities as homogeneous, regardless of the geographical distribution of enterprises in the city and the resulting distance issues. In China, the differences between prefecture-level cities are very obvious. Some prefecture-level cities have a huge area and are composed of many counties. The distance from east to west and from south to north is very long. Some prefecture-level cities are very small, consisting of only municipal districts and a few counties. In addition, the construction sites of China's HSR stations are also quite dissimilar. Some are rebuilt from the original railway stations, and these HSR stations are often closed to the city center.

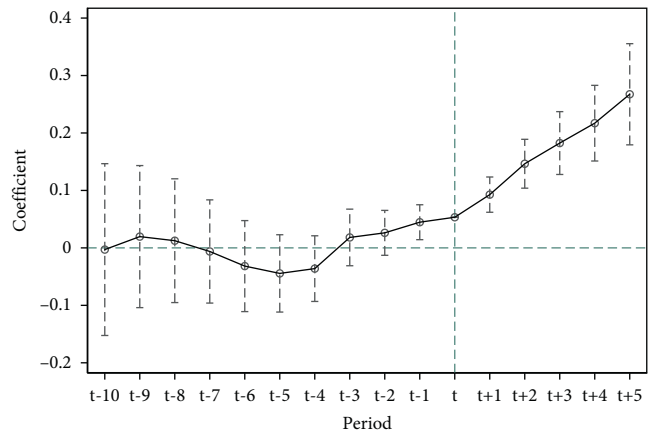

Figure 1: Parallel trend test on the export of agriculture-related enterprises.

Some cities elect to build HSR stations in the suburbs due to land rent; these HSR stations are often far from the city center and industrial parks. That makes the distance between enterprises and HSR stations very different. Some enterprises are close to the HSR station and can enjoy the convenience of transportation brought by the opening of the HSR, thereby helping enterprises make better use of the HSR to carry out economic and trade activities and drive the growth of exports. Enterprises that are far away from the HSR station take longer time to reach the HSR station and use the HSR less frequently so that the opening of HSR has almost no impact on the exports of such enterprises. We take a sample of agriculture-related enterprises in regions where HSR was opened in 2013 as an example and analyze the spatial distance distribution between agriculture-related enterprises and HSR stations (the radius is roughly calculated based on the area of the prefecture-level city's administrative and district. The calculation formula is $(s/\pi)^{(1/2)}$, where s is the area and π is the ratio of the circumference of a circle to its diameter. Among them, the prefecture-level city's district is generally the central city where the prefecture-level city's government is located, and it is also a city in a narrow sense). As shown in Figure 2, taking 15 km as an interval, we can see that the distance between enterprises and HSR stations is mostly within 105 km, and the number of enterprises in 15–30 km interval is the largest. There are many enterprises within 45 km, and the apex of the normal distribution curve is also in 30–45 km interval. At the same time, we also discussed the radius of prefecture-level city's administrative area, the radius of prefecture-level city's districts, and the distance from HSR stations to a city's center. As shown in Figures 3–5, a large number of prefecture-level city's administrative area's radius in China are within 120 km, with the most in the range of 50–70 km, while the radius of prefecture-level city's districts is mostly within 20 km. The distance from the HSR station to city center is also mostly concentrated within 25 km.

4.4. Data Source and Variable Description. The first part is HSR data of prefecture-level cities, which is mainly from China Railway Corporation website, China Railway

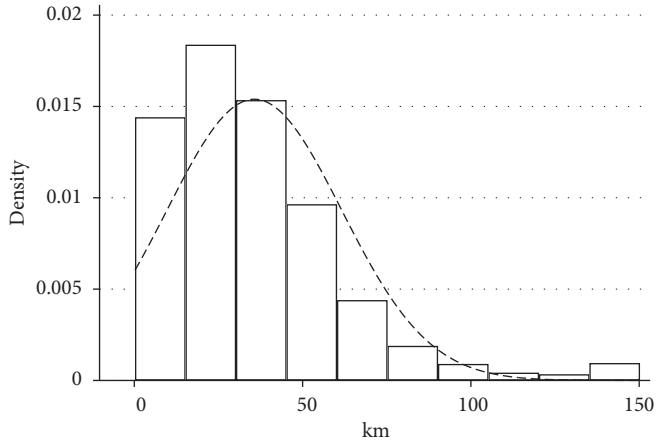

Figure 2: Distance between enterprises and HSR stations.

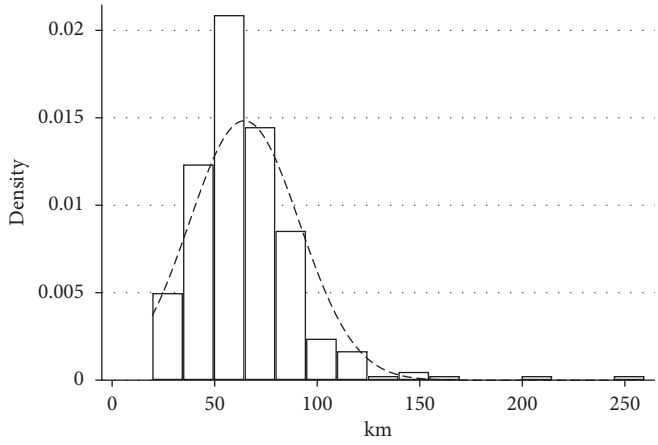

Figure 3: The radius of prefecture-level city's area.

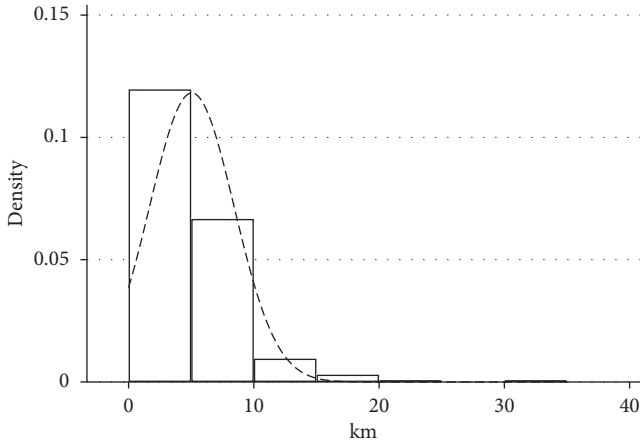

Figure 4: The radius of prefecture-level city's districts.

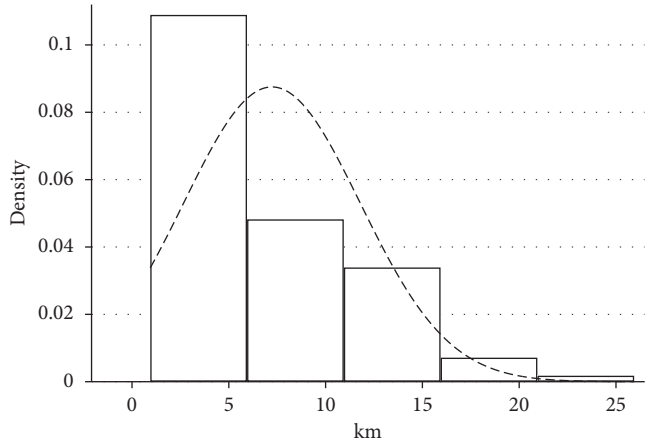

Figure 5: The distance from HSR stations to the city's center.

Yearbook, and 12306 website. We manually collect HSR lines and the opening time of each station from 2000 to 2013. We use the Baidu Map API to obtain the latitude and longitude coordinates of agriculture-related enterprises and HSR stations along the line and calculate the straight distance between agriculture-related enterprises and the nearest HSR station.

The second part is the microdata of agriculture-related enterprises, which mainly comes from two sources. The first is

from China Industrial Enterprise Database, which provides detailed enterprise information, including the year of establishment, total industrial output value, industrial sales output value, and industry. The second is the export data of enterprises, which comes from the Chinese Customs Database. The database records detailed trade information of enterprises, including export products, export values, quantities, prices, and export destination countries. We use the method of Brandt et al. to match the microenterprise data of these two databases to get export information of Chinese industrial enterprises and further obtain samples of agriculture-related enterprises from matching data [37]. We adopt two methods to identify whether the enterprise is an agriculture-related enterprise: The first is based on industry attributes in the Chinese industrial enterprise database. According to the classification method of the soft science research group of the Ministry Agriculture China, the industry category codes in Chinese industrial enterprise database are 13–23 and 29, including agricultural and sideline food processing, and food manufacturing belongs to agricultural product processing industries. The second depends on HS classification code in Chinese Customs Database. Export products of HS01–HS24 are usually classified as agricultural products, and we also classify enterprises that export such goods as agriculture-related enterprises. After screening export samples, we add them to the enterprise level by year. Then, we refer to methods of Brandt et al. [37, 38] and exclude samples with fewer than 8 employees, industrial output value, total assets, fixed assets, and sales revenue from main business with zero or missing, as well as samples that do not conform to GAAP, including enterprises whose both current assets and fixed assets are greater than total assets.

The third part is economic data at the regional level, which is mainly from the China Regional Statistical Yearbook and the National Bureau of Statistics of China, including economic development, road traffic conditions, agricultural output level, population, and informatization in each region. Descriptive statistics: mean, standard deviation, minimum, median, and maximum values for each variable are shown in Table 1.

5. Results and Discussion

5.1. Benchmark Regression Results. Under the controlling of firm fixed effects, province-time fixed effects, and industry-time fixed effects, we sequentially add control variables for regression (because provincial capitals and municipalities have obvious political advantages in the HSR construction planning, in order to eliminate the estimation bias on the model results, the sample of enterprises located in provincial capitals and municipalities will be deleted). The results are shown in Table 2. With the successive addition of control variables, the coefficients of HSR are all significantly positive at the 1% level, indicating that HSR can significantly promote agriculture-related enterprises' export growth. In column (10), the result shows that HSR will increase the export growth of agriculture-related enterprises by about 6.9%, compared with enterprises in regions without HSR. When more and more small- and medium-sized cities and counties open HSR, enterprises and individuals in these regions will enjoy the policy dividends brought by HSR. Especially for Chinese agricultural and rural areas, HSR provides an opportunity to conduct external communication and exchanges in the Chinese agricultural system. It will reduce the threshold and cost to accept peripheral information and expand market search radius for agriculture-related enterprises. At the same time, HSR guides economic and trade activities to gather in the region of HSR's location through passenger transportation, strengthening the local advantage in economic and trade competition with non-HSR regions. More importantly, HSR can encourage agriculture-related enterprises to participate in international competition and promote their products to the international market.

For the control variables, it is important to control the impact of other factors on the export of the enterprise so that we can accurately identify the impact of HSR's opening on enterprise exports. From the perspective of enterprise, the age, scale, export dependence, financing restrictions, and labor productivity of the enterprise will have an impact on the export. And, from the perspective city, economic development, road traffic conditions, agricultural output value, total population, and Internet informatization level will also have an impact on the export of agriculture-related enterprises. At the enterprise level, we can find that the coefficient estimates of control variables have a very significant positive impact on the export of agriculture-related enterprises. At the regional level, economic development has a critical negative impact on the export of agriculture-related enterprises. That is mainly because the region with higher economic development level has lower agriculture proportion. Correspondingly, the coefficients of the agricultural output value on the exports are significantly positive at the level of 5%. If a region has a higher agricultural output value, it can provide more abundant agricultural resources as raw materials for enterprise production. The coefficients of road traffic conditions on exports are also remarkable and positive. Ameliorating road traffic conditions can significantly reduce transportation time and cost and promote the outward of agricultural products. The coefficients of population density are not significant, while the level of Internet informatization has a positive impact on exports at the 10% level. It shows that, to a certain extent, the improvement of informatization can help enterprises to obtain market information, which is beneficial to export behavior. The coefficients of main control variables are statistically significant and in line with expectations and economic principles.

5.2. Dynamic Effect of HSR on Exports. In order to explore the dynamic impact of HSR on export, we examine the coefficient of HSR lag term on exports. As shown in columns (1)–(5) in Table 3, HSR has a clear dynamic impact on the exports of agriculture-related enterprises. It can be observed that, in 1–5 years after, HSR still has a positive effect in promoting export growth of local agriculture-related enterprises. Especially in the fourth to fifth year, the policy effect of HSR has been significantly improved, which can

Table 1: Descriptive statistics of each variable.

Variable	Variable explanation	Mean	SD	Min	p50	Max
lnexport	Logarithm of export value	14.099	1.902	8.189	14.381	17.771
HSR	Whether to open high-speed railway	0.253	0.435	0.000	0.000	1.000
lnage	Enterprise age, logarithm of opening time	2.083	0.648	0.000	2.197	3.761
lnsize	Enterprise size, logarithm of total assets	15.290	1.339	12.549	15.186	19.002
Open	Export dependence, export delivery value divided by total industrial output value*100%	48.420	42.243	0.000	46.928	123.246
Finance	Financing constraints, current assets divided by total assets*100%	55.784	26.114	1.513	58.833	97.832
lnlarborate	Labor productivity, logarithm of per capita gross industrial output	10.377	1.017	8.053	10.334	13.070
lnpgdp	The level of economic development, logarithm of per capita GDP	8.549	0.783	5.892	8.650	9.875
lnroad	Logarithm of local road density	0.708	0.223	0.186	0.710	1.158
lnagriculture	Logarithm of the agriculture gross domestic product	18.850	0.828	16.287	18.969	20.366
lnpopulation	Logarithm of local population density	6.632	0.769	4.212	6.563	8.375
lninternet	Internet penetration, number of computers per 100 households	13.425	1.033	10.608	13.505	15.512

Table 2: The impact of HSR's opening on the export: benchmark model results.

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
HSR	0.062***	0.076***	0.076***	0.074***	0.082***	0.068***	0.063***	0.068***	0.068***	0.069***
	(3.67)	(4.56)	(4.60)	(4.51)	(4.92)	(4.10)	(3.83)	(4.09)	(4.02)	(4.10)
lnage	0.318***	0.235***	0.207***	0.204***	0.195***	0.196***	0.195***	0.195***	0.195***	0.195***
	(19.61)	(14.77)	(13.12)	(13.00)	(12.49)	(12.53)	(12.45)	(12.41)	(12.41)	(12.37)
lnsize		0.345***	0.347***	0.351***	0.320***	0.320***	0.321***	0.321***	0.321***	0.320***
		(37.50)	(37.63)	(38.12)	(34.61)	(34.69)	(34.74)	(34.74)	(34.71)	(34.44)
Open			0.006***	0.006***	0.006***	0.006***	0.006***	0.006***	0.006***	0.006***
			(46.76)	(45.79)	(47.06)	(46.99)	(46.99)	(46.95)	(46.94)	(46.62)
Finance				0.002***	0.002***	0.002***	0.002***	0.002***	0.002***	0.002***
				(10.53)	(10.63)	(10.53)	(10.49)	(10.52)	(10.52)	(10.51)
lnlarborate					0.151***	0.152***	0.153***	0.152***	0.152***	0.152***
					(23.36)	(23.57)	(23.62)	(23.54)	(23.53)	(23.43)
lnpgdp						−0.192***	−0.203***	−0.206***	−0.206***	−0.209***
						(−3.45)	(−3.65)	(−3.69)	(−3.54)	(−3.60)
lnroad							0.184***	0.180***	0.180***	0.165**
							(2.70)	(2.63)	(2.63)	(2.42)
lnagriculture								0.098**	0.098**	0.102**
								(2.33)	(2.32)	(2.38)
lnpopulation									0.001	0.020
									(0.00)	(0.16)
lninternet										0.023*
										(1.66)
_cons	12.505***	7.435***	7.000***	6.885***	5.771***	7.492***	7.465***	5.652***	5.647***	5.212***
	(60.08)	(29.51)	(27.00)	(26.52)	(21.51)	(13.26)	(13.19)	(5.87)	(3.94)	(3.59)
Individual FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	179236	179228	170161	170161	169520	169520	169520	169319	169319	167886
Adj. *R*-sq	0.086	0.107	0.135	0.136	0.143	0.143	0.143	0.143	0.143	0.143

Note. ***, **, and * indicate the significance level of 1%, 5%, and 10%, respectively, and the *t* statistic value is in parentheses.

increase export growth by about 10%. In addition, we multiply HSR and time dummy variable after opening as the explained variable and add it to the model. As shown in column (6) in Table 3, in 2008, when HSR was first put into operation, the export growth of agriculture-related enterprises was not obvious. After 2009, the coefficient of the interaction term was very positive and gradually increased, and it was 0.093 and 0.110 in 2012 and 2013, respectively, and both were significant at the 1% level, which was consistent with the regression results of the lag term. The main reason is that there are only 3 HSR lines opened in 2008, and the lines have very short mileages and few stations (the 3 HSR lines is the Jing-Jin intercity railway from Beijing to Tianjin, the He-Ning section of the Ning-Rong railway from Hefei to Nanjing, and the Jiao-Ji railway from Jinan to Qingdao). Since 2009, the lines of HSR have gradually increased. China has successively opened many main lines such as the Beijing-Guangzhou HSR and the Beijing-Shanghai HSR. As the HSR network has gradually improved, a large number of regions along the lines have been included in the HSR network,

Table 3: The impact of HSR on the exports of agriculture-related enterprises: dynamic effects.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
L.HSR	0.090***					−0.028
	(4.75)					(−0.72)
L2.HSR		0.087***				0.061**
		(4.28)				(2.33)
L3.HSR			0.080***			0.061***
			(3.28)			(2.65)
L4.HSR				0.107***		0.065***
				(3.28)		(2.99)
L5.HSR					0.106*	0.093***
					(1.80)	(3.95)
HSR ∗ year						0.110***
						(3.83)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes	Yes	Yes	Yes
Province-year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes	Yes	Yes	Yes
N	118238	89899	67320	50387	37828	167886
Adj. *R*-sq	0.092	0.076	0.074	0.075	0.075	0.143

Note. ***, **, and * indicate the significance level of 1%, 5%, and 10%, respectively. And, the *t* statistic value is in parentheses. The results of other control variables are not displayed in the table, the same as below.

which has strengthened communication and connection between inland regions along HSR lines and the developed coastal areas or port cities. As a result, the policy effect of HSR on local enterprises' exports has gradually increased, which is consistent with the results in Figure 1. It is foreseeable that the HSR will play an increasingly important role in the export process of Chinese agriculture-related enterprises in the future.

5.3. Distance Threshold for the Impact of HSR on Exports. The policy effects of HSR may be affected by the distance between agriculture-related enterprises and HSR stations. We calculated the straight distance between each agriculture-related enterprise and the nearest HSR station, taking 15 kilometers as an interval and dividing it into 0~15, 15~30, 30~45, 45~60, 60~75, 75~90, and 90~105 km. Then, we examine the HSR's coefficients of different distance thresholds on exports. As shown in Table 4, when the distance is within 45 km, HSR will significantly enhance export of agriculture-related enterprises. It will promote the export growths about 7.9% within 15 km and 10% between 15 to 45 km especially. When the distance exceeds 45 km, HSR will no longer have apparent impact on exports. Therefore, we can see that HSR has a very obvious spatial distance threshold about 45 km for exports.

Figures 2–5 show the distance between agriculture-related enterprise and HSR's station, the radius of prefecture-level city's administrative region and district, and the distance from the HSR station to the city center. We can find that the threshold of 45 km is roughly equivalent to 2 times the radius of prefecture-level city's district and 2 times the distance between the HSR station and the city center. We use a simplified diagram to analyze the influence of the distance threshold, as shown in Figure 6: the circle *N* represents the range of the city's districts, the region out of *M* represents the county, township, and rural area, *O* represents the city center, *ON* represents the radius of city's districts, and the distance of *ON* is 20 km. According to the distance between the HSR's station and the city center, we first assume that the HSR's station is located in the center of city, as expressed by point *S*. It can affect the surrounding agriculture-related enterprises within 45 kilometers (within the circle *M*). The enterprise *u* within the scope can conveniently use HSR to carry out business communication and trade activities, and foreign enterprises can also easily reach the enterprise *u* through the HSR station, thereby promoting trade opportunities and export orders of enterprise *u*. The enterprises *v* outside this range are far away from the HSR's station, and it takes longer time to reach the HSR's station, leading to less frequent economic and trade activities through HSR to other regions and reducing the willingness and subjective initiative to conduct market search and expansion. It is unfavorable for the enterprise *v* to carry out economic and trade activities. When the HSR's station is located outside the circle *N*, it can also cover the entire districts of the city, and the result is consistent with the former.

5.4. Resolution of Endogenous Problems. In this study, the endogenous problem mainly comes from the nonrandom nature of HSR construction. Regions with better economic development conditions tend to have more possibility of opening HSR, and they may have more export trade activities. We use the instrumental variable regression method to do further endogeneity processing [39]. Firstly, we learn from the method of Faber and use the "least-cost path-spanning tree network" as an IV for the opening of HSR [27]. Secondly, we use China's railway lines in 1961 as an IV. A historical railway line of 1961 has reference meaning for the designing of HSR. Therefore, historical lines have a high correlation with HSR lines, and it is not related to other factors that affect enterprises' export, meeting the exogenous assumption. Finally, we also use the railway passenger

Table 4: The impact of HSR on the export: different geographical distance intervals.

Variable	[0, 15) (1)	[15, 30) (2)	[30, 45) (3)	[45, 60) (4)	[60, 75) (5)	[75, 90) (6)	[90, 105) (7)
HSR	0.079**	0.105***	0.100**	0.006	0.074	0.138	−0.164
	(1.97)	(2.90)	(2.39)	(0.13)	(1.01)	(1.33)	(−0.95)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	34360	36949	30203	24169	13113	8613	5305
Adj. *R*-sq	0.153	0.171	0.163	0.192	0.143	0.112	0.159

Note. ***, **, and * indicate the significance level of 1%, 5%, and 10%, respectively, and the *t* statistic value is in parentheses.

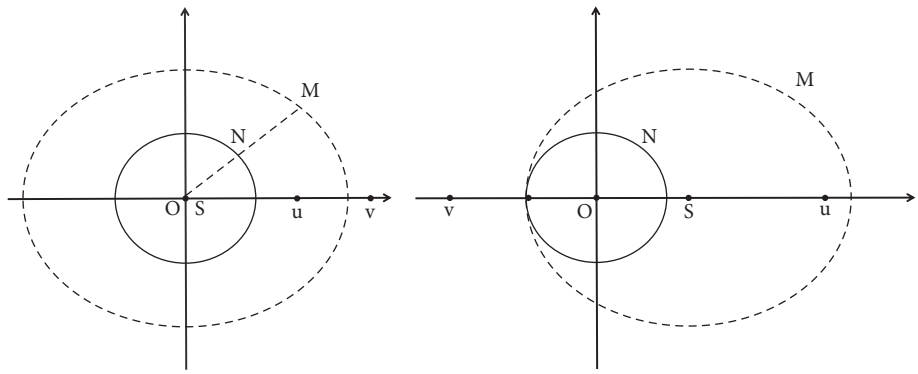

Figure 6: Distribution of the city center, HSR's station, and enterprises.

volume of each region in 1998 as an IV. HSR needs to give priority to regions with more transport demand and satisfy correlation assumptions. Moreover, it is unlikely that historical traffic and transportation pattern are related to other factors affecting current enterprise's export, which satisfies the exogenous assumption.

The results of IV regression are shown in Table 5: the coefficients of HSR in IV regressions are 0.394, 0.335, and 0.371, which are all very positive at the 1% level, and coefficients of these three are relatively close. At the same time, compared with coefficient of 0.069 in the benchmark regression model, the coefficients of IV regression are only expanded by 4–6 times. Jiang analyzed the papers using IV regression in the top financial journals and found that IV estimation expanded the coefficient by an average of 9 times [40]. The expansion of HSR's coefficients in this study is in an acceptable range, indicating that the estimation of IV is more reliable. In addition, the first-stage regression coefficients of IV for HSR are, respectively, 0.050, 0.030, and 0.023, which are significantly positive at the 1% level. The Kleibergen-Paap *F* statistic far exceeds the first-stage empirical value of 10 [41], so the hypothesis of weak instrumental variables can be rejected, which fully reflects the effectiveness of IV.

5.5. Robustness Test. We will adopt the following methods to verify the robustness of the estimation results: (1) we replace the explained variables and use the total export volume and per capita export delivery value instead of export value to perform model regression. (2) We will add samples of enterprises in the municipalities and provincial capitals. (3) Keep data from 2008–2013 and shorten the sample period. (4) Keep odd and even year data separately. (5). Extending the sample period to 2016, use the export data of agricultural products from the 2000–2016 for model regression (we will not be able to control the influencing factors at the enterprise level by using the export data of agricultural products in Chinese Customs Database from 2000 to 2016. Only the influencing factors at the city level can be controlled). The robust results are shown in Table 6; all coefficient are significantly positive at the 1% level and relatively close to the 0.069 obtained in benchmark model results (the average value of seven coefficient estimates is 0.063), which can explain why the empirical results obtained by model estimation are robust and reliable.

After checking the robustness of the benchmark regression results, we need to further verify the robustness affected by distance threshold of HSR to agriculture-related enterprises' export. In Table 4, we conducted a segmented regression with 15 km as an interval. Therefore, we first change the interval and use the 14 and 16 km adjacent to 15 km for segmentation. Secondly, we use half of the 45 km interval at 22.5 km, then use the 22 and 23 km adjacent to 22.5 km for segmentation, and verify the robustness of the distance threshold through squeeze theorem. The results are shown in Table 7; in columns (1)-(2), the coefficients of HSR are significantly positive within 42 and 48 km, indicating that HSR has an apparent effect on increasing the export of agriculture-related enterprises

Table 5: Regression results of instrumental variables.

Variable	Least-cost path-spanning tree network			Was the railway connected in 1961			Railway passenger traffic in 1998		
	(1)			(2)			(3)		
HSR second stage	0.394***			0.335***			0.371***		
	(7.59)			(3.93)			(3.30)		
IV reduced regression		0.020***			0.010***			0.008**	
		(5.42)			(2.78)			(2.33)	
IV first stage for HSR			0.050***			0.030***			0.023***
			(48.03)			(29.21)			(21.45)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	156232	167886	167886	156232	167886	167886	156232	167886	167886
Adj. *R*-sq		0.119	0.423		0.119	0.402		0.119	0.397
Kleibergen-Paap *F* statistic		5169.985			1890.736			1127.994	

Note. ***, **, and * indicate the significance level of 1%, 5%, and 10%, respectively, and the *t* statistic value is in parentheses.

Table 6: The impact of HSR's opening on the export: robustness check.

Variable	Export volume	Per capita export delivery value	All cities	2008–2013	Odd years	Even years	2000–2016
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
HSR	0.056***	0.020***	0.076***	0.044***	0.070***	0.081***	0.092***
	(3.00)	(3.07)	(5.06)	(2.91)	(3.42)	(3.37)	(5.63)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes	Yes	Yes	Yes	No
N	167886	164740	211985	109814	84257	83629	201438
Adj. *R*-sq	0.078	0.744	0.142	0.098	0.166	0.162	0.026

Note. ***, **, and * indicate the significance level of 1%, 5%, and 10%, respectively, and the *t* statistic value is in parentheses.

Table 7: Robustness check for different geographical distance intervals.

The interval of 14 km		The interval of 16 km		The interval of 22 km		The interval of 22.5 km		The interval of 23 km	
(1)		(2)		(3)		(4)		(5)	
[0, 14)	0.083**	[0, 16)	0.087**	[0, 22)	0.117***	[0, 22.5)	0.120***	[0, 23)	0.114***
	(2.01)		(2.30)		(3.71)		(3.81)		(3.67)
[14, 28)	0.126***	[16, 32)	0.068*	[22, 44)	0.057**	[22.5, 45)	0.056**	[23, 46)	0.062**
	(3.29)		(1.89)		(2.18)		(2.17)		(1.98)
[28, 42)	0.094**	[32, 48)	0.123***	[44, 66)	0.009	[45, 67.5)	0.028	[46, 69)	−0.003
	(2.31)		(3.11)		(0.25)		(0.73)		(−0.08)
[42, 56)	−0.006	[48, 64)	−0.008	[66, 88)	0.081	[67.5, 90)	0.056	[69, 92)	0.122
	(−0.13)		(−0.16)		(1.06)		(0.71)		(1.52)
[56, 70)	−0.000	[64, 80)	0.085	[88, 110)	−0.175	[90, 112.5)	−0.139	[92, 115)	−0.188
	(−0.00)		(1.06)		(−1.29)		(−0.98)		(−1.32)

Note. ***, **, and * indicate the significance level of 1%, 5%, and 10%, respectively, and the *t* statistic value is in parentheses.

within this distance. In columns (3)–(5), the coefficient estimates are very positive at the level of 5% within 45 km, indicating that the estimation of spatial distance threshold is robustness and reliability. We have further changed the division of distance intervals. For example, we divided by 13, 17, 21, and 24 km and performed model regression, which had no effect on the robustness of results. The effect of HSR on the export of agricultural enterprises is about 45 km, and once exceeding this distance, HSR will no longer have an impact on the export of agricultural enterprises.

5.6. Placebo Test. We conduct a placebo test on the regression results of the benchmark model. This placebo test has two main parts: firstly, we make the policy shock of HSR on agriculture-related enterprises in specific regions become random (the policy shock is generated randomly by a computer) and estimate the impact of HSR on agricultural enterprises' exports. Then, we repeat this random process 200 times to obtain the distribution of coefficients and *t* statistic values of policy shock. If the coefficient estimates and *t* statistic of HSR are concentrated around 0, it indicates that policy effect is not random, but it is indeed from HSR.

Secondly, we advance the time of HSR's opening by 5 to 8 years. During this period, when HSR was not opened in the same area, we follow the benchmark model settings and use data from 2000 to 2007 to perform the model regression again. If we get the same significant and positive results, it means that the causality in the benchmark model is not correct.

The results of the placebo test are shown in Figure 7 and Table 8. In Figure 7, the coefficients of policy shock obtained after random processing are distributed between −0.02 and 0.02, and most of the t statistic values are also between −1.96 and 1.96 (between the dotted lines in Figure 7) and clustering around 0, indicating that the random policy shock of HSR has almost no impact on exports of agriculture-related enterprises. In Table 8, at each advanced time, all the coefficients of HSR are far less than 0.069, the benchmark result, and they are not statistically significant. The result of the benchmark model also has robustness and reliability. The opening of HSR can significantly promote the export growth of local agriculture-related enterprises.

6. Further Discussion

In the benchmark regression model, endogenous treatment, robustness check, and placebo test, we finally concluded that HSR can bring about growth in agriculture-related enterprises' export. Therefore, we will further discuss the mechanism of HSR on export growth of agriculture-related enterprises from two aspects: market access and siphonic effect, combined with distance threshold between enterprises and HSR's stations.

6.1. Mechanism Analysis

6.1.1. Mechanism of Market Access. We learn from Donaldson to measure the market access caused by HSR, identifying the mechanism of HSR on export growth of agriculture-related enterprises, as shown in the following formula:

$$\mathrm{MAHSR}_a = \sum_{b=1} \tau_{ab}^{-\theta} \mathrm{GDP}_b. \tag{18}$$

Due to the opening of HSR and the improved transportation convenience, the local market access level has been greatly improved. MAHSR refers to the market access level brought by the opening of HSR. In formula (18), MAHSR_a represents market access brought by HSR. We set our benchmark model to deform, and we can get

$$\ln \mathrm{export}_{ict} = \beta_m \mathrm{MAHSR}_{ct} + \beta_2 E_{ict} + \beta_3 C_{ct} + \xi_i + \xi_{pt} + \xi_{nt} + \mu_{ict}. \tag{19}$$

In order to explore the impact of market access on the export of agriculture-related enterprises in different distance threshold, we divided the distances from enterprises to HSR's stations every 15 km. The results are shown in Table 9: the results in column (1) showed that the construction of HSR has improved the level of local market access, reduced the cost of time and space, facilitated local agriculture-related enterprises to conduct more frequent foreign exchanges, strengthened the division of labor and cooperation between enterprises, and reduced the degree of information asymmetry, thereby improving the matching efficiency. It can encourage agriculture-related enterprises to expand their market search radius, enhance their subjective initiative to enter the international market, and obtain more export opportunities. In the segmented regression of different geographic distance thresholds, the results in column (2)–(4) showed that market access brought by HSR to enterprises gradually reduced, with the impact on enterprises' exports within 45 kilometers. HSR has only increased exports of the agriculture-related enterprises in 0–45 km. This is consistent with the results in Table 4, which is mainly because these enterprises are closer to HSR's station. When the HSR is opened, they can enjoy the improved market access brought by HSR in spatial priority and grasp opportunities for external communication brought by HSR to strengthen economic and trade exchanges with outside market more effectively. When the distance exceeds 45 km, the agriculture-related enterprises are not efficient in using HSR, and their communication frequency with outside regions has little changed. At the same time, higher market entry barriers also make these enterprises be less willing to take part in domestic market division of labor cooperation and international trade, which thus cannot significantly promote the export.

In order to further identify the impact of market access caused by HSR on the export, we divided samples according to regional traffic conditions and enterprise's productivity level. Firstly, according to the regional traffic conditions, the average road traffic level in the top 50% of the country from 2000 to 2007 is divided into regions with higher traffic conditions, and the bottom 50% is divided into regions with lower traffic conditions. Secondly, according to the level of the enterprise's productivity, the top 50% of the annual per capita total industrial output value is classified as a higher labor productivity of the enterprise, and the bottom 50% is classified as a lower labor productivity of the enterprise. The results are shown in Table 10: in columns (1)-(2), compared to regions with high-level traffic conditions, HSR has brought bigger effects of export growth to agriculture-related enterprises located in regions with low-level traffic conditions. Regions with backward transportation, such as the central and western provinces of China, have poor economic foundations and inherently inadequate terms of trade. HSR provides enterprises in these regions with late-mover advantages and more opportunities for foreign exchanges and participation in the industrial division of labor and cooperation, thus obtaining more international and domestic market information to promote international trade. In columns (3)-(4), compared with low-level productivity enterprises, high-level productivity enterprises can gain greater competitive advantage from the opening of HSR. According to the heterogeneous-firm trade theory, high-productivity firms have a higher tendency of export. These agriculture-related enterprises often possess advanced production technology and

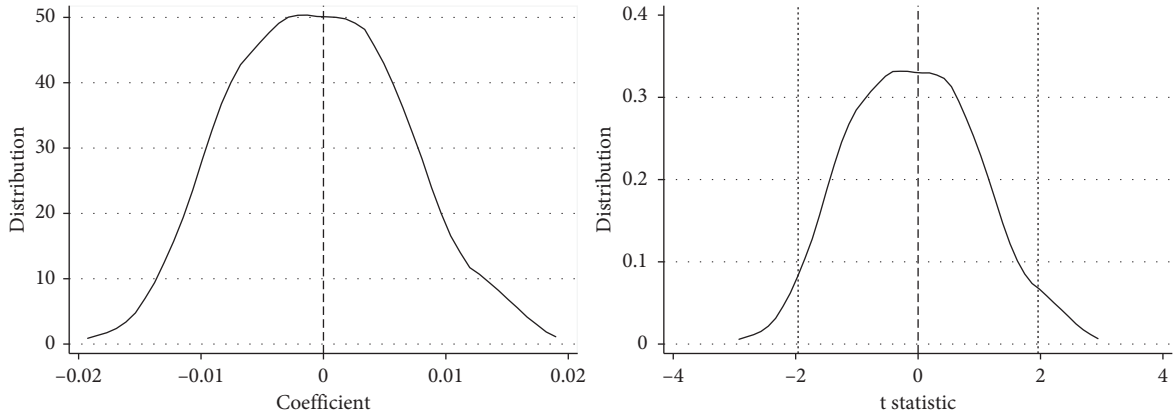

Figure 7: Placebo test: random impact.

Table 8: Placebo test: time advanced.

Variable	Forward_8 years (1)	Forward_7 years (2)	Forward_6 years (3)	Forward_5 years (4)
HSR	−0.026	−0.014	0.014	0.013
	(−1.25)	(−0.76)	(0.61)	(0.55)
Control variables	Yes	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes	Yes
Province-year FE	Yes	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes	Yes
N	72764	72764	72764	72764
Adj. *R*-sq	0.146	0.146	0.146	0.146

Note. ***, **, and * indicate the significance level of 1%, 5%, and 10%, respectively, and the *t* statistic value is in parentheses.

Table 9: The impact of market access on the export under different geographic distances.

Variable	All (1)	[0, 15) (2)	[15, 30) (3)	[30, 45) (4)	[45, 60) (5)	[60, 75) (6)	[75, 90) (7)	[90, 105) (8)
MAHSR	0.003***	0.007**	0.005**	0.006**	−0.000	0.002	0.005	−0.014
	(2.99)	(2.34)	(2.26)	(2.07)	(−0.12)	(0.47)	(0.63)	(−1.02)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	166480	34360	36949	30130	24009	12935	8359	5143
Adj. *R*-sq	0.144	0.153	0.171	0.163	0.193	0.144	0.110	0.170

Note. ***, **, and * indicate the significance level of 1%, 5%, and 10%, respectively, and the *t* statistic value is in parentheses.

Table 10: The impact of market access under different levels of traffic and productivity conditions.

Variable	Traffic		Productivity	
	High-level (1)	Low-level (2)	High-level (3)	Low-level (4)
MAHSR	0.003***	0.022***	0.006***	0.000
	(2.59)	(3.35)	(3.42)	(0.13)
Control variables	Yes	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes	Yes
Province-year FE	Yes	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes	Yes
N	154713	11767	80485	85995
Adj. *R*-sq	0.147	0.134	0.136	0.163

Note. ***, **, and * indicate the significance level of 1%, 5%, and 10%, respectively, and the *t* statistic value is in parentheses.

management experience, with a stronger willingness and tendency to participate in the export. So, they can easily grasp the policy opportunities of market access brought by HSR to enter the international market.

6.1.2. Mechanism of Siphon Effect. HSR can improve the local market access level, reduce communication and information barriers, and strengthen the understanding of outside and international market information. However, HSR will also widen gaps in infrastructure construction between local regions and surrounding areas without HSR. Regions with HSR can obtain more communication and information convenience compared with other places. They have more advantages in regional export trade competition,

so they may take away export trade opportunities from surrounding regions. As a result, their agriculture-related enterprises' export increases. Meanwhile, exports of enterprises in surrounding regions without HSR will relatively decrease, forming a siphonic effect of export. In this regard, we verify the siphonic effect mechanism by deform formula (16):

$$\ln \text{export}_{ift} = \beta_n \text{NEARHSR}_{ct} + \beta_2 E_{ift} + \beta_3 C_{ft} + \xi_i + \xi_{pt} + \xi_{nt} + \mu_{ift}. \tag{20}$$

In formula (20), when the region c, which is the closest to region f, does not open HSR, $\text{NEARHSR}_{ct} = 0$, and after opening HSR, $\text{NEARHSR}_{ct} = 1$. For example, Jiangsu Nantong did not open HSR, while JiangSu WuXi, the nearest city to NanTong, opened HSR in 2010. Therefore, for JiangSu NanTong, $\text{NEARHSR}_{ct} = 0$ before 2010 and $\text{NEARHSR}_{ct} = 1$ after 2010. The coefficient β_n reflects whether siphonic effect exists. When $\beta_n < 0$ $\sqrt{s/\pi}$ and it is statistically significant, it indicates that HSR in surrounding regions will have a significant siphonic effect. We also divide the distance into 7 intervals and perform model regression, respectively. The results are shown in Table 11; the results in column (1) indicate that the mechanism of siphonic effect is established. HSR breaks the balance of regional export behavior, and agriculture-related enterprises in the region where HSR is opened can obtain more outside and international market information, thereby forming a competitive advantage and relatively obtaining more export opportunity. The results in columns (2)–(4) show that export of agriculture-related enterprises in this interval will drop sharply with the opening of HSR in neighboring regions, resulting in a stronger siphonic effect. When the distance is longer than 45 kilometers, siphonic effect becomes very small. From the absolute value of the coefficient, we can see that siphonic effect is greater than market access, which means that, in these two mechanisms, the siphonic effect of inter-regional competition triggered by opening HSR is the dominant mechanism which leads to export growth of agriculture-related enterprises. Enterprises with HSR could not only gain greater trade competitive advantage compared to those regions where HSR is not open but also seize export opportunities and orders from similar enterprises in surrounding areas, thereby strengthening their exports' growth.

In Table 12, the results in column (1)-(2) demonstrate that regions with low-level traffic conditions have a bigger siphon effect after HSR's opening in adjacent regions. In recent years, a series of fierce competition about the direction of HSR lines and the distribution of stations have erupted in China. Regions with HSR have gained economic and trade competitive advantage over those without HSR. That is more noticeable in the central and western regions with poor traffic conditions. In regions with backward transportation, limited resources are mainly located in regions where HSR is opened, allowing enterprises in such places to obtain more resource input and trade opportunities. It makes export orders flow from enterprises in regions without HSR to enterprises in regions where HSR was opened. From perspective of productivity conditions, the results in columns (3)-(4) show that the siphonic effect produced by HSR has greater impact on agriculture-related enterprises with high-level productivity. High-productivity enterprises have a higher tendency of export and are also more susceptible to unfavorable market competition brought by HSR. These enterprises in regions without HSR are at a disadvantage in competition with similar enterprises in regions with HSR, and their exports are relatively declined.

6.2. Heterogeneity Analysis

6.2.1. Heterogeneity of Enterprises Ownership. As to different ownership types of agriculture-related enterprises, the impacts of HSR on export may also be different (the main ownership types of Chinese enterprises are as follows: state-owned/collective enterprises, Sino-foreign joint/cooperative, exclusively foreign-owned enterprises, and private enterprises). The model estimates are carried out according to different ownership types, and results are shown in Table 13: HSR has a significant positive effect on the export of state-owned/collective, Sino-foreign cooperation/joint, and private agriculture-related enterprises, and the most obvious effect is in state-owned/collective enterprises. However, exclusively foreign-owned enterprises cannot benefit from HSR. The main reason is that exclusively foreign-owned enterprises are more focused on the Chinese market, and the proportion of domestic sales is higher than that of export, so export promotion effect brought by HSR is limited. More importantly, the planning and construction of HSR are closely related to the local government. Domestic enterprises, including state-owned/collective, Sino-foreign cooperative/joint, and private agriculture-related enterprises, are more adaptable to local conditions and have actual advantages in grasping policy changes. They can accurately adjust their business and export strategy according to changes in the external environment.

6.2.2. Heterogeneity of Enterprise Development Stage. We divide agriculture-related enterprises into three different development stages, start-up, developing, and maturity (the start-up are enterprises in the early stages of development. According to the definition of the Global Entrepreneurship Observation (GEM) report, they usually refer to enterprises established within 42 months, that is, within 3.5 years. The enterprises that have been established for more than 10 years are relatively mature enterprise, while those in between are an enterprise that in the developing stage), to discuss the differences of enterprises' export in three stages affected by HSR. Results are shown in Table 14: HSR can effectively promote export growth of agriculture-related enterprises in the developing and maturity stage. For the agriculture-related enterprises of start-ups, HSR cannot bring significant export growth. The main reason is that, compared with enterprises in developing and mature stages, most enterprises in start-up stages are in danger of survival within 3 years after their establishment, and nearly half of them survive less than 5 years (the data comes from the "Report on

Table 11: The impact of siphonic effect on export under different geographical distances.

Variable	All (1)	[0, 15) (2)	[15, 30) (3)	[30, 45) (4)	[45, 60) (5)	[60, 75) (6)	[75, 90) (7)	[90, 105) (8)
NEARHSR	−0.074***	−0.154***	−0.093**	−0.114***	−0.012	−0.075	−0.128	0.152
	(−4.52)	(−3.89)	(−2.51)	(−2.66)	(−0.27)	(−1.05)	(−1.60)	(1.43)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	167886	34360	36949	30203	24169	13113	8613	5305
Adj. *R*-sq	0.143	0.154	0.171	0.163	0.193	0.143	0.112	0.159

Note. ***, **, and * indicate the significance level of 1%, 5%, and 10%, respectively, and the *t* statistic value is in parentheses.

Table 12: The impact of siphonic effect under different levels of traffic and productivity conditions.

Variable	Traffic		Productivity	
	High-level (1)	Low-level (2)	High-level (3)	Low-level (4)
NEARHSR	−0.069***	−0.244***	−0.098***	−0.033
	(−4.05)	(−3.26)	(−3.88)	(−1.46)
Control variables	Yes	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes	Yes
Province-year FE	Yes	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes	Yes
N	155053	12833	81322	86564
Adj. *R*-sq	0.147	0.129	0.135	0.163

Note. ***, **, and * indicate the significance level of 1%, 5%, and 10%, respectively, and the *t* statistic value is in parentheses.

Table 13: The impact of HSR's opening on the export with different enterprises' ownership.

Variable	State-owned/collective (1)	Sino-foreign joint/cooperative (2)	Exclusively foreign-owned (3)	Privately-owned (4)
HSR	0.214**	0.075**	0.028	0.064**
	(2.33)	(2.11)	(0.89)	(2.46)
Control variables	Yes	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes	Yes
Province-year FE	Yes	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes	Yes
N	11358	43920	47287	65321
Adj. *R*-sq	0.137	0.142	0.144	0.179

Note. ***, **, and * indicate the significance level of 1%, 5%, and 10%, respectively, and the *t* statistic value is in parentheses.

the Survival Time of Chinese Domestic Enterprises" in 2013). They are not yet familiar with the international export market, and their export behavior is unstable and fragile, so HSR cannot drive the exports growth of these enterprises. The business and trade relations of developing and mature enterprises have gradually stabilized. The opening of HSR has just provided these enterprises with a larger market search radius and more potential trade opportunities to promote export growth.

6.2.3. Regional Heterogeneity of Enterprise. We divide regions into three parts: the east, central, and western parts, and discuss different impact of HSR on different regions. The results are presented in Table 15; from the perspective of policy effects, the coefficients of HSR increase from east to west, but only in the eastern and western regions are statistically significant. The eastern region has a geographical advantage along coast, and HSR has strengthened the dominant position of local enterprises in industrial chain, division of labor, cooperation with similar enterprises, and integrating market information, thereby improving the efficiency of eastern agriculture-related enterprises in export trade. In the western region, due to its low level of overall transportation infrastructure, HSR has gained infrastructure advantages over surrounding regions, which can greatly enhance competitive advantage in the international market. For enterprises in the central region, the impact of HSR on their exports is not statistically significant. The foremost reason is that the central region lacks coastal location advantage compared with the eastern region, and they also lack of strong trade potential and late-comer advantages

Table 14: The impact of HSR's opening on the export with different development stages.

Variable	Start-up (1)	Developing (2)	Mature (3)
HSR	−0.038	0.093***	0.070**
	(−0.64)	(4.10)	(2.54)
Control variables	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes
Province-year FE	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes
N	31675	79192	57019
Adj. *R*-sq	0.231	0.100	0.095

Note. ***, **, and * indicate the significance level of 1%, 5%, and 10%, respectively, and the *t* statistic value is in parentheses.

Table 15: The impact of HSR's opening on the export with different regions.

Variable	Eastern (1)	Middle (2)	Western (3)
HSR	0.068***	0.116	0.542**
	(3.92)	(1.34)	(2.12)
Control variables	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes
Province-year FE	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes
N	154934	9956	2996
Adj. *R*-sq	0.144	0.159	0.189

Note. ***, **, and * indicate the significance level of 1%, 5%, and 10%, respectively, and the *t* statistic value is in parentheses.

compared with the western region. With the continuous upgrading of HSR's network, many low-end industries gradually transfer from the eastern region to the central and western regions. The central region will become an important gathering place for agriculture-related enterprises and their export to the international market. At that time, HSR will play a significant role in promoting the export of agriculture-related enterprises in the central region.

7. Conclusions and Suggestions

We take the opening of HSR in China as a quasi-natural experiment, analyze its impact on the export of agriculture-related enterprises, and then explore the mechanism about it. On the basis of early research, our research has many expansions and innovations. In the research on the impact of transportation infrastructure construction on the economy, we pay attention to the impact of China's HSR on trade, and there are few economists who paid attention to the impact of China's HSR; In the discussion of the mechanism of the impact of transportation infrastructure on exports, early studies have shown more that the construction of transportation infrastructure can reduce the transportation cost of enterprises, and enterprises can carry out export activities at a lower cost, thereby promoting the growth of exports. In our research, because HSR does not directly transport goods, we have opened up new mechanisms including market access and siphon effect to explore the impact of HSR on exports; in the literature on the China story, the research on Chinese agriculture is a very important part. Unlike previous studies, our research combines Chinese agriculture with China's HSR and explores the impact of the opening of HSR on agricultural enterprises.

More specifically, the results of our research show that HSR can promote the agriculture-related enterprises' export growth by 6.9%, and this result is robust because we get almost consistent results in the regression of changing different control variables. Meanwhile, the effect of this policy has continued to increase over time. Furthermore, the policy effect of HSR is closely related to geographical distance. HSR has only an effect on the export of enterprises within 45 km, but when the distance exceeds 45 km, HSR will no longer have apparent impact on exports. HSR improves local market access level, strengthens the frequency of communication, reduces the information barriers to the outside world, and lowers the cost for obtaining information. It can help local agriculture-related enterprises to enter the international market. At the same time, HSR has strengthened local infrastructure advantage compared with regions without HSR, which became a competitive strength in economic and trade activities. As a result, it has formed a siphonic effect in export. The policy effect of HSR has distance threshold for market access and siphonic effect. When the distance is within 45 km, both the market access and siphonic effect are established, but when the distance exceeds 45 km, the HSR has neither market access nor siphonic effect on export. Compared with the market access, HSR has a stronger siphon effect on exports for agriculture-related enterprises. In addition, market access and siphonic effects are more pronounced in regions with lower primitive traffic conditions and enterprises with higher productivity. Finally, the results of heterogeneity analysis show that HSR has different effects for different types of enterprises; for agricultural enterprises with different ownership, HSR has a significant positive impact on the export of state-owned/collective, Sino-foreign cooperative/joint ventures, and private agricultural-related enterprises, and the effect is most obvious in state-owned/collective enterprises. However, exclusively foreign-owned enterprises cannot benefit from HSR. For agricultural enterprises at different stages of development, HSR can effectively promote the export growth of agricultural enterprises in the mature stage of development. For start-up agriculture-related enterprises, HSR cannot bring significant export growth. As a populous country with abundant land resources, China's agricultural development is of vital importance. In the process of sustainable agricultural development, HSR also provides a new opportunity for the increasingly involved agricultural sector, which has great significance for transformation and upgrading Chinese agricultural industry and its export-oriented development path. Armed with this research, we come up with views and policy recommendations.

Firstly, the results of this paper shows that HSR can significantly promote the export growth of agriculture-related enterprises, indicating that the Chinese government should comprehensively focus on the development opportunities brought by HSR to the agricultural sector and rural

revitalization, encourage agriculture-related enterprises to make use of opportunities to integrate agricultural resource in counties and townships, and vigorously develop export-oriented agriculture. On this basis, high-quality agriculture-related enterprises should be encouraged to actively explore the international market and promote the export of famous agricultural products to earn income. This will drive Chinese agriculture to go global.

Secondly, HSR only has an impact on the export of agriculture-related enterprises within 45 km around HSR stations. The local government can rationally plan industrial development based on the location of HSR's stations and accelerate the construction of modern industrial parks, industrial strong towns, and characteristic industrial clusters near transportation stations. At the same time, local governments should guide newly-built enterprises to geographically get close to transportation stations so as to improve the convenience of external communication by means of transportation advantages. The central government should actively promote the transfer of low-end industries such as agricultural products processing industries from developed cities in eastern coastal regions to inland counties along HSR routes, strengthen the industrial and economic foundations of counties and townships, and promote the growth of agricultural exports in these regions.

Thirdly, there are two main mechanisms for the impact of HSR on the export of agriculture-related enterprises: market access and siphonic effect. The market access effect indicates that we should strengthen the construction of transportation infrastructure, reduce the local market barriers and restrictions, so as to attract external and international enterprises to enter the local market for economic and trade activities, and help more local enterprises enter the international market. The siphon effect is greater than the market access effect, indicating that Chinese HSR's construction is still unbalanced, triggering economic and trade competition between regions. It is necessary to accelerate the popularization of HSR networks, rationally plan the layout of HSR routes, and promote the coverage of HSR in inland areas, counties, and other backward regions. HSR should be fully covered in cities and counties where conditions permit. At the same time, we should vigorously develop cargo transportation for HSR to reduce the time and cost of cargo transportation, so as to fundamentally reduce the trade costs of Chinese agricultural sector and agricultural products.

Finally, HSR has different export effects on different types of agriculture-related enterprises. It can significantly promote the export of high-productivity enterprises and mature enterprises, but it has no impact on the export of low-productivity and start-up enterprises. The results of this paper show that we should encourage agriculture-related enterprises to increase investment in scientific and technological innovation, continuously improve technological level and total factor productivity, and transform from low-end quantity-driven export mode to the high-end quality-driven export mode. Local governments should encourage cooperation among different ownership enterprises. State-owned enterprises, foreign-funded enterprises, and private enterprises should give full play to their respective advantages and work together to promote export growth.

Data Availability

The data used to support the findings of this study are available from corresponding author upon request.

Conflicts of Interest

The authors declare that they do not have any conflicts of interest.

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Review Article

A Literature Review of Social Network Analysis in Epidemic Prevention and Control

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Studying the structure and evolution characteristics of social networks is of great significance in assessing and controlling the outbreak of infectious diseases. Therefore, it is necessary to find research trends in this field. In this study, 1,752 documents (2001–2020) related to the relationship between the social network and epidemic published from Scopus, WOS (Web of Science), and CNKI (China National Knowledge Infrastructure) databases were studied to provide a more comprehensive overview of the frontiers of research in this field, including epidemics in social networks, spread of disease, influence of different factors on the spread of the epidemic, prevention and control strategies of the epidemic, and comparison of various strategies. Besides, several new research directions in this field worthy of attention of researchers are discussed.

1. Introduction

Public health is one of the major concerns of governments and international health agencies around the world. In addition to the thousands of new pathogens discovered over the past few decades, the resurgence of infectious diseases such as cholera, plague, and yellow fever is a cause of concern. Lifestyle changes, coupled with environmental and biological changes, have made epidemics of infectious diseases more likely than ever before and spreading farther and faster. The COVID-19 is now wreaking havoc worldwide, causing more than 157.7 million infections and nearly 3.3 million deaths (World Health Organization; "int/emergencies/diseases/novel-coronavirus-2019;" last modified May 8, 2021). The epidemic has seriously affected people's everyday lives. Therefore, efforts must be made efficiently to research and control infectious diseases and to design effective prevention and mitigation strategies.

On the one hand, the pandemic has a massive impact on the society. The Internet has become an essential thing in our daily lives. It promotes the continuous improvement of modern health systems and reduces the threat of epidemics. On the other hand, the ever-developing social networks have brought closer connections between people, thus accelerating the outbreak of pandemics, such as SARS in 2003, H1N1 influenza in 2005, H7N9 in 2013, HIV/AIDS in 2015, Ebola epidemic in 2019, and corona virus disease in 2020 which brought considerable losses to the national economy, caused disasters to people's lives, and brought colossal turmoil to the international community. Therefore, the existence of epidemics is a problem we must solve.

Social networks are one of the most effective and visual tools for measuring and characterizing social relationships. Newman's [1] previous research found that there seems to be a strong correlation between the network structure and the division of communities perceived by human observers, and it is this correlation that makes community structure analysis a helpful tool for understanding the behavior of network systems. A social network refers to a collection of social actors and their relationships. The fundamental elements include actors, relationships, and groups. All individuals, social entities, or events in a social network can be called actors, all connections between group members are called relationships, and a group is a collection of all actors. Social network analysis (SNA) is based on the interaction between social actors, using points to represent social actors and connections of points to represent a specific social relationship between actors to quantify these social

relationships [2]. SNA has two research orientations. One is the egocentric network analysis method, which takes the individual as the center, analyzes its external relations, and studies the connections between actors and others and the interrelationships between others who are directly related to them. The other is the complete global network analysis method, which studies the direct and indirect relationships between all actors in a group with a clear margin [3]. While epidemiological models can help design and analyze epidemiological surveys, they can identify trends, make general predictions, and estimate uncertainties in predictions based on collecting critical data [4]. With the rapid development of the interdisciplinary fields of computer science, network science, biology, and physics, it is necessary to conduct a comprehensive review of the current state-of-the-art technology and provide a road map to the research community to help organize future research in this field.

In conclusion, social networks' structural and evolutionary characteristics are of great significance for the assessment, control, monitoring, and prevention of epidemic diseases. This research aims to summarize the literature of the past 20 years and the application of manual social network analysis in epidemic prevention and control. At the same time, it looks forward to the future development direction and proposes more detailed research directions. Therefore, the contribution of this research is twofold. First, this article introduces in detail how social network analysis describes the spread of infectious diseases and its application in the prevention and control of infectious diseases, revealing this field's development. Secondly, it puts forward the shortcomings of existing research and new social environment, which hint at future research challenges and opportunities.

The rest of this article is structured as follows. Section 3 will introduce the network model and epidemic spread model designed for the construction of epidemic transmission problems. Section 4 introduces the prevention and control strategies for the spread of infectious diseases combined with social networks. Finally, in Section 5, we propose the deficiencies of existing research and future research directions. Figure 1 enables readers to have a more precise grasp of the structure of this article.

2. Approach to Literature Review

Creating a comprehensive literature review begins with an extensive search of relevant research studies. In order to obtain the best results and to be able to search existing publications consistently, we decided to use the Preferred Reporting Items for Systematic Reviews and Meta-Analyses methodology [5] for meta-analysis (Figure 2). Our literature search can be summarized in Figure 2, where we provide the number of reviewed publications and the screening process followed.

During the search for relevant sources, we used the most popular bibliographic databases: Scopus, Web of Science, and China National Knowledge Infrastructure, and we started with searching for social network analysis in epidemic prevention and control. We started with more generic keywords, to make sure that we do not oversee any research studies. We used the following set of keywords (i) to describe the social network analysis: complex network, small world network, networked system, social network, scale-free network, adaptive network, network, community structure, heterogeneous network, social network analysis, and SNA (ii) to describe the epidemic spread, prevention, and control: epidemic spreading, contagion spreading, infectious disease spreading, virus spreading, immunization, immunization strategy, and vaccination. We also used the combination of words describing the social network analysis process and the epidemic prevention and control to grasp all possible cases.

After searching through the database, we obtained 1,752 papers, and after preliminary screening, we obtained 279 papers that qualified for the eligibility check. The initial screening excluded papers that were based solely on titles that we can say that they do not fall into the category of "social network analysis" or "epidemic prevention and control."

During the qualification test, we discarded 130 papers that did not fall into the category of "social network analysis" or "epidemic prevention and control," but we did this by reading through the abstract and main text of the paper. For each paper that passed the qualification check, we checked its references (past cross check) and papers citing a given paper (future cross check) to see if any of these papers are eligible to be included in the final Meta-analysis. After that, we reached 149 publications that we included in the final review.

3. Modeling Work

In studying the application of social network analysis in epidemic prevention and control, a very significant point is to study the process of establishing a model. Two aspects need to be considered when establishing the model. (1) What kind of network is used for modeling because the connection modes of different network nodes are different? (2) What kind of infectious disease model is used to simulate the process of disease transmission, which directly affects the complexity of the model? In this article, we have introduced different modeling models used by scholars in the past 20 years, to study the transmission law of infectious diseases based on the social contact network and to solve different infectious disease transmission and prevention and control problems.

3.1. Propagation Modeling

3.1.1. Scale-Free Networks: The Barabási–Albert Model. The scale-free network was first proposed by Barabasi and Albert based on random networks [6]. The degree is the most important index describing the nature of a single node in the network. The degree of a node refers to the number of edges associated with the node and the number of points directly connected to the node [7]. When the degree of each node has a serious uneven distribution (a few nodes in the network called hub points have an extremely large number of connections, and most nodes have only a small number of

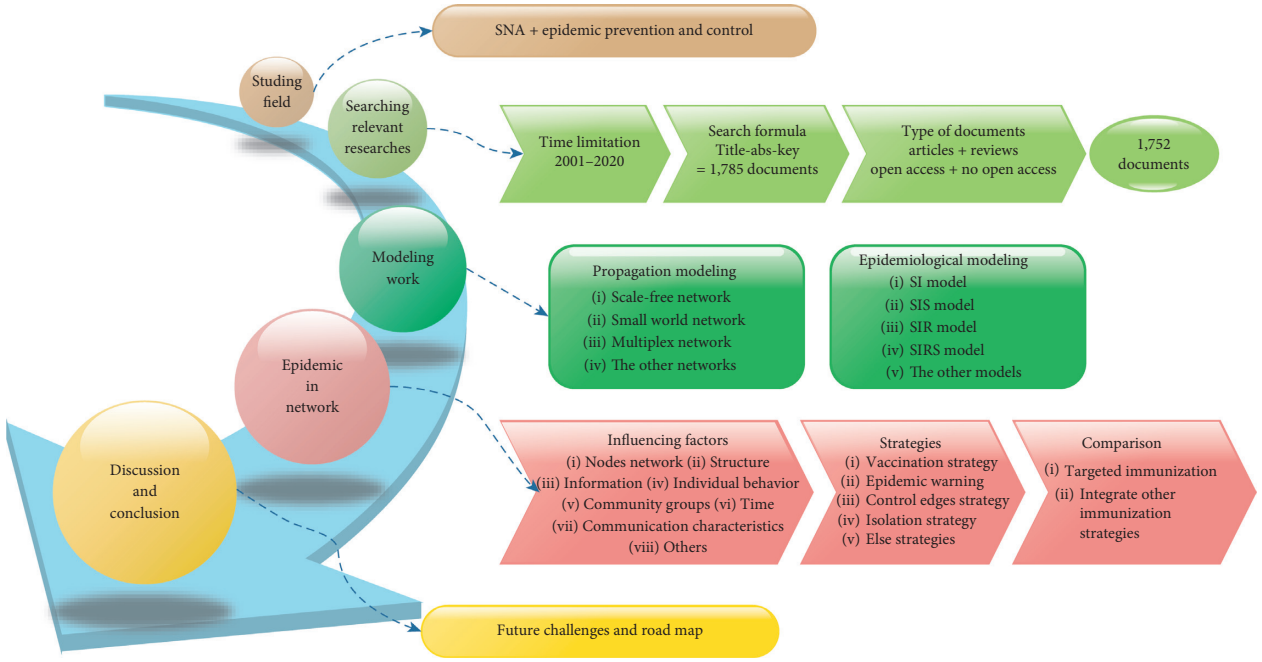

Figure 1: Article flowchart of the structure of this article. This review consists of 6 parts: Introduction, Approach to Literature Review, Modeling Work, Epidemic Research Based on Social Networks, Future Challenges and Road Map, and Conclusion.

connections), we call this network a scale-free network, while the BA diagram was introduced as a model of an evolving network (such as the Internet or the World Wide Web). Among them, links to highly connected nodes are successively established with a higher probability. On the Internet and other social networks, this is a fairly intuitive phenomenon. Under this phenomenon, new individuals are often more likely to establish connections with individuals who are already widely known and widely connected. The BA diagram is constructed using the following algorithm [8]. The BA scale-free network model can well reflect the two important characteristics of the network, such as the World Wide Web, router-level network, film cooperation network, and scientific research cooperation network: growth (the network scale continues to expand) and priority connection function (new nodes are more likely to be connected to "large" nodes with higher connectivity) [9]. Table 1 shows the work done by scholars using the BA scale-free network in infectious diseases.

(1) *Analysis of Infective Factors and Their Relationship*. Many factors affect the spread of epidemics, and different factors do not promote or inhibit the spread of epidemics, so different scholars have conducted different studies. In a scale-free network, Barthelemy et al. [10] studied the relationship between the average density of infected individuals and time. Yan [11] and Chu [12] used link weights to indicate the familiarity between two people and studied the detailed epidemic spreading process in scale-free networks. Wang et al. [13] focused on the analysis of epidemic threshold and AOS (average outbreak size). Meloni et al. [14] used analysis and numbers to calculate the outbreak of epidemics in SF networks when infectious diseases are driven by traffic or interactive flows. Cai et al. [15], Shen and Cao [16], and Yang [17] studied the influence of population density, human immunity, and feedback mechanism on the mechanism of disease transmission.

(2) *Analyze the Spread Mode in Combination with the Infectious Disease Model*. Analyzing the spread of epidemics under social networks will generally be combined with infectious disease models for analysis. For example, Zhou et al. [18] and Lou and Ruggeri [19] used SI models for simulation analysis on scale-free networks; Silva et al. [20], Small et al. [21], and Sun et al. [22] used SIS models to simulate the spread of epidemics and conduct related research and analysis; Chen et al. [23], Liu and Zhang [24], Gong et al. [25], Zhao et al. [26], and Madar et al. [27] combined dynamic SIR epidemiological models to study the spread of epidemics and the impact of immune strategies on the spread of the pathogen in multiple networks; used by Nian et al. [28] and Huo et al. [29], the SIRS epidemic model has been theoretically verified and computer simulated on the scale-free network to establish a more realistic model.

(3) *Analysis of the Attributes of the Infection Process*. May and Lloyd [30] discussed the properties of the infection process in scale-free networks and associated them with the node connection distribution that characterizes the network. Different social structures in the SF network will significantly affect the transmission characteristics of the epidemic: in an unstructured society, the average proportion of infected individuals increases with the growth of k; but in a structured community, the proportion of infected individuals decreases as g increases [31]. Under the limit of the unlimited network, the epidemic process in the scale-free network does not have an epidemic threshold, and a major epidemic outbreak or outbreak of an epidemic state cannot be generated below this threshold, which means no matter how small the probability of

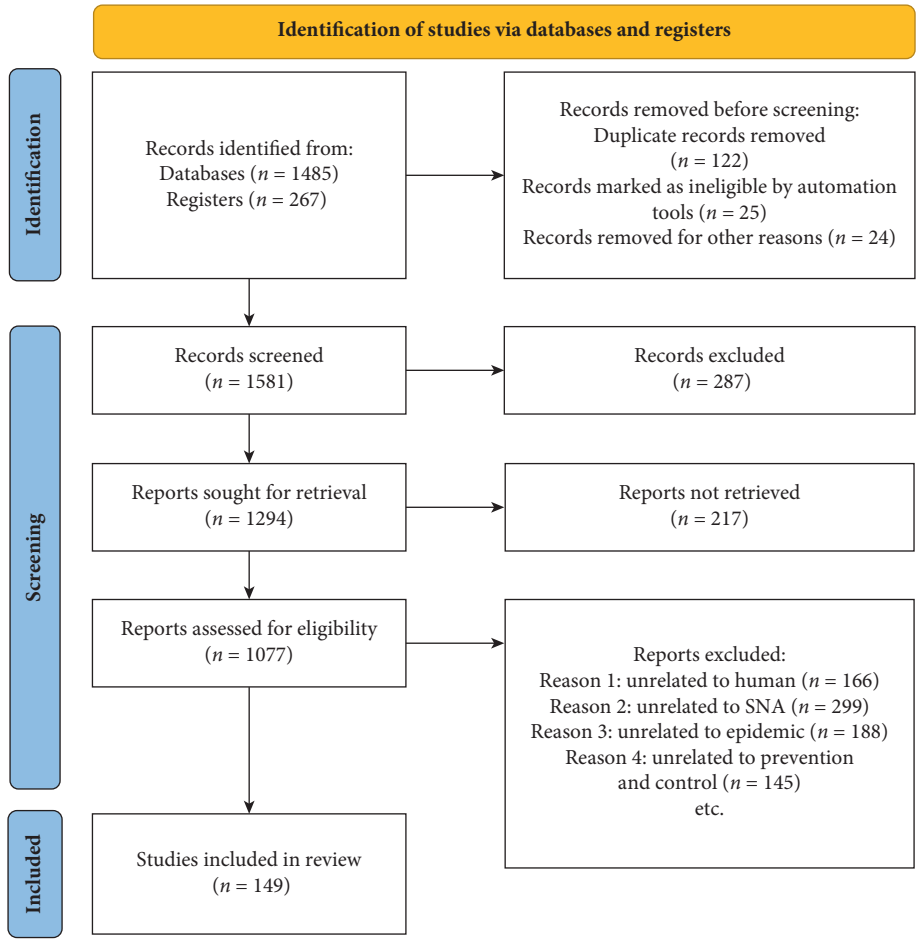

Figure 2: The process of screening articles: at the beginning, we retrieved 1752 papers on specific topics, then deleted 388 papers due to repetition, unqualified, or unavailable, and next eliminated 928 less relevant papers through abstract or full-text reading. Finally, we obtained 149 papers for the study.

Table 1: The work done on infectious diseases using the BA scale-free network: in the related work column, the research studies performed by researchers using the BA scale-free network are shown, and in the reference column is the relevant literature of the corresponding research.

Related work	Reference
Analysis of infective factors and their relationship	[10–17]
Analysis of the spread mode in combination with the infectious disease model	[18–29]
Analysis of the attributes of the infection process	[19, 24, 30–34]
Simulate the established model	[35–38]
The theoretical support for immunization strategies	[39]
The reliance on developing immune strategies	[8, 40]
Evaluation of immunization strategies	[41–45]

transmission, the disease will continue to spread [32, 33]. For a limited-scale scale-free network, Lou and Ruggeri [19] and Liu and Zhang [24] proved the local stability of disease-free balance and the persistence of the disease on the network. Chen and Zhang [34] studied the spread of the virus on a specific scale-free network under two different artificial immune strategies and simulated how the two immune strategies affect the spread of the virus.

(4) *Simulate the Established Model.* Wu et al. [35] used the Barabási–Albert (BA) scale-free network with degree distribution to perform Monte Carlo stochastic simulations of epidemic dynamics. Liu et al. [36] simulated the immune strategy in the BA network. Nian and Hu [37] simulated the spread of three immunization programs based on scale-free networks, namely, random immunization, high-risk immunization, and most common friend priority immunization. Alfinito et al. [38] tested the validity of the protocol on various networks from theoretical models to actual networks and considered the classic example of the Barabási–Albert (BA) model at the first level.

(5) *The Theoretical Support for Immunization Strategies*. Models are theoretical support, and researchers will apply different models to support their views. For example, Pastor-Satorras and espignani [39] concluded in the scale-free network that the lack of epidemic threshold is a key element of epidemiological theory, which opens up different scenarios in the network and rationalizes epidemic events.

(6) *The Reliance on Developing Immune Strategies*. The scale-free network can be considered as a limiting case of heterogeneous systems, and it is natural to find a specially designed immune strategy because the scale-free system does not have any key individual parts. Kuperman and Abramson [8] defined the best immune strategy named total immunity. Xia et al. [40] studied the immunity of highly clustered scale-free networks and proposed an improved local immunity strategy.

(7) *Evaluation of Immunization Strategies*. The evaluation of immunization strategies is inseparable from a specific environment. In the scale-free network, Dezso and Barabasi [41] evaluated random immunity, Shi et al. [42] evaluated directed immunity, Aihara et al. [43] compared immunization strategy of geographical embeddings with uniform or uneven distribution of vertices in a two-dimensional space, and Esquivel-Gomez and Barajas-Ramirez [44] studied the efficiency of isolation policy to control the spread of disease. Besides, Qu and Han [45] compared and analyzed the effects of random immunity and target immunity on BA scale-free networks.

3.1.2. Small World Network. The small world network was first proposed by Watts and Strogatz [46], and then, Newman and Watts [47] applied it to the model of disease transmission. If the average shortest path of the actual network is approximately equal to the average shortest path of the random network and the clustering coefficient of the actual network is greater than the random network, the actual network has the small world attribute. Many networks in the real world have the characteristics of the small world. In other words, the network has a higher clustering coefficient and a shorter average path length [48]. The small world may play an important role in the study of the influence of the network structure upon the dynamics of many social processes, such as disease spreading, formation of public opinion, distribution of wealth, and transmission of cultural traits. In the field of epidemic transmission, prevention, and control, the small world network has provided great help for studying the spread of the pathogen and making targeted immunization measures. Table 2 shows the work done by scholars on infectious diseases using the small world network.

(1) *Research Sites for Propagation Models*. The small world model is very suitable for studying the spread of epidemics. Moore and Newman [49] studied some simple models of disease transmission on small world networks. Kuperman and Abramson [8] observed disordered finite value transitions in a small world model and analyzed infection propagation models with different population structures. Han [50] proposed a susceptibility model with pandemic alert based on a two-dimensional small world network. Li et al. [51] proposed a dynamic small world network model that can simulate local and mobile connections in real life.

(2) *Analyze the Spread Mode in Combination with the Infectious Disease Model*. In order to use the simplest (minimum parameter) model to accurately simulate the qualitative characteristics of the SARS epidemic, Small and Tse [52] applied the small world model to simulate the spread of SARS in Hong Kong. Verdasca et al. [53] performed long-term stochastic simulations of individual-based cellular automata on a small world network with SIR and SEIR node dynamics.

(3) *The Reliance on Developing Immune Strategies*. Similar to the scale-free network, the small world network is also a platform for proposing immune strategies. For example, Yu et al. [54] proposed an analytical solution for the spread of epidemics and control measures on one-dimensional small world networks by analyzing certain parameters.

(4) *The Place of Simulating, Analyzing, and Verifying Immune Strategies*. Nian and Hu [37] simulated the spread of three immunization schemes based on the small world and scale-free networks. Alfinito et al. [38] tested the validity of the protocol on various networks ranging from theoretical models to actual networks. In order to verify the effectiveness of immunization, Nian et al. [28] conducted theoretical verification and computer simulation on the small world network with the SIRS epidemic model. Based on the UAU-SIS model in multiple networks with heterogeneous infection rates, Yang [17] compared the Monte Carlo simulation with the theoretical results on the proportion of infected nodes.

3.1.3. Multiplex Network. Although the research of Internet epidemiology has made great progress, the traditional single network cannot accurately imitate most real systems, especially in describing the interaction between empirical systems. In this sense, in recent years, multiplexing networks have attracted great attention.

As early as 2006, Jo et al. [55] proposed that a certain type of channel can be separated from the entire network, and a multilayer network model can be constructed in such a way that a different type of information is transmitted through different layers, and only when they are in certain node meets can they interact with each other. In 2014, Chen et al. [56] and Granell et al. [57] described a transmission process involving two competitions: information transmission prevented the spread of disease, and the node infected by the disease can support the information dissemination process by generating new conscious individuals. The abstract model is shown in Figure 3, considering a multiplexing network composed of two layers. The bottom layer is the physical connection network, and the top layer is the representative of the online social network. All nodes represent the same entity in these two layers, but the connectivity between them is different.

In the past four years, the multiplex network model has been further developed. Liu et al. [58] established the system

Table 2: The work done on infectious diseases using the small world network: in the related work column, the research studies performed by researchers using the small world network are shown, and in the reference column is the relevant literature of the corresponding research.

Related work	Reference
Research sites for propagation models	[8, 49–51]
Analyze the spread mode in combination with the infectious disease model	[52, 53]
The reliance on developing immune strategies	[54]
The place of simulating, analyzing, and verifying immune strategies	[17, 28, 37, 38]

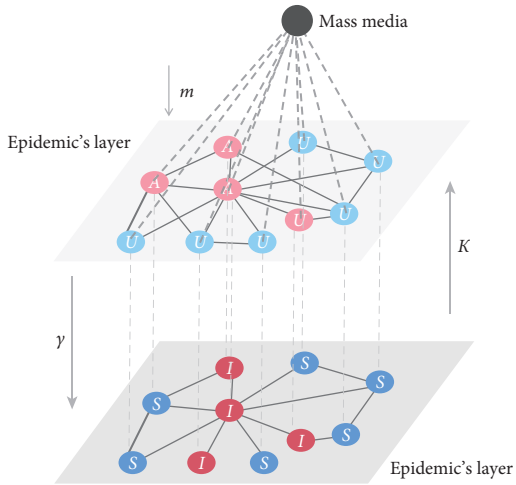

Figure 3: Awareness-epidemic model in the presence of mass media: the upper (information) layer is supporting the spreading of awareness, and nodes have two possible states: unaware (U) or aware (A). The lower (epidemic) layer corresponds to the network where the epidemic spreading takes place. The nodes are the same actors as in the upper layer, but here their state can be susceptible (*S*) or infected (*I*). The mass media are represented as a top node that provides information to the full system [57].

by mapping the multiplexed network to the two-layer network and combining the individual's risk awareness and explored the interaction between disease transmission and crowd response from the perspective of information dissemination and personal alertness. Li et al. [59] introduced observer nodes (which can identify infected neighbors and enable other neighbors to be vaccinated) into a multinetwork SIR model to study the impact of active immunity on the spread of epidemics. To analyze how the operation of information dissemination affects infected individuals and spreading conditions of epidemics, based on the assumption that the size of the community and individual awareness may affect the infection rate, Lu and Liu [60] proposed a SIR-A (susceptible infection-recovery-active) model to map infection and information dissemination to a two-layer network. Based on the UAU-SIS model in multiple networks with heterogeneous infection rates, Yang [17] compared the ratio of infected nodes to Monte Carlo simulations with theoretical results. Zhao et al. [26] used a multiple Erdös–Rényi (ER) stochastic network and combined it with a dynamic SIR epidemiological model to examine the impact of immune strategies on disease transmission in multiple networks. Buono and Braunstein [61] and Granell et al. [62] studied targeted immunization strategies against epidemics spreading through multilayer networks. Wang et al. [63] mainly studied the impact of acquaintance immunity on multiple networks. Zuzek et al. [64] used a partially overlapping multiplexing network, considering the SIR model to develop a mitigation strategy. Table 3 shows the work done by scholars on infectious diseases using the multiplex network in recent few years.

3.1.4. The Other Networks. The above models are commonly used or widely popular by scholars in the past 20 years. In order to ensure the scientific nature of this review, we try to exhaustively study the network models of social network analysis used in epidemic prevention and control.

(1) *Dynamic Bipartite Graph*. Eubank [65] discussed the use of dynamic bipartite graphs for modeling. He found that the network of connections between people is closely connected, similar to a small world graph, with a clear proportion of degree distribution. However, the location map is not scaled. By placing the sensor in the hub of the location network, efficient outbreak detection can be achieved.

(2) *Local-World Evolving Network*. The basic idea of the model is to retain the growth mechanism in the BA model and use the local priority connection mechanism to replace the global priority connection mechanism in the BA model [66].

(3) *Euclidean Distance Preferred Model*. Guo et al. [67] proposed a novel Euclidean distance preferred (EDP) model, which produces a small world network. In the EDP model, the infection probability of those susceptible individuals to an infected individual depends on the Euclidean distance.

(4) *Community Network Model/Modular Networks*. Wu and Liu [68] constructed a community network model to study the impact of the community structure on the spread of epidemics. The model has a constant degree distribution $f1$ or different clustering coefficients, and its community degree and clustering coefficient can be adjusted continuously. Min et al. [69] have developed a random weighted community network model that generates networks with different mixed styles under the same modularity. Then, the spread of the pathogen in networks with different mixed patterns is simulated. Masuda [70] focused on a network with a modular structure, that is, by definition, nodes in a network with a modular structure are divided into multiple modules so that the number of links connecting nodes in the same module is relatively large. Ren and Wang [71] proposed a community structure in which the network model changes over time, namely, a time-varying community network.

Table 3: The work done on infectious diseases using the multiplex network: in the related work column, the research studies performed by researchers using the multilayer network are shown, and in the reference column is the relevant literature of the corresponding research.

Related work	Reference
Study the relationship between the information layer and the physical layer	[17, 58–60]
The reliance on analyzing and formulating immunization strategies	[26, 61–64]

3.2. Epidemiological Modeling. An overall application of infectious disease modeling is the need to evaluate intervention strategies and their impact on emerging and re-emerging pathogens [72]. Here are some common epidemiological models.

3.2.1. SI Model. The SI model is the most basic representation of the epidemic spread model. In this model, individuals can be in two discrete states: susceptible (S) or infected (I). A vertex of the network represents each individual. The edges are the connections between individuals, and infection may follow these connections' spread [73]. This model describes the state of individuals or agents who change from susceptible to infected at all times. Therefore, the SI model helps capture the diffusion or penetration process in the entire network and describes the early epidemic stage when no control measures are deployed [74, 75]. Barthelemy et al. [10, 76] applied SI dynamically to each vertex, measuring the evolution of the number of infected individuals and other numbers. The model has not only theoretical significance but also practical significance outside the physical world. For example, Chu et al. [12] used the SI model to study the spread of epidemics and community-weighted networks, trying to understand how weights and social structures affect disease transmission dynamics. Pastor-Satorras and Castellano [77] used the SI model on unweighted and weighted networks to consider the localized phenomenon of the disease and study the local characteristics of disease transmission.

3.2.2. SIS Model. The standard SIS model relies on a coarse-grained description of individuals in the population. Individuals can only exist in two states: susceptibility and infection. If every vulnerable node is connected to one or more infected nodes, it will be infected at every time step. At the same time, the infected node may become suspicious again. Individuals randomly go through the cycle of susceptibility $\longrightarrow$ infection $\longrightarrow$ susceptibility [78]. This model does not consider the possibility of individual evacuation due to death or immunization. It is suitable to describe some epidemics that are not only spread through the vector but also spread between individuals through direct contact [79]. It is mainly used as a model for the study of infectious diseases, that is, the degree of transmission of the infection in the population [39]. The advantage of using the SIS model is that it is relatively simple (similar to the early stage of an epidemic outbreak [21, 80]) and can also be widely used.

The SIS model is widely used. In studying the spread of epidemics in different populations, Joo and Lebowitz [81] analyzed the weights of the edges distributed between two nodes. Since the weights depend on the connectivity of these nodes, the saturation effect in the SIS model is especially considered. Gross et al. [82] studied the sensitivity to infection susceptibility (SIS) models on adaptive networks. Dan et al. [66] performed a simulation in an epidemic SIS model. Sandro [14] analyzed the SIS model of epidemic infection to study the outcome of the epidemic spreading process driven by transportation rather than reaction events. Ji and Ge [83] used the SIS virus propagation model to test the side-immunity strategy. Taking the SIS model on a scale-free network as an example, Zhang et al. [84] explained that the density of infected individuals I(t) and the number of deleted edges for different strategies have the same expansion rate. Wu et al. [35] and Bansal and Meyers [85] used the SIS kinetic method to study the effect of definitive vaccines. Ren and Wang [71] considered the SIS model and performed numerical simulations to study the effect of mobility on dynamic behavior. Juang and Liang [86] studied a general SIS model with complex network vectors. Guo et al. [67] used the standard SIS model to study the epidemic dynamics on the EDP small world network.

In addition to applying standard models, some scholars have made innovations in the SIS model. In the SIS epidemic model, called MR-SIS (multiple relational susceptibility-infection-susceptibility) epidemic models, the effective transmission rate is calculated by different formulas [87]. Shi et al. [42] proposed and simulated an SIS model of epidemic spread with infected media on a complex network. Yang [17] nested the SIS model in multiple networks using the UAU-SIS model to study the spread of consciousness and epidemics.

3.2.3. SIR Model. The agent in the SIR model can access three states S (susceptible), I (infected), and R (recovered). Initially, the state of the node selected for immunization is set to R, and all remaining nodes are in the S state. The infection starts from a random susceptible node and then changes its status to I [88]. At any time, all susceptible (S) individuals are unlikely to be infected (I), and any infected individual may be removed (R): through death, isolation, recovery, or subsequent immunity [52]. These pathogens not only switch between susceptibility and infection (as in the SI model) but also tend to recover in the SIR epidemic model [89]. The dynamics of the SIR model is controlled by two parameters: infection rate β and recovery rate γ: a healthy node may be infected by an infected neighbor with the transmission probability (that is, the infection rate on the link); and, the infected node can also recover with probability γ and never be infected again [66, 90, 91]. The SIR infection process has the following characteristics: (1) all nodes are equally susceptible to infection; (2) infection

always starts from a single location; (3) infectious node can infect any node connected to it with probability p; (4) the transmission probability is the same; (5) no node is infected twice. Similarly, once a node is infected, it will be infected until it infects one of its neighbors [92]. The SIR model is simple and useful for understanding cascading faults in the network [53]. One disadvantage is the unrealistic assumption of random contact in a large population that is completely mixed [93].

The application of standard SIR dynamics to the social network model is prosperous. Zhang and Xinchu [94] studied the impact of immune function on disease transmission in a complex network with homogeneous properties and then considered the immune function in a complex network with inhomogeneous properties and the impact of inhomogeneous properties on disease transmission. Chu et al. [9] studied the SIR model's dynamic behavior with weighted transmission rate and nonlinear infectivity. Zhao et al. [26] used SIR dynamics as an epidemiological model to examine the impact of immune strategies on disease transmission in multiple networks. The SIR model helps to analyze the spread of epidemics. Chen et al. [23], Gong et al. [25], and Min et al. [69] used the SIR model to simulate the epidemic dynamics in the generated network. To study the effectiveness of community blockade in preventing the spread of epidemics, Gosak et al. [95] simulated a random SIR model on different social networks. The SIR model helps to study immune strategies. Wang et al. [13] used classic and degree-related SIR models to evaluate the effectiveness of incomplete targeted immunity in scale-free networks. Based on the SIR model, Parousis-Orthodox et al. [96] analyzed the spread of infection in the network to introduce vaccination technology; Liu et al. [36] studied the proportion of tuberculosis infection at the end of disease transmission and the time step of disease transmission; Taghavian [87] compared the performance of different immunization methods. Xu and Xu [97] focused on the modeling and control strategy of epidemic spread SIR with the network community structure. To test the immune effect, after immunizing (removing) a certain percentage of nodes, Huang et al. [98] used the classic SIR virus to spread on the remaining network. Vassallo et al. [99] studied the extension of the susceptible infection recovery (SIR) epidemic model using loop vaccination in complex and spatial networks. Buono and Braunstein [61] and Li et al. [59] studied the spread of pathogens and improved immune models based on the SIR infectious disease model in a layer of multiple networks. To understand the influence of overlapping nodes in the epidemic process, Alvarez-Zuzek et al. [100] conducted an empirical evaluation of primary deterministic immunity based on overlapping node strategies. Besides, based on the basic SIR epidemic model in a complex network and the phenomenon that infected individuals have different infection rates, Qu and Han [45] proposed an infectious disease model with two infection rates and transition probability.

3.2.4. SIRS Model. The SIRS model assumes that individuals are always in three discrete states: susceptible (S), infectious (I), and immune (R). The rules for transfer between individuals are susceptible (i.e., healthy). Infected people will be infected with probability β; infected people will be cured with probability γ and enter the immune state; immunized people will lose immunity with probability δ, and at the same time, some healthy people can be vaccinated to make them with probability α and directly enter the immune state. When $\alpha = 0$, the model is simplified to the standard SIRS infection model [34, 101].

Examples of the application of the SIRS model are as follows. By studying the SIRS epidemiological dynamics, Yan et al. [102] studied the influence of different degrees of the community structure on the dynamics. Based on the Watts–Strogatz (WS) small world network model and the BA model, Nian and Hu [37] established a standard susceptibility to infection recovery susceptibility (SIRS) epidemic model and proposed a new immunization program: "the most common friend's first immunization." In the following years, in order to verify the effectiveness of immunization, Nian et al. [28] conducted theoretical verification and computer simulations on different networks with SIRS epidemic models. Huo et al. [29] constructed a more realistic SIRS epidemic model with age of infection and recurrence on the scale-free network. Based on the integrated SIRS model, Cai et al. [15] studied the influence of the feedback mechanism and individual transmission on disease transmission in a scale-free network for population density and artificial immunity.

3.2.5. Other Epidemiological Models. In addition to the infectious disease models introduced above, there are other infectious disease models as follows:

(1) *SEIRS* [24]. Let Sk(t), Ek(t), Ik(t), and Rk(t) be the densities of susceptible, exposed, infected, and recovered vertices of degree k. The infection transmission is defined by the spreading rate λ at which each susceptible individual acquires the infection from an infected neighbor during the one-time step. A susceptible individual first goes through a latent period after infection, before becoming infectious.

(2) *SEIAR* [103]. Based on the transmission process of H1N1, Jin proposed the SEIAR model by dividing the population into susceptibility (S), exposure (E), asymptomatic infection (A), symptomatic infection (I), and removal/immunity (R). Wards with asymptomatic infections include those with no obvious symptoms or mild flu-like symptoms. They have no confirmed cases, but they can spread the infection.

(3) *SIVR (Susceptible-Infective-Variant-Recovery)* [104]. This model considers two different factors in the process of virus transmission: the same virus mutation factors, and it analyzes the steady-state effects of different infection rates, recovery rates, and mutation rates on the dynamic characteristics of the model.

(4) *SEIR*. Since most of the existing epidemiological studies are concentrated in closed areas with fixed population size, Tian et al. [105] proposed a susceptible exposure-infection-recovery model with variable contact rate to describe individuals of the dynamic spread of an epidemic heterogeneous in open limited areas. Different numbers of individuals and dynamic migration rates are considered in

the model. In the case of COVID-19, Medo [106] used an SEIR epidemic model to monitor the spread of disease.

(5) *SIQRS*. To implement isolation as a control measure and analyze its efficiency distribution in different degrees of scale-free networks, Esquivel-Gomez and Barajas-Ramirez [44] constructed the SIQRS model. In this model, each node of the network can only exist in one of four discrete states, namely, susceptible to infection, infected, isolated or removed, and pathogens spread among nodes with the first three states. Besides, Nagatani and Tainaka [107] combined the reaction (SIQRS model) with migration, and the dynamics can be described using the diffusively-coupled SIQRS model.

4. Epidemic Research Based on Social Networks

As we all know, the outbreak of severe infectious disease will not only have a significant impact on social life and medical care but also affect the economy through reduced productivity and high treatment costs. Therefore, it is important to understand the spread of infectious diseases and take relevant measures. Understanding the changes in the network itself and the role of human adaptive behavior in the process of disease transmission can propose effective measures to control the spread of viruses in the real network [108]. In this section, on the one hand, we analyze which factors will affect the spread of the epidemic; on the other hand, we summarize the plans of epidemic prevention and control plans and compare some commonly used plans.

4.1. Influencing Factors of Network Structure on Disease Transmission

4.1.1. The Impact of Nodes. Identifying the most efficient "communicators" in the network is an essential step in optimizing the use of available resources and ensuring more effective information dissemination [109]. The important influence of the node on the spread of the virus is mainly concentrated on its initial configuration. Volchenkov et al. [31] found that the actual spread of the disease largely depends on the initial distribution of infected individuals on the population, and the process can be manifested as the spread of the disease is short and the cure rate is low. Dan et al. [66] established a comparison between the node with the largest degree and the node with the smallest degree in the initial infection network. With the increase of the parameter M/m, the propagation threshold is on a downward trend. Besides, Buono et al. [110] found that shared nodes' existence will increase the popularity threshold of isolated networks with lower propagation capabilities.

4.1.2. The Influence of Individual Behavior. The impact of behavioral activities is divided into two parts, one is to promote the spread of the epidemic, and the other is to slow down or hinder the spread of the epidemic. On the one hand, Grabowski and Kosiński [111], Wang et al. [112], Hancean et al. [113], and Mbah et al. [114] believed that human activities have a significant impact on the dynamic processes in social networks. They found that the activity of an individual (the relative time spent interacting with others each day) is positively related to its degree. Goncalves et al. [115] incorporated social behavior into the key factors for further spread of infection, and through simulations, they proved the impact of different social behaviors on the epidemic threshold. On the other hand, Sun et al. [22] found that individuals' adaptive behaviors during the spread of disease can quickly reduce the incidence. At the same time, through theoretical analysis and computer simulation, Cai et al. [15], Mirzasoleiman et al. [116], and Yan et al. [89] showed that artificial immunity can reduce the stability ratio of the system and increase the transmission threshold of the system.

4.1.3. The Influence of Communication Characteristics. First of all, we must introduce the concept of the threshold value of the transmission probability, which is a very critical factor in disease transmission. Threshold transmission is defined as a fixed operation for t time steps, and the threshold value is defined as the minimum transmission probability. In the case of the immunological pathogen, the threshold probability is limited [91]. In other words, the higher the threshold, the less likely the disease is to spread; on the contrary, the lower the threshold, the easier the disease is to spread. The second is the infection rate or contagiousness. An increase in the infection rate will lead to more infections [89]. And, the epidemic threshold depends not only on the infectivity of individuals but also on the infectivity between individuals and animals. Shi et al. [42] researched the infectivity between humans and mosquitoes. The next is transmission speed. Chu et al. [12] found that, in the weighted case, the spread of infection in a network with a community is slower than in the unweighted case. Ren and Wang [71] came up with a critical value for the flow rate. In all communities, epidemics with a prevalence rate greater than the critical value broke out, and epidemics with a flow rate less than the critical value died. Meloni et al. [14] proved that the prevalence threshold is determined by the contact flow, and the prevalence is closely related to the emergence of epidemic transmission channels defined and driven by the traffic flow. Besides, the value of the popularity threshold depends on the delivery rate: the smaller the delivery rate, the greater the popularity threshold. Finally, dynamic aggregation is conducive to the spread of infectious diseases. Degree centrality and connectivity centrality can describe infecting ability and infection susceptibility [117].

4.1.4. The Influence of Time. Here, we discuss two-time factors, one is the time of the outbreak and spread of infectious diseases and the other is the time of epidemic detection and vaccination. Through analysis and numerical results, Barthelemy et al. [10] showed that the evolution of the burst time follows precise stratified dynamics. Once it reaches the most closely connected hub, the infection will gradually spread to the entire network at a smaller level. Ren and Wang [71] found that the epidemic can break out in communities where no infected individuals initially existed,

and the outbreak time decreases as the migration rate increases. For the network model, Jin [102] proved that the size of disease-free equilibrium depends on the start time of vaccination. Wang [43] found that reducing detection time is often critical to successful immunization.

4.1.5. Impact of Information. Even if the funds are limited, the network information can be used to monitor and control epidemics [118]. Strona et al. [119] and Yang [120] et al. found that increasing the rate of information dissemination could increase the peak density of information disseminators and the scale of information dissemination at the information layer, which had an inhibitory effect on the spread of the epidemic. Granell et al. [57] studied the influence of multiple network model's three main parameters: immunity, self-awareness, and mass culture. The result shows that although self-awareness has no effect on dynamics after infection, the degree of immunity of conscious individuals and mass media do change the spread of the epidemic in critical areas. Also, through simulation, Wang [43] found that geographic information also plays a role in hindering the spread of epidemics.

4.1.6. Impact of Network Structure. Network structure has a major impact on the dynamics of the epidemic [72, 121]. When there is no immune strategy, the network structure is the key factor that affects the number of all infected vertices under the law of time evolution. For different immunity probabilities and trigger time (time to trigger the control strategy), the percentage of infection using the immunity strategy has different maximum values [54]. The study of Chakraborty et al. [122] and Olinky and Stone [33] indicated that the same pathogen can produce different epidemic dynamics on different networks, so the spread of epidemics depends on infection schemes and network structures. Next, we will illustrate the influence of the network structure on the spread of the epidemic from the weight of the network, the uniformity, and the relevance of the network.

(1) Yan et al. [11] used link weights to express the familiarity between two people and studied the detailed epidemic spreading process in scale-free networks. Numerical studies have shown that nodes with higher strength are preferentially infected, and it is proved that a large dispersion of network weights will cause slower propagation speed. Besides, from the numerical simulation, the global stability of the disease-free state and local balance of the adaptive weighted model with a time delay can be obtained. It can be observed that strong adaptability can suppress the global epidemic to a lower level [22].

(2) Dan et al.'s [66] simulation results showed that the more uneven the network, the smaller the critical value of the virus spreading on it.

(3) Verdasca et al. [53] discovered the long-term characteristic dynamics related to the structure of the network in a quantitative way. In particular, the increase in spatial correlation (i) exacerbates the fluctuations around endemic states, (ii) reduces the effective transmission rate by screening for infectivity and susceptibility, and (iii) increases the period of incident oscillation due to the lower effective transmission rate. Wang et al. [63] considered the impact of the degree of correlation between network layers and found that the increase of this value is beneficial for reducing the immune threshold based on multinode acquaintance immunity.

4.1.7. Impact of Community Groups. First of all, in real life, the population density will affect the infection rate of the epidemic: the greater the population density, the higher the infection rate of the system and the lower the transmission threshold [15, 123]. Second, the size of the community, the strength of the community structure, and the distance between communities can all affect the spread of epidemics. In the study of Liu et al. [58], the spread of the epidemic has changed significantly after the immunization strategy took effect. More specifically, the final incidence of the disease is higher in large subgroups, while the epidemic disappears in small subgroups, which indicates that the size of the community is affecting individual immune behavior. In other words, the more communities the network has, the fewer the chances of network infection. The study of Liu et al. [124] found that a large family size N and a high intrafamily infection rate β are more likely to cause disease transmission. Wu and Liu [68], Yan [101], and Chu et al. [12] used numerical simulations to demonstrate that the spread of epidemics mainly depends on the extent of the community and decreases as the extent of the community increases. For a fixed level of community, the efficiency will decrease as the clustering coefficient increases. Xu [96] believed that a network with a stronger community structure will be more conducive to the control of infectious diseases than a smaller network. Gupta et al. [125] believed that effective use of the community structure can find influential nodes, thereby achieving target immunity of specific nodes and reducing the probability of epidemics in the entire network. Through simulation and demonstration, Li et al. [51] found that the strong community structure inhibits virus transmission. In the real network, the more frequent the mobile contacts between communities, the higher the probability of healthy individuals being infected and the easier the virus will break out. Xu [73] studied the geographic impact of disease transmission in lattice-free embedded networks and found that the more the geographical restrictions on the network, the smoother the epidemic spread.

4.1.8. Other Influencing Factors. Other epidemics have a weakening effect on the epidemics of current research. Through bond filtration theory and numerical simulation, Wang et al. [126] and Matamalas et al. [127] found that the synergy effect will promote the spread of another disease, thereby increasing the epidemic threshold and reducing the scale of the epidemic. Min et al.'s [69] simulation results showed that, under the same modular conditions, (1) the mixing method significantly affects the size, speed, mode, and immune strategy of the epidemic and (2) the increase in the number of communities magnifies the effect of the mixed style.

4.2. The Prevention and Control Measures of Epidemic

4.2.1. Vaccination Strategy. Vaccination is one of the most important and effective epidemic prevention and control strategies [128]. Vaccination strategies have two core objectives: lower and delay the peak size and reduce the final infected population to limit morbidity [129]. When vaccination coverage is highest, population immunity is greatest because it can increase the critical threshold of disease transmission on complex networks and reduce the spread of infectious diseases [100], so most scholars start researching immunization strategies with vaccines. The common immune control strategies are uniform immunization, proportional immunization, and targeted immunization. However, due to the difficult and uneconomical characteristics of uniform immunization (the strategy of immunizing all nodes in the network), it will not be discussed here. In the following, we will introduce random immunization, proportional immunization, targeted immunization, reactive immunization, and mixed strategies.

(1) *Random Immunization*. Random immunization is to randomly select a part of the entire population for vaccination [72]. Yan's [89] research showed that a significant increase in the system's epidemic threshold will reduce the risk of disease epidemics in the system. Each node can play multiple roles in different topological connections. Inspired by this fact, Zhao et al. [26] proposed immune strategies on multiple networks, including random (target) immunization based on multiple nodes and random (target) immunization based on layer nodes. Interestingly, both types of random immunization strategies show higher efficiency in controlling disease transmission on multiple Erdös–Rényi (ER) random networks. Mirzasoleiman [114] believed that everyone in the network is eager to voluntarily pay for the vaccine and get the immunization. To improve the results of the immunization strategy, he provides the vaccine to the individuals selected by the algorithm at a discount so that most of them could accept it. The simulation results found that the proposed random immunity based on pricing is more influential than target immunization.

(2) *Proportional Immunization*. Proportional immunization requires immunity to a large number of nodes in the network. Guo et al. [67] proposed local immunization and found that there is a key immune radius that can effectively suppress the epidemic. Based on the importance of clustering, Xia et al. [40] proposed an improved local immune strategy, which takes into account the degree of nodes and the clustering coefficient. The strategy involves randomly selecting the initial individual, then selecting his acquaintances (friends) with many friends and scattered friends, and then immunizing the selected acquaintances. This process is repeated by sequentially selecting immunized subjects as the initial input until the number of immunized individuals is reached. Yan [89] proposed a local strategy, which is to vaccinate only at bridge nodes in the community where the epidemic originated. This strategy helps reduce infections at an early stage and may eliminate epidemics in the community. Gupta [122] believed that community centers and bridges are both influential nodes in the network and play a key role in the spread of epidemics. Therefore, centralized measures need to be taken to mark nodes that have a good balance of internal and external connections in the community as influential.

(3) *Targeted Immunization*. Although a unified mass immunization strategy can help control the prevalence, an established immunization strategy for a specific immune group can better control endemic diseases [102]. Through quantitative analysis, Chu et al. [9] found that controlling individual contact is more important than the infection ability of the disease itself. Therefore, we can protect the entire network from infection by defending a small number of nodes. In addition to random immunization, if the extent of each node is known, an effective immunization strategy can be proposed called targeted immunization, which means the primary vaccination of the largest node [72]. Its advantages are (1) contrary to conventional vaccination, target vaccination has better effects, and there is little demand for vaccines (or antiviral drugs). If new patients are discovered quickly enough, the epidemic can be curbed with relatively few vaccines [110]. (2) It may be of practical significance to establish dynamic control strategies among people with different connectivity patterns. Especially over time, targeted immunization strategies may be particularly effective in controlling epidemics [75]. Through simulation, Chen et al. [23] found that target immunization can effectively control the spread of influenza A H1N1. This is similar to the method of isolating infected patients in real life, cutting off the source of transmission and preventing the continued spread of infectious diseases in the population. Here, we will classify and discuss targeted immunization again: targeted immunization and acquaintance immunization.

The applications of targeted immunization are as follows. According to the weighted network, a "high contact priority" immunization strategy is proposed by Holme [130] and Nian et al [28]. In high contact priority immunity, the nodes that are connected to the infected node and have a high frequency of contact should be inoculated first. Taking into account the development of appropriate vaccination strategies on the dynamic contact network, Shahzamal et al. [131] proposed a strategy based on local contact information, called the individual's movement-based vaccination strategy. Numerical simulations by Yang [17] and Parousis-Orthodox [95] showed that networks with a higher modularity index are more likely to be affected by the central vaccination technology between nodes, so immunization of central nodes is a good way to alleviate epidemics. Based on the concept of independent set, Huang [74] proposed a new immune strategy for complex networks, an immune method with the largest vertex of independent concentration, called independent set target immunity. From the perspective of the network structure, it is clarified that when the sum of degrees of independent centralized immune nodes is equal to the sum of degrees of target immune nodes of the whole network, the target immune strategy of independent sets is more effective than the target immune of the whole network. Liu et al. [132] proposed a new type of immunization strategy that relies on local information. The proposed strategy initializes the score of each node with its

corresponding degree value and then recalculates the score of a specific immune node based on the degree of the two nodes themselves and their nearest neighbors. After that, an immune node tries to find an unimmunized high score neighbor to replace itself. Vassallo's [98] circular vaccination is a mitigation strategy, which involves contacting and vaccinating contacts of sick patients, whose purpose is to provide immunization and stop the spread of the disease. Some scholars have also optimized targeted immunization. Wang et al. [133] used community structure information such as in-degree and out-degree of nodes to select candidate seeds and then selected immune nodes from the candidate set instead of the entire network to narrow the search space. Alfinito et al. [38] used an accurate score based on a local-global hybrid strategy to modify the TI scheme. Specifically, it introduced a modified score that aims to treat the center and people at risk of infection as related to the spread of the epidemic. Jadidi et al. [115] proposed to allocate a limited number of vaccines among different populations and vaccinate the most effective candidate vaccines to disrupt the transmission chain of diseases in each population.

Cohen et al. [134] pointed out that global information is often difficult to collect and may not even have a good definition, so he proposed an immunization strategy that works under low immunization rates and eliminates the need for global information. The advantage of this method is that it can be used before the epidemic begins to spread because it does not require any knowledge of chain infection. Wang et al. [63] proposed immunity to acquaintances who do not need to fully connect information on multiplex networks. According to topological characteristics, this scheme can be divided into two categories: immunity based on multiplexing nodes and acquaintance immunity based on layer nodes. Based on the generating function, it is shown that these two strategies are effective in preventing the spread of the disease, and their theory can accurately predict the immune threshold in the two cases, regardless of the potential interaction topology. Since controlling nodes in the overlapping subnets will help effectively suppress the spread of the epidemic, Nian [86] proposed a more feasible and effective epidemic immunity strategy, which is to use the acquaintances in the overlapping subnets to immunize key nodes in many places as much as possible.

(4) *Reactive Immunization*. Given certain social factors, such as religious beliefs and human rights, immunization is not a mandatory behavior but is determined by the individual. In this case, an individual's vaccination decision depends on the neighbor's strategy (i.e., whether to vaccinate), the neighbor's perceived risk of infection, the perceived safety and efficiency of the vaccine, and the financial costs associated with vaccination and disease infection [72]. Therefore, individual vaccination behavior depends on their local information. For convenience, we call dynamic immunity reactive immunity, which is also called information-driven vaccination or information-dependent vaccination. The impact of reactive immunity on the epidemic threshold and the critical value of the initial epidemic outbreak is negligible, but it can effectively suppress the epidemic outbreak [79]. Wang [123] believed that self-consciousness control strategies play an important role in suppressing the epidemic of cooperation. In particular, increasing the rate of immunization or isolation can raise the epidemic threshold, reduce the outbreak scale of cooperative epidemics, and lead to the transition from discontinuous to continuous crossover. Through simulation, Wu et al. [35] found that voluntary vaccination based on historical information can effectively control the outbreak of epidemics.

(5) *Hybrid Strategy*. Eubank et al. [65] proposed a combination of vaccination and early detection. Through establishing the large-scale model, he found that the outbreak can be controlled by combining targeted vaccination strategies with early detection without resorting to mass vaccination of the population. Liu et al. [36] proposed to establish a hybrid strategy to slow the spread of infectious diseases. Through three simulations (single target immunization, single acquaintance immunization, and mixed immunization), the following conclusions are drawn: target immunization plays a leading role in the mixed immunization strategy. In these three simulations, the trend curve of the proportion of "deleted" nodes or the time step is close to the curve of single target immunity. Therefore, targeted immunity plays a leading role.

4.2.2. Epidemic Warning. Epidemic early warning belongs to the active defense of the pathogen. It includes three aspects: monitoring system, alarm system, and early warning implemented to individuals. First of all, for the monitoring system, Barthelemy et al. [10] suggested that an effective way to contain the epidemic may depend on the deployment of dynamic containment measures, which are focused on gradually changing the categories of the population. More specifically, global surveillance is the main key aspect of epidemic control, and immunization strategies must evolve at different stages of transmission. Li et al. [59] proposed an observer node model that can identify infected neighbors and allow other neighbors to be vaccinated. The simulation results showed that, to maximize the suppression efficiency, we should set up limited observer nodes based on the epidemics' layer. Then, for the alert system, the intuitive solution to limit the damage caused by the infection is to detect it as early as possible. The monitor can be installed on certain network nodes and equipped with the necessary intelligence to detect the infection as soon as it reaches the node. After successful detection, an alarm can be triggered and necessary measures can be taken immediately [135]. Han's [50] model verification shows the impact of pandemic alerts on the spread of the pathogen: first, announcing accurate and timely pandemic alerts can reduce the speed of spread and help control the spread of pandemics. Second, as most health organizations do, there is a need to lead more and more accurate and timely pandemic alerts because accurate and timely pandemic alerts will lead to more decelerating effects on the spread. Finally, Gong et al. [25] found that personal vigilance can effectively slow the spread of the epidemic and delay the arrival of peak infections.

4.2.3. Control Edge Strategy. The edge immunity strategy is to delete edges based on the relationship between edges and

important nodes. The first is to sort according to the degree of nodes, select a certain number of nodes from high to low, and delete the edges directly connected to the nodes. In order to reduce the spread of the virus between nodes with large degrees, it is necessary to delete the edges between important nodes and common neighbors. As the average connection distance between nodes with large degrees increases, the threshold for virus spread increases. To effectively immunize the virus, the proportion of a given number of nodes should be gradually increased, and then, edges should be deleted in the same way [82]. The advantage of this strategy is that it can better preserve the integrity of the network during the control of epidemics on the scale-free network [83]. The result of Brethouwer et al. [136] showed that reductions of long-distance transmission are highly efficient for curbing the spread of COVID-19.

4.2.4. Isolation Strategy. According to Barthelemy et al. [10, 75] and Chu et al. [12], we learn that the infection first occurred on a subset of individuals with the largest number of connections and then gradually invaded individuals with a reduced number of connections. Because of the spread of infectious diseases, we can prevent and control the spread of the epidemic through isolation strategies. These strategies, in particular, can reduce the peak of infection and delay the peak time leading to offer ample time for the development of a vaccine and prevent hospitals from reaching their maximum patient capacity [137]. Gosak et al.'s [94] research shows that, in the absence of community lockdowns, only stricter isolation or mobility restrictions can be used to achieve the same effect as mitigating epidemic spreading.

Zheng [93] studied the epidemiological process on the hierarchical social network in the SIR model and proposed that if the spread of the epidemic is to be limited, the "dimension" of the infected node must be at least temporarily reduced. One way to achieve this is to isolate the infected node. Shen and Cao [16] also proposed an efficient new immune strategy from the perspective of weighted networks. This is achieved by reducing the weight of certain edges. Because the formation of tightly linked clusters of susceptible populations at high infection density can make the disease persist, the disease will not last at low infection density [81]; it is very important to reduce infection density or increase isolation. Small and Tse's [52] simulations showed that only by increasing isolation can the exponential growth of the epidemic be prevented. For this reason, they proposed measures such as school suspension, travel restrictions, and improvement of quarantine and public health procedures. Li et al. [51] believed that, in real life, although most people are limited to local activities and there is a relatively little movement across associations, the impact of movement between associations on the spread of the virus cannot be ignored. Strengthening the control of movement between associations is beneficial to suppress the spread of the virus. By comparing the results of different situations, Tian [104] found that the scale of the outbreak depends mainly on the average likelihood of infection of individuals and the number of infected individuals in the area. So, isolation on highly mobile people and most popular venues are most likely to be effective. Gross [81] proposed that a high rewiring rate can significantly increase the popularity threshold and reduce the popularity rate. And, they have shown that adaptive rewiring can promote the isolation of infected individuals, which can significantly increase the epidemic threshold. So, Givan et al. [138] hoped that epidemic containment based on link outages can be an effective tool that can maintain the network's function and control the epidemic spreading. Wang [43] believed that once the source of infection is detected, the organization responsible for epidemic control must decide which immunization strategy needs to be implemented to prevent the spread of the disease. If the propagation path along the network structure can be predicted, an effective method is to immunologically connect a certain number of vertices to the original source of infection based on the network structure. The prevention and control measures for the apex can be considered from the perspective of the apex (or the individual). Chen and Zhang [34] and Buono and Braunstein [61] found that artificial immunity can effectively reduce the proportion of steady-state infections and increase the transmission threshold of the system, thereby effectively controlling the spread of viruses on complex networks. When an epidemic occurs, collect and release the spread of the epidemic promptly to allow people to actively cut off contact with the infected population; actively carrying out artificial immunization to increase the artificial immunization rate of the group and limiting the frequent flow of social groups and contact with others are all effective measures to control the spread of the pathogen. When the infection rate is large enough that the disease cannot be controlled, the infectious disease may break out in a short time. In this case, we can defend against infectious diseases by improving individual response levels [35]. Self-consciousness control strategies play an important role in restraining the epidemic of cooperation. In particular, it can increase the immunization or isolation rate, raise the epidemic threshold, reduce the outbreak scale of cooperative epidemics, and lead to the transition from discontinuous to continuous crossover [123]. Jose [44] studied the efficiency of isolation in conjunction with the self-protection process and found that increasing the self-protection process can improve the efficiency of curbing the spread of the pathogen. So, raising awareness through social health programs can be a good strategy to reduce the number of people infected during the spread of the pathogen. In addition, prompt intervention played a significant role in mitigating the COVID-19 outbreak, and isolation with a high level of contact tracing and quarantine is the most effective intervention strategy [139].

4.2.5. Other Strategies. As we mentioned in the previous section, other epidemics have a certain impact on the current research epidemic [123]. Zhou et al. [140] investigated the impact of one disease's immunization on the spread of another disease and found that, under some interaction parameters, an increase in the percentage of one disease's

immunization would lead to the mutual damage of another disease. This phenomenon indicates that the control of one disease may lead to the outbreak of other pathogen. Besides, high-risk groups in the network play a decisive role in the spread of the epidemic on the network. Therefore, reducing the number of susceptible and high-risk groups and avoiding the recurrence of displaced persons are effective measures to control the spread of epidemics [29]. At the same time, an increase in the quarantine rate is useful for suppressing the spread of infectious diseases, so establishing an effective quarantine policy is an effective auxiliary means [106].

4.3. Comparison of Various Schemes. Through the introduction in the previous section, we have known some of the epidemic prevention and control strategies, but the application effects of various programs are not very clear. In this section, we will mainly introduce scholars' comparison of the effectiveness of various epidemic prevention and control strategies.

Fu [21] and Lou and Ruggeri [19] discussed proportional immunization and targeted immunization and estimated the threshold of each strategy. By comparing the thresholds of different immunization strategies, it is believed that the targeted immunization strategy is more effective than the proportional strategy. Juang [85] proved that, in scale-free networks, targeted immunization and acquaintance immunization are more effective than uniform immunization and active immunization, and active immunization is the least effective strategy among the four methods. Xia et al. [141] increased the quota for the first round of selection according to the evaluation criteria of degree centrality and then considered another characteristic parameter of the node. Simulation results showed that the proposed strategy based on two rounds of sorting is effective for heterogeneous networks, and its immune effect is better than that of high immunity. In order to find out whether the vaccination target of the targeted immunization strategy is the most connected node in the entire network (global strategy) or the node in the original community where the epidemic began to spread (local strategy), through the use of analysis methods and simulations, Yan [89] observed that the answer depends on how close the communities are. If communities are closely connected, then global strategies will be better than local strategies. When expanding the scope of the investigation from a network of two communities to a network of multiple communities, he studied the patterns of community connection and the location of the community where the epidemic began to spread. Both simulation results and theoretical predictions show that, in most cases, local strategies are a better choice for immunity. However, if the epidemic starts from a core community, then in some cases, the global strategy will be superior. Taghavian [87] and Salathe and Jones [142] evaluated different immunization methods in different synthetic networks and actual networks. The results show that the performance of local methods is far from that of global methods because they are constrained by node-level calculations. Xu's [103] research on preliminary immunization strategy, long-term immunization strategy, and comprehensive immunization strategy found that, (1) in the early stage of immunization, only susceptible individuals are randomly immunized and the immune cycle is short; (2) the long-term immunization stage has no pre-immune effect, and only the healthy individuals in the network are long-term immunized; (3) the comprehensive immunization strategy is an immune strategy that combines pre-immunity and long-term immunity. Based on the long-term immunization strategy, the immunization targets are healthy groups in the network. Through the comparison of the above three immunization strategies, they found that, under the same immunization intensity, the peak and final steady-state values of the disease population density show a decreasing trend from long-term immunization and pre-immunization to comprehensive immunization. This shows that the comprehensive immunization strategy is superior to other immunization strategies mentioned above.

In summary, the targeted immunization is a strategy with more use, more submethods, and better effectiveness. At the same time, if we integrate other immunization strategies, such as the combination of long-term strategies and short-term strategies, the effect of epidemic prevention and control on social networks will be even more surprising.

5. Future Challenges and Road Map

5.1. Future Challenges. It can be seen that there are considerable research bases on the evolution of the social network structure and the control of social network epidemic transmission at home and abroad. While, many scholars considered the factors or scenarios that are a little simple, there were some gaps between the analysis of epidemic spreading in the real world, which may have an impact on subsequent prediction and epidemic prevention research.

In studying the spread of infectious diseases, (1) when studying the evolution model, some authors lack rigorous selection of areas and individuals. In the future, we should further study the theoretical analysis value of the propagation characteristic of the virus in the local world. For example, after fusion analysis with the actual observation data, modify related parameters. (2) Many scholars studied the spread of epidemics in a relatively static state, but many real-life systems will not remain static during the spread of epidemics. At least we should consider the influence of time, such as introducing time-series networks into the propagation model. (3) In the existing research, the factors considered in the propagation model are relatively simple. For example, most studies only consider human-to-human transmission and do not consider the attenuation or mutation of the virus during the transmission process.

In terms of combining research with the real world, (1) the control method in the researchers' model is relatively simple, but in the real world if a certain area is declared as a dangerous area, more health support, such as immunization, can usually be obtained. This will result in a further reduction in the speed of transmission. Therefore, in future research, different analyses can be carried out for different

regions. (2) Many authors have given an ideal assumption in the existing research. However, in actual situations, an infected person will only come into contact with a few susceptible persons within a time step, and there will be differences in the contact pattern and frequency of contact among people. (3) It is a bit difficult to leap from theory to practice. For example, the key to a targeted immunization program is to find specific communicators, but in practice, these communicators, especially supercommunicators, are difficult to identify.

In terms of sets of variables in the model, on the one hand, existing research does not have a sufficient theoretical basis for setting the threshold of node infection. Therefore, in future research, we call on researchers to determine the infection threshold of nodes under specific conditions through investigation. On the other hand, we should also consider the correlation between parameters and the impact of this correlation on the spread of prevention and control strategies.

5.2. Road Map. With the advent of large databases and efficient analysis algorithms, the spread of these pathogens can be better predicted and controlled [143].

In terms of modeling, first, the simple model [32] is very instructive, but many other components should be considered to represent a more realistic real epidemic. It is also necessary to add simple rules to define the network's time pattern, such as the frequency of formation of new connections, the actual length of time the connections exist, or different types of connections. Secondly, it is necessary to consider further the adaptive dynamic behavior on time-varying networks and the corresponding model with double delay [22, 144], such as the delay system's disease freeness and the global asymptotic stability of local equilibrium. Moreover, for large-scale networks with thousands of nodes or more, the algorithm to solve the optimal immunity problem needs to improve the computational efficiency, and the method of calculating the approximate optimal immunity may also require higher accuracy. Finally, considering the synergy may better understand the complex systems of epidemics and human vaccination in future societies. For example, the synergy between mathematical modeling and theoretical exploration and data-driven research, the feedback effect between disease or behavior and vaccination [145], and the combination of adaptive coevolution processes [63].

In terms of scope and environment, first of all, through a secure global immunization organization can the network be optimized for immunization [61]. Unfortunately, the Internet's self-organizing nature does not allow it to figure out how the organization operates quickly. Therefore, in future research, we can study the selective immunity strategy in depth by studying the high-traffic network operation mode. Second, a good immunization strategy should consider many real-life factors, such as politics, economy, culture, and region. Future research can learn more about the different situations in a region through case studies, making network analysis and epidemic prevention and control more practical here. For example, we want to study the U.S. epidemic prevention and control measures and give valuable suggestions. We can first determine a social network model through field research, questionnaires, and data searching. According to each state's policies, population density, economic development level, and so on, different node characteristics and transmission rate of pathogens between nodes are set to determine each group's attributes in the network. Next, perform simulations to observe the characteristics of the spread and rate of pathogens. Finally, analyze the reasons and adopt effective targeted strategies for the area. Finally, if we want to study a more extensive network structure, such as studying the spread of the pathogen in a country, we can use cities as nodes and the number of infected people as the characteristics of nodes and build the entire network based on the data of population migration between cities.

In terms of prevention and control strategies, first, we can use the existing AI technology to extract a large amount of confidential information and knowledge from data with time series for epidemic prediction. For example, we can learn and analyze a large amount of data with the help of some deep learning algorithms. Second, we can learn how to control the epidemic in practice. Chinese achievements in the prevention of COVID-19 are remarkable. Summarizing the experience of areas with better epidemic prevention and control can make up for the abovementioned theoretical research deficiencies and help to add new ideas for dealing with major public incidents in the region. For example, using the widespread popularity of Internet connections and the miniaturization of equipment to collect epidemiological information with the direct participation of a large number of individuals, the emergence and development of the epidemic can be monitored in near real time, so as to estimate the disease prevalence and vaccination rate and more effectively deploy the epidemic prevention and control work [72]. Finally, we would actively integrate new technologies into network governance. The rise and rapid development of cloud computing and Hadoop technology make it possible to extract and calculate useful information from large-capacity data. If we can use such technology to improve the network's information, our social network analysis will be more efficient and better serve the prevention and control of the epidemic.

6. Conclusion

The research results show that the epidemic prevention work can adopt a multiperspective method for social network analysis and application. Combining the epidemic spread model with the network model can analyze the factors affecting the spread of epidemics. We can conclude that nodes, individual behavior, communication characteristics, time, information, network structure, and community groups are critical factors affecting the spread of epidemics. The analysis of social networks has paramount guiding significance for the prevention and control of epidemics. For example, we can use vaccination strategy, epidemic warning, control edge strategy, isolation strategy, or a combination of several

strategies to control and prevent the spread and occurrence of serious diseases.

Due to the limitations of various technical factors, the previous research results are difficult to avoid defects. However, with the advent of large databases and efficient analysis algorithms, the spread of pathogens can be better predicted and controlled in a more realistic environment. On the one hand, future research can add some simple rules to define the time mode of the network and make the static network dynamic. If supplemented by more accurate and efficient algorithms, it can simulate the spread of viruses in large-scale networks with thousands of points or more. On the other hand, future research can take the COVID-19 pandemic as an example, use cloud computing, Hadoop, and other technologies to extract and calculate useful information from large-volume data, improve network information, and determine social network models and related variable parameters. Then, combined with SNA simulation analysis, we can propose more convenient and effective prevention and control strategies.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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Research Article

Coupling Coordination between Technology Transfer in Universities and High-Tech Industries Development in China

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Only through successful transformation and application in industries, technology achievements in universities can promote economic and social development. Meanwhile, technological progress in high-tech industries depends in part on universities' technology achievements. Coupling coordination between technology transfer in universities (TTU) and high-tech industries development (HTID) is of great significance to the sustainable development of the regional sci-tech innovation system. In this paper, the coupling mechanism of TTU and HTID is analyzed and comprehensive evaluation index systems are established by using the evaluation indicator to screen and assign weights based on information contribution rate. The coupling coordination index (CCI) and productivity index (PI) are introduced to derive the spatiotemporal characteristics of the coupling and coordination of TTU and HTID from 2010 to 2019 in China and analyze its influence factors by System-Generalized Method of Moments (SYS-GMM). The results show the following: (1) the overall national TTU-HTID CCI shows a gradual upward trend and large regional differences; (2) CCI of most provinces is increasing, but the differences are widening; (3) the national TTU PI is in a state of volatility and decline, but the ability of TTU is still much higher than the level of HTID; (4) technological innovation in high-tech industries, high-tech industry technology absorption capacity, high-tech industry development level, industry-university cooperation, and technological finance development have significant roles in promoting the coupling coordination of TTU-HTID. Meanwhile, the sci-tech innovation level in universities, technology transferability in universities, government support, development of sci-tech intermediary, and development of other research institutions have no significant impact.

1. Introduction

Both universities and industries are the key actors of the innovation system of any country, contributing to knowledge production and transformation [1]. Collaborations between companies and universities are critical drivers of the innovation economy [2]. Guiding the integration of the industrial chain and innovation chain is the key to promoting industries to take a leading position in the global value chain and form a core and sustainable competitiveness. Compared with low- and medium-tech industries, high-tech industries (HTI) are mainly characterized by knowledge and technology intensity and marked by technological innovation [3]. Some studies show that 40% of the companies were attached to universities or research institutions [4]. Meanwhile, universities are the birthplace of advanced scientific knowledge and the important incubators of cutting-edge sci-tech [5].

According to statistics from "China Universities' Science and Technology Statistical Data Collection 2019" (statistics for 2018) by Ministry of Education of the People's Republic of China and "China Intellectual Property Statistical Yearbook 2018" by China National Intellectual Property Administration, the number of patents applied by Chinese universities in 2018 reached 310,276 and increased 72.5% year-on-year, and invention patents accounted for 61.5% of the three types of patents, which was much higher than the domestic average of 14.8%. However, statistics from "China Intellectual Property Survey Report 2018" by China National Intellectual Property Administration show that the effective

patent implementation rate of Chinese universities in 2018 is 15.1%, far below the national average of 52.6%. Furthermore, the effective patent industrialization rate of universities is only 3.6%, which is much lower than the national average of 36.3%. Although sci-tech innovation capacity in Chinese universities has been greatly improved, the transfer rate is still low, and the proportion of achievements transformed into industrial development is lower.

Universities play an important role as a source of fundamental knowledge and, occasionally, industrially relevant technology in modern knowledge-based economies [6]. But only through successful transformation and application in industries, technology achievements in universities can promote economic and social development. Thus, university-industry collaboration (UIC) has emerged as a sustainable enabling solution for technology transfer and a booster for new inventions [7, 8].

In order to improve the efficiency of TTU, the United States formulated the Bayh-Dole Act in 1980, which entrusted the ownership of the achievements generated by financial support to universities, encouraged universities and scientists to transfer their achievements independently, and solved the rule predicament [9, 10]. It has not only greatly promoted the number of patent applications in universities of the United States [11] but also transferred patent achievements in large numbers and become an important driving force for the development of HTI and the revitalization of regional economy [12]. The benefits from university-industry collaborations for businesses and universities are reciprocal [13]. It not only reduces the cost of internal R&D in enterprises [14] but also provides economic support and an industrial platform for the R&D development of universities [15, 16]. Stanford and Berkeley's promotion of the development of Silicon Valley is the best example of the coupling development of TTU and HTI [17], which has been imitated by many countries and regions [18]. To solve the key technical problems in the high-tech industries development (HTID) and strengthen the construction of regional technological innovation system, enterprises, universities, governments, and other parties participate in the establishment of a collaborative innovation platform with the triple or quadruple helix structure [19, 20]. All the platforms accelerate the integration process of the industry chain and innovation chain and strengthen the coupling coordination between technology transfer in university (TTU) and HTID, which can reinforce regional technological innovation driving development, promote the progress of the core and key technology, and advance national innovation system.

However, in China, the contradiction of unbalanced development inadequate performance is more obvious in the field of technology and industry. There is a bigger difference among the different areas in the energy of TTU, the scale of the technology market, and the level of HTID, which led to unbalanced and insufficient coupling coordination between TTU and HTID. This paper studies the level of coupling coordination in different regions and provinces in the past ten years. It also compares the development level of TTU and HTID across the country, which can supplement the level of coupling and coordination. Finally, it also studies the factors that affect the level of coupling and coordination. We not only established the TTU-HTID Coupling System and comprehensive evaluation index systems based on information contribution rate analyzing the spatiotemporal characteristics of the coupling and coordination of TTU and HTID from 2010 to 2019 but also estimated the influencing factors of coupling and coordination by SYS-GMM.

The rest of this article is organized as follows. Section 2 discusses related supporting literature. Section 3 designs the calculation model. Section 4 carries out a numerical analysis. Section 5 summarizes the full text.

2. Literature Review

2.1. TTU. Technology transfer, also called technology commercialization [21], is the process of transferring sci-tech achievements into marketable products and services [22, 23]. Research on TTU mainly focuses on mechanism model [24], performance evaluation [25], influencing factors [26], value assessment [27], and UIC [28]. Derrick discovered that the flexibility of policies to meet the needs of researchers and open and transparent rewards oriented to the collective are crucial to the transformation of scientific and technological achievements [29]. Blohmke proposed that technology transfer should emphasize the purpose of economic development and the performance of technology, and the evaluation of technology complexity should be incorporated into the technology transfer mechanism [30]. Soares et al. relied on data from a recent survey conducted by the Brazilian Innovation and Technology Transfer Managers National Forum (FORTEC Innovation Survey) and explored how the interplay of the quality of university regulations and regional economic development impacts new patent applications and licensing agreements in the context of Brazilian universities [31].

2.2. HTI. The high-tech industry is one of the most important industries in a knowledge-based economy [32]. Liang proposed that high-tech industries with high investment, high growth, high yield, and high risk should have the following general characteristics. They have (1) a high degree of uncertainty, (2) high value with regard to human resources, and (3) a highly correlated value of intangible assets [33]. According to the explanation from China's National Bureau of Statistics of the People's Republic of China, high-tech industries can be defined as a set of enterprises that use high technology as their foundation and execute intense R&D activities, which include six types of manufactures: medicines; aircraft and spacecraft, and related equipment; electronic equipment and communication equipment; computers and office equipment; medical equipment and measuring instrument; electronic chemicals [34].

Research on high-tech industry focuses on innovation performance [35], agglomeration effect [36], and influencing factors [37]. These researches showed that internationalization [38], technology diversification of industry level [39], strengthening intellectual property rights [40], foreign

investment [41], the different directions of external knowledge search [42], institutional elements, and market conditions [43] all can contribute to the performance of HTID.

2.3. The Relationship between TTU and HTID. There are also extensive studies about the interactive relationship between university sci-tech innovation and industrial development, which introduces factors that influence the interaction between the two and technology transfer institutions. University management [44], financial and knowledge obstacles [45], organizational proximity [46], and experience accumulated [47] can affect the interactive performance between TTU and HTID. The interaction between TTU and HTID depends not only on their capacity of reciprocal effective adaptation over time but also on the ability to adapt proactively to social and environmental development [48]. To mitigate such cognitive, geographical, organizational, and social distance, a growing number of intermediary organizations, such as Technology Transfer Offices (TTOS), University Incubators (UIs), and Collaborative Research Centers (CRCs), have been established [49]. Brescia et al. studied the organizational structure of technology transfer offices in the world's top 200 universities, emphasizing the role of external, internal, and mixed organizational models [50]. Cassia et al. analyzed 46 entrepreneurship research centers around the world and believed that external stakeholders of knowledge transfer should enrich and support the performance of scientific research [51]. Bikard and Marx called a geographic concentration of patenting by firms in a specialized technical field as hubs. They highlighted the role of hubs of industrial R&D as an interface between academic science and industrial technologies [52]. Goraczkowska Jadwiga found incubators contribute to an increase in the introduction of product innovations by enterprises and in conducting R&D activities [53].

2.4. The Influences between TTU and HTID. These two systems of TTU and HTID are mainly coupled in the form of technology transfer, technology licensing, technology investment, and university-industry collaboration (UIC). The coupling contents include technology, knowledge, information, products, market, capital, human resources, facility, and other elements. Industry-university cooperation (*cooper*) is the link between TTU and HTID and represents the scale of their cooperation. For the HTID system, technology innovation is the basis of its survival. Through interactive cooperation with universities, it can take advantage of the rich accumulated knowledge and research human resources to transfer the sci-tech achievement to industry technology, effectively reduce the risk of industries R&D input, and save the cost in basic research and applied research [54]. The university sci-tech innovation level (*Utech*) has a direct impact on the output of scientific and technological achievements in universities, is an important part of the regional scientific and technological innovation system, and promotes HTID.

As for the TTU system, HTID provides human power, facility, capital, and market for the incubation and application of sci-tech achievements [55], which reflects the last link that realizes the value. At the same time, HTID provides a training platform for university researchers to improve their practical abilities. The higher the High-tech industry technology absorption capacity (*Habsorb*), the stronger the ability of the industry to identify, digest, integrate, and use external sci-tech for technological innovation, and the more it can promote TTU. The higher the Technological innovation level in high-tech industries (*Htech*), the greater the demand for technological innovation in the industry, and the easier it is to promote the coupling coordination of TTU and HTID.

The coordinated development of the TTU-HTID coupling system requires favorable external conditions, including regional economic development level [56], infrastructure construction [57], human capital accumulation [58], market-opening level [59], etc. Both the system of TTU and HTID not only depend on external conditions but also influence the external conditions through their development, and then influence the other system. The TTU-HTID Coupling System also produces coupling with other external bodies including government (government support (*gover*) is an important part of the scientific and technological innovation system and promotes scientific and technological innovation by formulating policies, supporting funds, government procurement, innovation subsidies, and tax incentives) [60], sci-tech intermediaries (development of sci-tech intermediary (*interme*) integrates information and resources based on their intersecting position between supply and demand, which can help high-tech industries identify nonredundant information, expand resource acquisition channels, and promote the introduction, transfer, and diffusion of regional scientific and technological achievements) [61], sci-tech finance (sci-tech finance (*fina*) is an important part of the national sci-tech innovation system and financial system) [62, 63], and other research institutions (other research institutions (*insti*) correspond to the "research" in the sci-tech innovation system, which is an important part of the system) [64]. These bodies form an integrated sci-tech innovation system of "government-industry-university-research-finance-intermediary."

2.5. The Coupling Mechanism between TTU and HTID. Coupling, which originates from physical science, is a phenomenon in which two or more systems influence each other through various interactions [65]. In this paper, both TTU and HTID are regarded as open systems. These two systems interact, penetrate, and couple to TTU-HTID coupling system with new structure and functions. The coupling mechanism is shown in Figure 1.

3. Research Method and Model

3.1. Comprehensive Evaluation Index

3.1.1. Evaluation Index System. According to related references [66–69], the evaluation index systems for the ability of TTU and the level of HTID are determined, respectively, as shown in Tables 1 and 2.

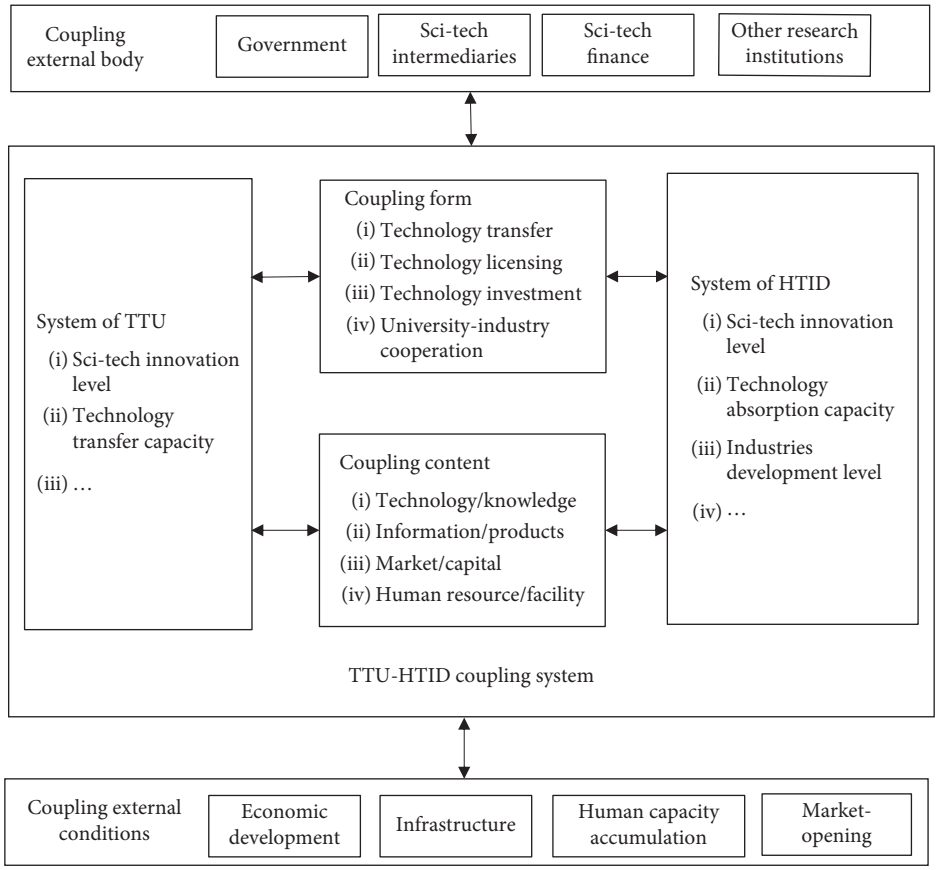

Figure 1: TTU-HTID coupling system.

Table 1: Evaluation index system of ability of TTU.

First-level index	Second-level index
(i) Conditions and basis	(i) Number of colleges (ii) Research and development staff (iii) R&D achievement application and technical service personnel (iv) Research and development project funding/thousand yuan (v) R&D achievement application and technology service project funding/thousand yuan (vi) Research and development institution (vii) Research and development project (viii) R&D achievement application and technology service project
(ii) Scientific and technological achievements	(ix) Published scientific and technological work (x) Published academic paper (xi) Number of patents granted (xii) The number of national awards won by the achievements
(iii) Transfer effect	(xiii) Number of signed contracts for technology transfer (xiv) Actual income in the year of technology transfer/thousand yuan

Table 2: Evaluation index system of level of HTID.

First-level index	Second-level index
(i) Scale of development	(i) Number of companies (ii) Average number of employees (iii) Investment/100 million yuan (iv) Main business income/100 million yuan
(ii) Innovation ability	(v) R&D personnel equivalent to full-time equivalent/person-year (vi) Internal expenditure of R&D funds/10,000 yuan (vii) New product sale revenue/10,000 yuan (viii) Number of valid invention patents
(iii) Development profit	(ix) Total profit/100 million yuan

3.1.2. Index Screening. Considering that there is multicollinearity between the second-level indicators in Tables 2 and 3, it is necessary to screen the indicators. This paper uses the information contribution rate to filter and assign weights to the indicators. This is because indicators screening and weighting based on the information contribution rate can overcome the factor analysis method that does not take into account the distortion of the comprehensive evaluation results due to the high overlap rate of information between the indicators. Therefore, screening indicators based on the information contribution rate can reduce information overlap between evaluation indicators and ensure a scientific and reasonable evaluation indicator system [70]. The calculation steps are as follows:

(1) Calculate the eigenvalues λ_j ($j = 1, 2, \ldots, m$) of m indexes correlation coefficient matrix $X^T X$:

$$\left|X^T X - \lambda_j E_m\right| = 0. \tag{1}$$

In equation (1), X is the index data matrix standardized by Z and E_m denotes the unit matrix of order m.

(2) Determine the key factors to be retained. If the cumulative variance contribution rate Ω_p of p factors with larger variance contribution rate ω_j satisfies the following:

$$\Omega_p = \sum_{j=1}^{P} \omega_j = \sum_{j=1}^{P} \frac{\lambda_j}{m} > M_0. \tag{2}$$

Then retain these p key factors.

In equation (2), M_0 takes the larger value 90%.

(3) Calculate factor loading matrix $A = (a_{ij})_{m\times p}$:

$$A = \left(\lambda_1^{1/2}\xi_1, \lambda_2^{1/2}\xi_p, \ldots, \lambda_p^{1/2}\xi_p\right). \tag{3}$$

In equation (3), ξ_j ($j = 1, 2, \ldots, p$) is the eigenvector corresponding to the jth eigenvalue λ_j of the index set correlation coefficient matrix.

(4) Calculate the information contribution rate I_i of the index X_i, that is, calculate the ratio of the index X_i to explain the information contained in the original index set.

$$I_i = \sum_{j=1}^{P} I_{ij} = \sum_{j=1}^{P} \omega_j \left(\frac{a_{ij}^2}{\sum_{j=1}^{m} a_{ij}^2}\right). \tag{4}$$

(5) Calculate the cumulative information contribution rate R_s.

$$R_s = \frac{\sum_{i=1}^{s} I_{mi}}{\sum_{i=1}^{m} I_i}. \tag{5}$$

In equation (5), I_{mi} is the information contribution rate of the i-th largest index after all m indicators are sorted from large to small.

(6) Screen indicators with high information contribution rate. If the relative cumulative information contribution rate R_s satisfies: $R_{s-1} < R_0 \le R_s$ ($R_0 = 0.7$), then s indexes with a larger information contribution rate are reserved.

(7) Check the necessity of eliminating information overlap indicators. If the ill-conditioned index of the remaining t indexes is not greater than 10, it means that the overall information overlap level of the remaining indexes is not high, and there is no need to eliminate the information overlap indicators; otherwise, it means that the overall information overlap level of the remaining indexes is high. One step further eliminates some of the information overlap indicators and reduces the overall information overlap level between indexes. The ill-conditioned index CI_t can be determined according to the following equation:

$$\mathrm{CI}_t = \sqrt{\frac{\lambda_1^*}{\lambda_t^*}}. \tag{6}$$

In equation (6), λ_1^* and λ_t^* are the maximum and minimum eigenvalues of t index correlation coefficient matrices, respectively.

(8) Eliminate indicators with a high degree of information overlap. The index with the relatively small information contribution rate is eliminated from the two largest absolute value of the Person correlation coefficient among the remaining t indexes. Then, the step (7) and (8) are repeated and iterate over the remaining indexes, until the ill-conditioned index of the remaining k indicators CI_k is not greater than 10, the elimination of the information overlap indicators is stopped.

(9) Determine the weight of the evaluation index. Assuming that the final retained indicators after indicator screening are $X_1^*, X_2^*, \ldots, X_k^*$, and the corresponding information contribution rates are $I_1^*, I_2^*, \ldots, I_k^*$, according to the normalization method, the weight ω_u of the available index X_u^* ($1 \le u \le k$) is as follows:

$$\omega_u = \frac{I_u^*}{\sum_{j=1}^{k} I_j^*}. \tag{7}$$

According to the above algorithm, the evaluation index systems for the ability of TTU and the level of HTID are shown in Tables 3 and 4.

3.1.3. Determining the Comprehensive Evaluation Index. According to Tables 3 and 4, the comprehensive evaluation index of the ability of TTU is calculated as follows:

$$U_1 = \sum_{i=1}^{n} u1_i \omega 1_i. \tag{8}$$

Table 3: Evaluation index system of ability of TTU after screening.

Screened indexes	Weight
(i) Published scientific and technological work	0.3418
(ii) Actual income in the year of technology transfer/thousand yuan	0.2597
(iii) Number of signed contracts for technology transfer	0.2108
(iv) Number of patents granted	0.1877

Table 4: Evaluation index system of level of HTID after screening.

Screened indexes	Weight
(i) Average number of employees	0.2907
(ii) Number of companies	0.1918
(iii) R&D personnel equivalent to full-time equivalent/person-year	0.1811
(iv) Investment/100 million yuan	0.1766
(v) Internal expenditure of R&D funds/10,000 yuan	0.1598

The comprehensive evaluation index of the level of HTID is calculated as follows:

$$U_2 = \sum_{j=1}^{m} u2_j \omega 2_j. \tag{9}$$

In the above two equations, $u1$ and $u2$ are the standardized numerical values of the evaluation indexes for the ability of TTU and the level of HTID, respectively, and $\omega 1$ and $\omega 2$ are the corresponding weights of the indexes.

3.2. Coupling Coordination Index. The coupling index (CI) describes the mutual influence between two or more systems themselves and external factors [71]. This article uses the CI model to describe the relationship between the ability of TTU and the level of HTID. Following Wang and Wang [72], the CI is as follows:

$$C = \left[\frac{U_1 \times U_2}{\left((U_1 + U_2)/2 \right)^2} \right]^{1/2}. \tag{10}$$

According to equation (10), coupling index $C \in [0, 1]$. When $C = 1$, TTU and HTID are resonance coupling; when $C = 0$, there is no coupling between TTU and HTID.

Although CI can reflect the strength of the interaction between the ability of TTU and the level of HTID, it is not enough to fully reflect coordination between them. When comparing and analyzing the ability of TTU and the level of HTID in different provinces, the CI between the ability of TTU and the level of HTID may be the same as that of provinces with lower levels. Relying solely on the CI cannot effectively present the regional differences between the ability of TTU and the level of HTID. Therefore, based on the CI function, the coupling coordination index (CCI) model is proposed as follows:

$$\begin{aligned} D &= \sqrt{C \times T}, \\ T &= \alpha U_1 + \beta U_2. \end{aligned} \tag{11}$$

D is CCI of the ability of TTU and the level of HTID (TTU-HTID CCI), T is the comprehensive coordination index of them, α and β are undetermined coefficients that depend on the importance of each subsystem in the system. Because TTU and HTID both have a significant impact on the coupling system, it is set $\alpha = 0.5$ and $\beta = 0.5$.

Research on quantitative evaluation of CCI with related literature [73], TTU-HTID CCI is divided into 4 levels from low to high to intuitively reflect the coupling coordination between them. The classification criteria are shown in Table 5.

3.3. Productivity Index. CI and CCI are both measured values jointly displayed by TTU and HTID. They are a measure of the close relationship between TTU and HTID and the level of coupling development which cannot indicate the comparative relationship between TTU and HTID. To reflect the difference between TTU and HTID, the concept of productivity index (PI) is proposed. TTU PI refers to the ratio of the ability of TTU and the level of HTID, which is a measure of the degree of advancement or lag in TTU relative to the HTID. The formula can be expressed as follows:

$$P = \frac{U_1}{U_2}. \tag{12}$$

In equation (12), P on behalf of TTU PI, when $P < 1$, U_1 lags the U_2, when $P = 1$, U_1 is equivalent to U_2, when $P > 1$, U_1 is ahead of U_2.

3.4. Rank Correlation Coefficient between CCI and PI. To better show the time series characteristics of TTU-HTID CCI and TTU PI in each province, the Spearman rank correlation coefficient method was used to analyze the trend of changes in related indicators from 2010 to 2019. The calculation formula of the rank correlation coefficient is shown as follows:

$$R_n = 1 - \left[\frac{6 \cdot \sum_{i=1}^{n} (X_i - Y_i)^2}{N^3 - N} \right]. \tag{13}$$

In equation (13), R_n is rank correlation coefficient, X_i is the serial number from 2010 to 2019 in descending order of evaluation value, Y_i is the serial number arranged by time, and N is the number of samples.

Table 5: Classification standard of CCI.

CCI	Coupling coordination level
[0, 0.3)	Low coupling coordination (L)
[0.3, 0.5)	Moderately coupling coordination (M)
[0.5, 0.8)	Highly coupling coordination (H)
[0.8, 1]	Extremely coupling coordination (E)

The absolute value of R_n is compared with the critical value W_P in the rank correlation coefficient statistics table. If $|R_n| \geq W_P$, it indicates that the changing trend is significant. When R_n is positive, it shows an upward trend, and when R_n is negative, it shows a downward trend. Therefore, when the R_n of TTU-HTID CCI is positive, it means that CCI displays an upward trend and CCI is increasing; otherwise, it is showing a downward trend and CCI is decreasing. When the R_n of TTU PI is positive, it indicates an upward trend for PI; otherwise, it shows a downward trend.

3.5. Influencing Factor Measurement Mode. According to TTU-HTID Coupling System (shown as Figure 1), in addition to TTU and HTID, the TTU-HTID coupling system also includes external entities such as government, sci-tech intermediaries, sci-tech finance, other research institutions, and other external subjects and environment which may also affect the TTU-HTID coupling coordination. Considering the influence of the external environment is multifaceted and invisible, which is easy to mix with other factors, this study only analyzes the influence of the internal subjects of the sci-tech innovation system "government, industry, university, research, and financial institutions" on TTU-HTID CCI, except for external environmental factors.

Table 6 shows the summary of influencing factors and the corresponding evaluation index.

Based on the above analysis of influencing factors, the following measurement model is established:

$$C_{i,t} = \beta_0 + \beta_1 \ln Utech_{i,t} + \beta_2 TTAU_{i,t} + \beta_3 \ln Htech_{i,t} + \beta_4 \ln Habsorb_{i,t} + \beta_5 HTI\ DL_{i,t} + \beta_6 \ln cooper_{i,t} + \beta_7 \ln gover_{i,t} + \beta_8 \ln interme_{i,t} + \beta_9 \ln fina_{i,t} + \beta_{10} \ln insti_{i,t} + \varepsilon_{i,t}. \quad (14)$$

In equation (14), i and t represent province and year, respectively; C is explained variable and TTU-HTID CCI whose data is calculated from the above; β_0 is constant term; ε represents the random error term. Considering the large values of some explanatory variables, to facilitate analysis, these variables are processed in logarithm.

Since TTU-HTID CCI has a reverse causal relationship to the related influencing factors of TTU and HTID, to overcome the possible endogenous problems, SYS-GMM is used to estimate the measurement model. In the specific estimation process, the three-period lags of explanatory variables are selected as instrumental variables.

3.6. Data Selection. Panel data of the TTU and the HTID in 31 provinces in Mainland China from 2010 to 2019 is selected for empirical analysis (Due to the limitation of data collection, Hong Kong, Macao, and Taiwan regions are not included, the same below). Data sources include "Compilation of Statistics on Science and Technology of Higher Education Institutions," "Statistical Yearbook of China's High-tech Industry," "Yearbook of Statistics of China's High-tech Industry," etc. Some of the data of HTID in 2017 are missing, used by the linear interpolation method to complete [66]. To eliminate the influence of different magnitudes and dimensions among various indicators and make the data comparable, the original data of each indicator is processed without dimension.

4. Results and Discussion

4.1. Coupling and Coordination Analysis

4.1.1. Analysis of Each Region. Based on the comprehensive evaluation of TTU and HTID in 31 provinces in China from 2010 to 2019, the average value of TTU-HTID CCI and TTU PI in each year of the country and the four major regions are calculated using the CCI and PI model, shown in Figure 2.

It can be seen from Figure 2 that from 2010 to 2019, the national TTU-HTID CCI showed a gradual upward trend, and the average value reached the moderate coupling coordination level in 2016; the TTU PI was fluctuating and decreasing, after reaching the lowest value of 3.118 in 2015 there has been an increase again, indicating that the growth rate of the level of HTID is higher than the ability of TTU, but the ability of TTU is much higher than the level of HTID, the conversion efforts of scientific and technological achievements of universities into high-tech industries still needs to be improved.

Related policies successively released in 2015-2016 have further promoted the transformation and development of TTU, stimulated the vitality of the transformation of TTU, and made the PI of the transformation of TTU show an upward trend after 2016. In terms of subregions, in the past five years, the TTU-HTID CCI shows East > Central > Northeast > West, and TTU PI shows the spatial distribution characteristics of Central < East < West < Northeast. The specific analysis of the four major regions is as follows:

Table 6: Influencing factors and evaluation index.

Influencing factor	Evaluation index
Utech	Internal expenditure of university R&D funds
cooper	Enterprise funds in university R&D funds
Habsorb	Cost of technological transformation of the high-tech industry
Htech	Internal expenditure of R&D funds in high-tech industry
gover	Government funds in the internal expenditures of R&D
interme	Technical market turnover
fina	Other funds in the internal expenditures of R&D expenditures
insti	Internal expenditures of R&D funds of research and development institutions

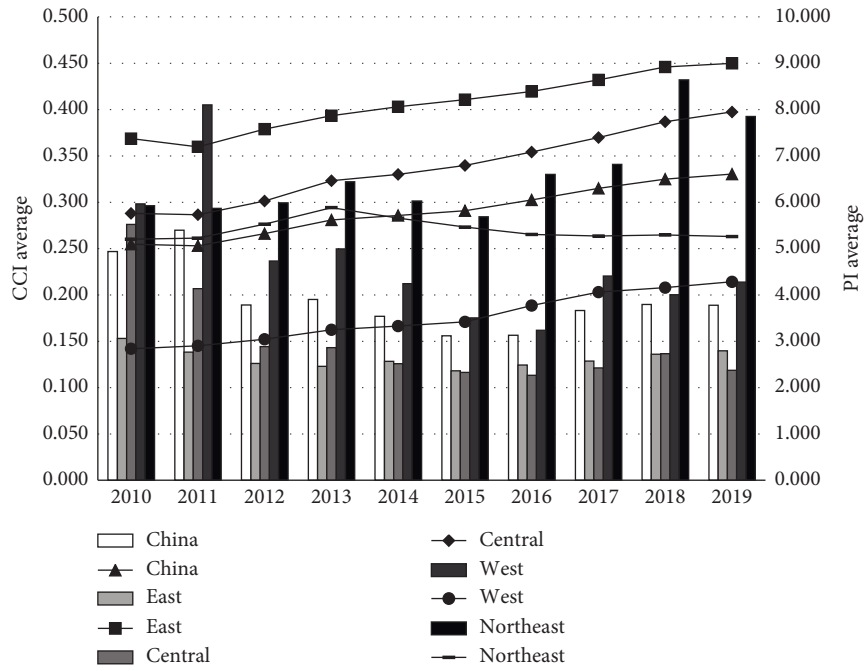

Figure 2: 2010–2019 Chinese and four major regions TTU-HTID CCI and TTU PI average.

(1) *East Region*. The TTU-HTID CCI is the highest, which is much higher than the national average, showing an upward trend year by year. It exceeded 0.3 in 2010, reaching the level of moderately coupling coordination, and reached 0.450 in 2019, approaching highly coupling coordination. This suggests that the interactive relationship between TTU and HTID tends to be close and the development is in a good stage. TTU PI is lower than the national average level, showing a state of declining volatility, reaching the lowest value of 2.359 in 2015, indicating that although the ability of the TUU comprehensive evaluation index is ahead of the level of HTID, the ability of TUU and the level of HTID tend to be balanced and can be developed relatively coordinated.

(2) *Central Region*. The TTU-HTID CCI is slightly higher than the national average, and it is also showing an upward trend year by year. It was at low coupling coordination in 2010 and has reached moderate coupling coordination since 2012, which shows the interactive relationship between TTU and HTID is gradually improving, representing a healthy state of development. TTU PI was higher than the national average in 2010, and then the downward trend was more obvious. It has reached the lowest level in the country since 2014, but it is still greater than 2. It shows that the comprehensive evaluation index of the ability of TTU is also ahead of the level of HTID, and the ability of TTU and the level of HTID tend to be balanced.

(3) *West Region*. The TTU-HTID CCI is far lower than the national average, but it still shows an upward trend year by year. The CCI in 2019 was 0.214, which is still at low coupling coordination, showing that the interaction between TTU and HTID is gradually improving. However, the mutual coupling and coordination are at a low level, as well as the development situation. TTU PI is higher than the national average level and shows a state of declining fluctuations, reaching the lowest value of 3.235 in 2016, indicating that the TUU level is ahead of the HTID.

Considering TTU and HTID are in a state of low coupling coordination, it shows that they cannot support each other well. TUU's support for HTID is not enough, and the HTID foundation is poor.

(4) *Northeast Region*. The TTU-HTID CCI was slightly higher than the national average before 2013 and was in a slow-growth state; after 2014, it gradually declined and was lower than the national average, and the CCI was always below 0.3, at low coupling coordination, which shows that the interaction between TTU and HTID is gradually getting worse, and mutual support weakens. In recent years, TTU PI is much higher than the national average. Combining the CCI between TTU and HTID shows that the ability of TUU has increased to a certain extent, but it has not been transformed into the driving force of HTID, which is in a state of shrinking.

4.1.2. Analysis of Each Province. Table 7 shows the R_n of TTU-HTID CCI and TTU PI in each province from 2010 to 2019 (specific data shown in Table 8: 2010–2019 CCI and PI of each province).

This study collected 10 years of data, $N = 10$, to check the critical value of Spearman's rank correlation coefficient $W_P = 0.564\,(\alpha = 0.05)$. Data greater than 0.564 are indicated by "*" in Table 7.

It can be seen from Table 7 that, except for the three provinces of Tianjin, Liaoning, and Heilongjiang (indicated by "—" in Table 7), the R_n of TTU-HTID CCI in all provinces are positive, indicating that CCI is on an upward trend, and the upward trend in most provinces is more obvious. The R_n of Shanghai, Tibet, and Jilin are lower than the critical value, indicating that the TTU-HTID CCI has not increased significantly.

There are 13 provinces with positive R_n of TTU PI, including Beijing, Jiangsu, Zhejiang, Shandong, Guangdong, Hainan, Shanxi, Inner Mongolia, Sichuan, Guizhou, Liaoning, Jilin, and Heilongjiang. Among them, the R_n of Jiangsu and Liaoning exceeded the critical value, indicating that PI increased significantly, and the growth rate of the ability of TTU was significantly restored compared with the level of HTID. Totally there are 18 provinces with negative R_n (indicated by "—" in Table 7). Among them, the absolute values of R_n in Hebei, Anhui, Hubei, Hunan, Chongqing, Qinghai, and Xinjiang, exceed the critical value, indicating that the level of HTID has increased significantly faster than the ability of TTU.

Based on the classification standard of CCI of each province, it can be classified as follows.

Only Jiangsu is at the level of extreme coupling coordination. According to the statistics in 2019, there are a total of 149 universities in Jiangsu, 24,368 patents authorized by universities, and 2,515 technology transfer contracts. The three indexes above all rank the first in China, and other indexes of TTU also rank the top. There are 48 high-tech zones at or above the provincial level, among which 18 are national levels, ranking first in China. The HTI also performs well in various indicators. TTU and HTID both are showed high activity ($|R_n| \geq W_P$) and good balance (TTU PI = 1.225), and CCI shows an outstanding performance.

Provinces with high coupling coordination include Guangdong and Zhejiang, but Guangdong has a much higher CCI. Guangdong has a very outstanding development level of HTI, ranking first in many indicators in China. Its TTU PI is less than 1, but TTU PI Rank Correlation Coefficient is close to W_P, indicating a significant growth trend of TTU. In the future, the CCI of Guangdong will increase faster, and Zhejiang increases stably.

14 provinces are in the level of moderately coupling coordination, distributed in 4 regions and divided into 4 types:

(i) The first type includes the characteristics with CCI rank correlation coefficient a positive number, TTU PI higher than 1, and TTU PI rank correlation coefficient a negative number (represented as "++−"), including Hebei, Shanghai, Anhui, Hunan, Hubei, Henan, Chongqing, and Shaanxi. CCI of the provinces above is ascending every year, and TTU higher than HTID with the gap narrowing, indicating a good development trend of CCI. Because the absolute value of both rank correlation coefficients is higher than W_P in Hebei, Anhui, Hunan, Hubei, and Chongqing, the CCI of the 5 provinces will increase at a faster rate.

(ii) CCI rank correlation coefficient of Fujian and Jiangxi is a positive number, TTU PI lower than 1, and TTU PI rank correlation coefficient a negative number and the absolute value lower than W_P (represented as "+−−"). It means that the base of TTU is weak and a narrowing gap compared with HTID exists. CCI of the two provinces will have a relative development.

(iii) The indexes of Beijing, Shandong, and Sichuan can be represented as "+++." The ability of TTU is higher than the level of HTID, and the gap existing is not an appreciable expansion. It means there are very rich resources in the three provinces, but not enough to transfer to HTID. Therefore, it should overcome this barrier to guarantee the promotion of CCI.

(iv) The indexes Liaoning can be represented as "−++," which means the ability of TTU is higher than the level of HTID, and the gap is becoming more and more obvious. Most important of all, CCI of Liaoning shows a downward trend. The gradually improved ability of TTU has not brought the development of HTID, and CCI is getting worse and worse.

There are 14 provinces in the level of low coupling coordination, distributed in 4 regions and also divided into 4 types:

(i) The indexes of Hainan, Shanxi, Inner Mongolia, Guizhou, and Jilin can be represented as "+++." The ability of TTU is higher than the level of HTID, and

Table 7: TTU-HTID coupling coordination indexes of each province.

Region	Province	CCI 2010	⋯	CCI 2019	Classification standard 2019	CCI rank correlation coefficient	TTU PI	TTU PI rank correlation coefficient
East	Hainan	0.075	...	0.093	L	0.661*	5.536	0.285
	Tianjin	0.259	...	0.260	L	−0.309 —	1.812	−0.261 —
	Hebei	0.246	...	0.323	M	0.915*	2.728	−0.576 —*
	Fujian	0.301	...	0.353	M	0.927*	0.966 —	−0.261 —
	Shanghai	0.379	...	0.432	M	0.055	3.298	−0.103 —
	Beijing	0.410	...	0.461	M	0.721*	8.768	0.042
	Shandong	0.416	...	0.476	M	0.842*	1.795	0.139
	Zhejiang	0.403	...	0.541	H	0.952*	1.367	0.212
	Guangdong	0.572	...	0.750	H	0.952*	0.429 —	0.552
	Jiangsu	0.627	...	0.809	E	0.976*	1.225	0.697*
Central	Shanxi	0.189	...	0.227	L	0.891*	4.227	0.055
	Jiangxi	0.237	...	0.364	M	0.988*	0.852 —	−0.442 —
	Anhui	0.318	...	0.402	M	0.721*	1.362	−0.952 —*
	Hunan	0.300	...	0.444	M	0.976*	2.596	−0.855 —*
	Hubei	0.323	...	0.464	M	1.000*	2.445	−0.733 —*
	Henan	0.361	...	0.483	M	0.976*	2.767	−0.285 —
West	Xizang	0.019	...	0.025	L	0.515	3.844	−0.248 —
	Qinghai	0.039	...	0.073	L	0.879*	1.358	−0.697 —*
	Ningxia	0.045	...	0.100	L	0.891*	2.990	−0.394 —
	Xinjiang	0.068	...	0.101	L	0.830*	5.544	−0.685 —*
	Gansu	0.127	...	0.161	L	0.879*	8.111	−0.297 —
	Inner Mongolia	0.126	...	0.177	L	0.952*	7.160	0.285
	Yunnan	0.133	...	0.213	L	0.939*	6.575	−0.491 —
	Guangxi	0.173	...	0.216	L	0.927*	1.802	−0.188 —
	Guizhou	0.129	...	0.224	L	0.964*	3.159	0.515
	Chongqing	0.233	...	0.398	M	0.988*	3.301	−0.612 —*
	Shaanxi	0.297	...	0.418	M	1.000*	4.666	−0.382 —
	Sichuan	0.315	...	0.465	M	0.964*	2.796	0.188
Northeast	Heilongjiang	0.229	...	0.232	L	−0.103 —	9.008	0.309
	Jilin	0.216	...	0.233	L	0.297	5.205	0.285
	Liaoning	0.336	...	0.323	M	−0.661 —*	9.337	0.697*

the gap existing is not an appreciable expansion. Combined with the low indexes of HTID and insufficient ability of TTU in these provinces, the development of CCI will be slow.

(ii) The indexes of Tianjin can be represented as "−+−." It means CCI of Tianjin is going down, and the ability of TTU is higher than the level of HTID, but the gap is becoming close. Both the ability of TTU and the level of HTID are shrinking.

(iii) It can be represented as "++−" of the indexes of Xizang, Qinghai, Ningxia, Xinjiang, Gansu, Yunnan, and Guangxi. Given the weak foundation for development, the growth of CCI will be relatively slow. Because the absolute value of both rank correlation coefficients is higher than W_P in Qinghai and Xinjiang, CCI will increase at a faster rate.

(iv) The indexes Heilongjiang can be represented as "−++," which is same to Liaoning. Considering its poorer foundation, CCI of Heilongjiang will be getting worse and worse.

4.2. Influencing Factors of Coupling Coordination of TTU and HTID. Since the TTU-HTID coupling coordination degree has a reverse causal relationship for the transformation of university scientific and technological achievements and the development of high-tech industry related factors, in order to overcome the possible endogenous problems, the system GMM method is used to estimate the measurement model. In the specific estimation process, the three-period lag of the explanatory variable is selected as the instrumental variable, and the measurement results are shown in Table 9. It can be seen from Table 9 that the indicators of the Arellano-Bond test, Sargan test, and Hansen test meet the requirements, and the number of instrumental variables does not exceed the number of endogenous variables, and they are all valid, indicating that the system GMM estimation results are effective.

From SYS-GMM estimation results, it can be seen that the influencing factors of the HTID subsystem have a significant impact on the TTU-HTID CCI, but *Utech*, *TTAU* in the TTU subsystem have no significant influence. *Htech*, *Habsorb*, *HTIDL* all have significant promoting effects on

Table 8: 2010–2019 CCI and PI of each province.

Province	2010		2011		2012		2013		2014		2015		2016		2017		2018		2019	
	CCI	PI	CCI	PI	CCI	PI	CCI	PI	CCI	PI	CCI	PI	CCI	PI	CCI	PI	CCI	PI	CCI	PI
Beijing	0.4102	9.6267	0.4225	8.3325	0.4262	7.8826	0.4489	8.3976	0.4488	8.4308	0.4465	8.2936	0.4625	8.8083	0.4603	8.4762	0.4440	7.9559	0.4608	8.7682
Tianjin	0.2590	2.0673	0.2703	2.3990	0.2678	1.7672	0.2664	1.7358	0.2713	1.5736	0.2568	0.9116	0.2583	1.3178	0.2647	1.7366	0.2594	1.8061	0.2604	1.8118
Hebei	0.2459	3.5524	0.2502	3.4584	0.2662	3.1129	0.2722	2.4762	0.3020	2.8332	0.3145	2.4245	0.3231	2.4557	0.3341	2.6794	0.3238	2.5131	0.3229	2.7284
Shanghai	0.3790	2.2860	0.4027	3.1473	0.4293	3.5304	0.4259	3.0078	0.4025	2.5245	0.3977	2.3531	0.3819	2.1765	0.3916	2.4446	0.3868	2.3355	0.4315	3.2983
Jiangsu	0.6267	1.2007	0.6071	0.9118	0.6739	1.1228	0.6872	1.1170	0.7241	1.3163	0.7400	1.3333	0.7384	1.2541	0.7689	1.4221	0.7965	1.5583	0.8094	1.2246
Zhejiang	0.4027	1.3155	0.3866	1.3689	0.4031	1.2037	0.4302	1.2777	0.4355	1.1864	0.4230	0.8808	0.4707	1.2462	0.4955	1.3982	0.5122	1.3207	0.5413	1.3668
Fujian	0.3006	2.4693	0.2347	0.7592	0.2739	1.0928	0.3114	1.4681	0.3314	1.6609	0.3486	1.8920	0.3499	1.4166	0.3597	1.3173	0.3667	1.3000	0.3533	0.9665
Shandong	0.4165	2.5551	0.3769	1.3935	0.3894	0.9413	0.4067	0.9050	0.4246	0.9419	0.4735	1.2537	0.4836	1.2569	0.4700	1.1777	0.5463	2.2072	0.4756	1.7948
Guangdong	0.5719	0.3668	0.5659	0.3307	0.5702	0.2675	0.5881	0.2892	0.5874	0.2749	0.6146	0.3023	0.6284	0.3068	0.6819	0.3831	0.7222	0.3853	0.7501	0.4286
Hainan	0.0745	5.1571	0.0802	5.5229	0.0882	4.3062	0.0964	3.8988	0.1020	4.8879	0.0926	3.9445	0.0992	4.6176	0.0929	4.6974	0.1022	5.7963	0.0933	5.5356
Shanxi	0.1890	6.4826	0.1808	5.0395	0.1928	3.7270	0.1988	3.3752	0.1943	3.1729	0.1911	3.4117	0.2107	4.0579	0.2220	5.4760	0.2487	6.3516	0.2271	4.2265
Anhui	0.3179	5.8459	0.3312	6.5281	0.3297	3.8664	0.3779	4.9055	0.3973	4.4620	0.4066	3.6850	0.3933	2.1354	0.3964	1.7016	0.3894	1.4379	0.4023	1.3620
Jiangxi	0.2372	1.6953	0.2311	1.3856	0.2377	1.0222	0.2427	0.8490	0.2443	0.6655	0.2497	0.5635	0.3147	1.1307	0.3386	0.9820	0.3472	0.9351	0.3644	0.8523
Henan	0.3606	7.7709	0.3403	3.0690	0.3677	2.2843	0.3860	1.8679	0.4055	1.6844	0.4194	1.5350	0.4332	1.5625	0.4499	1.9738	0.4858	2.9463	0.4834	2.7670
Hubei	0.3231	4.7916	0.3328	4.2141	0.3578	3.0388	0.3780	2.7607	0.3883	2.4572	0.4002	2.3128	0.4083	2.4394	0.4244	2.3820	0.4460	2.5296	0.4639	2.4445
Hunan	0.3003	6.5260	0.3026	4.5754	0.3219	3.3777	0.3561	3.4164	0.3507	2.6406	0.3709	2.4592	0.3642	2.2484	0.3881	2.0238	0.4047	2.1940	0.4437	2.5964
Inner Mongolia	0.1259	8.1920	0.1170	3.5015	0.1426	4.0665	0.1453	3.3998	0.1515	3.1244	0.1620	3.1256	0.1763	4.2993	0.1798	8.7790	0.1863	4.6968	0.1766	7.1602
Guangxi	0.1727	2.7413	0.1609	1.8738	0.1637	1.5817	0.1879	2.3568	0.1944	2.0528	0.1829	1.4025	0.2056	2.1105	0.2091	1.9525	0.2148	2.1360	0.2155	1.8024
Chongqing	0.2331	6.6252	0.2470	7.0368	0.2548	3.8474	0.2752	3.6407	0.2734	2.4798	0.2788	1.6250	0.3359	2.3573	0.3704	2.9133	0.3822	3.3699	0.3985	3.3012
Sichuan	0.3146	2.7506	0.3223	2.4312	0.3489	2.0921	0.3567	1.7863	0.3374	1.4704	0.3637	1.7505	0.4034	2.3006	0.4434	2.2099	0.4507	2.5572	0.4647	2.7964
Guizhou	0.1288	1.7022	0.1337	2.1648	0.1239	1.1275	0.1424	1.4628	0.1578	1.4527	0.1681	1.8444	0.1800	1.6029	0.2052	1.8397	0.2207	2.5418	0.2241	3.1595
Yunnan	0.1325	7.7715	0.1302	7.0114	0.1440	6.3721	0.1395	5.0339	0.1415	4.3412	0.1521	4.6489	0.1673	4.9795	0.1912	5.5768	0.1842	3.9005	0.2127	6.5746
Xizang	0.0185	4.0543	0.0159	30.1583	0.0067	0.2651	0.0207	7.3457	0.0267	9.0624	0.0173	6.8450	0.0160	1.6524	0.0198	2.7576	0.0210	6.8547	0.0251	3.8441
Shaanxi	0.2972	5.5775	0.3106	5.6820	0.3211	4.7382	0.3446	4.4747	0.3605	3.8677	0.3639	3.7030	0.3838	4.1953	0.3890	4.2764	0.4035	4.8820	0.4176	4.6659
Gansu	0.1268	10.8348	0.1248	11.6658	0.1326	7.7838	0.1513	8.4265	0.1501	7.3388	0.1527	7.9875	0.1649	8.1849	0.1653	13.0387	0.1556	6.9321	0.1612	8.1105
Qinghai	0.0387	2.9862	0.0500	8.7506	0.0463	3.0959	0.0574	3.9321	0.0689	5.3017	0.0710	3.4243	0.0677	1.6697	0.0646	0.9047	0.0725	1.4372	0.0728	1.3583
Ningxia	0.0446	3.5176	0.0516	6.2216	0.0604	6.0040	0.0488	2.2045	0.0512	2.2715	0.0626	2.0205	0.0746	1.3907	0.0886	2.1513	0.1032	3.9314	0.1001	2.9904
Xinjiang	0.0681	14.8292	0.0758	10.7327	0.0817	15.7898	0.0788	15.8442	0.0817	8.1531	0.0748	3.6599	0.0880	4.0747	0.1105	6.4647	0.0990	4.7832	0.1012	5.5444
Liaoning	0.3357	4.5532	0.3314	4.9306	0.3442	4.7010	0.3678	5.2263	0.3372	3.9367	0.3260	4.3850	0.3036	6.4898	0.3142	6.7998	0.3305	8.6202	0.3234	9.3366
Jilin	0.2157	3.6976	0.2228	3.2776	0.2362	2.9903	0.2574	3.9731	0.2537	3.5389	0.2417	2.7564	0.2450	2.5395	0.2371	3.3646	0.2423	4.5025	0.2335	5.2053
Heilongjiang	0.2289	9.5153	0.2300	9.4015	0.2484	10.2658	0.2570	10.1257	0.2578	10.6012	0.2523	9.9106	0.2472	10.7652	0.2389	10.2851	0.2209	12.7955	0.2320	9.0080

Table 9: Influencing factors of TTU-HTID coupling coordination by SYS-GMM.

Variable	Coefficient	*P* value
lnUtech	0.014	0.242
TTAU	0.156	0.133
lnHtech	0.014**	0.015
lnHabsorb	0.006***	0.008
HTIDL	0.504***	0.000
lncooper	0.012**	0.021
lngover	−0.037	0.104
Lninterme	−0.001	0.922
lnfina	0.014***	0.005
lninsti	0.030	0.052
_cons	−0.344***	0.001
P	≤0.001	
AR (1)	0.035	
AR (2)	0.512	
Sargan	0.083	
Hansen	0.449	

Note. The symbols *** and ** indicate significant at 1% and 5%, respectively.

the CCI, whose influence coefficients are 0.014, 0.006, 0.504. The reason is that from the perspective of national and regional TTU PI, TTU is much higher than HTID, and the improvement of TTU-HTID CCI is more dependent on HTID. Because the evaluation of *Utech* and *TTAU* is based on the quantity index, the patent quality, which represents the ability of sci-tech achievements of universities, does not increase significantly with the increase of quantity [74]. However, sci-tech achievements with high quality are more likely to be transferred to HTI. It should improve quality rather than quantity to promote the ability of sci-tech achievements of universities. As an important channel for the technology transfer from universities to HTI, *cooper* has a significant impact on CCI.

Of all the external entities, only *fina* has a significant impact on CCI, but *gover*, *interme,* and *insti* have no significant influence. Innovation requires more than technology. It also needs capital to commercialize it, hence, the need for customers to develop connectivity with the capital markets [75]. Technology finance provides financial support for TTU and HTID through a variety of systems such as the four major financial systems represented by banks, guarantees, insurance, and bonds, which is the lifeblood of TTU and HTID. The reason why *gover* has no significant influence on CCI may be in the following: the vast majority of the government funds to universities are invested in basic research and experimental development research rather than technology transfer. The expected results of the funding are more about the cultivation of students, the publication of articles, the acquisition of patent authorization, etc., and there are few indicators of technology transfer. *interme* represented by the technology market has a low degree of development and low added value of technology. According to the Statistical Yearbook of China Science and Technology, as the seller in 2019, the value of contract deals in technical markets of high education is 59 million yuan, which is only 2.6% of the whole market. Moreover, the proportion has been decreasing year by year (from 4.6% in 2012 to 2.6% in 2019), which means *interme* has failed to build a good bridge between universities and HTI. Although *insti* is in a competitive and cooperative position with universities in the industry-university-research system, they have their own advantages, and the development degree of *insti* does not have a significant impact on the coupling.

5. Conclusion and Enlightenment

5.1. Main Conclusions. This paper focuses on coupling coordination between TTU and HTID in China, analyzes the coupling mechanism of TTU and HTID, and constructs the tailored coupling system for them and based on the conclusions obtained can provide decision-makers with decision-making ideas. The methods adopted here are based on the information contribution rate to screen the evaluation indicators of the two subsystems and assign weights. Two comprehensive evaluation index systems are established and TTU-HTID CI, TTU-HTID CCI, and TTU PI models are introduced as well. Furthermore, the spatiotemporal characteristics of the coupling and coordination of TTU and HTID from 2010 to 2019 are analyzed and the SYS-GMM is applied for estimating its influencing factors. The main conclusions derived from this paper are summarized as follows:

(1) The overall national TTU-HTID CCI shows a gradual upward trend, but the level of coupling coordination is not high. From a regional perspective, TTU-HTID CCI East > Central > Northeast > West, the CCI of Northeast showed a trend of first rising and then falling; TTU PI showed the spatial distribution characteristics of Central < East < West < Northeast. Affected by various factors, the TTU-HTID CCI difference among provinces in each region is East > West > Central > Northeast, and the TTU-HTID CCI difference of each province shows a gradually expanding trend.

(2) The national TTU PI is in a state of volatility and decline, and it has risen after reaching the lowest value of 3.118 in 2015, which shows the growth rate of the level of HTID is higher than the ability of TTU, but the ability of TTU is still much higher than the level of HTID. The transformation of Technology in universities into high-tech industries still needs to be improved.

(3) Specific to each province, TTU-HTID CCI has large regional differences, showing a trend of high in the east and low in the west, high in the coast, and low in the inland. Except for Tianjin and Hainan in the east, the TTU-HTID CCI levels of all provinces are relatively high, and the CCI of Jiangsu, Guangdong, and Zhejiang have reached highly coupling coordination. Apart from Shanxi Province in the central, all provinces TTU-HTID CCI have reached moderately coupling coordination. The TTU-HTID CCI of all provinces in the west is generally low, but Sichuan, Shaanxi, and Chongqing have reached moderately coupling coordination. Heilongjiang and Jilin in the

northeast are at low coupling coordination, while Liaoning has been at moderately coupling coordination, but CCI has not increased significantly.

(4) Except for Tianjin, Liaoning, and Heilongjiang, the TTU-HTID CCI of other provinces is on an upward trend which is obvious in most provinces. TTU PI in 13 provinces is in a state of growth, of which Jiangsu and Liaoning provinces have a significant growth in TTU PI, and the ability of TTU has increased significantly faster than the level of HTID. The TTU PI of 18 provinces is in a state of decline. Among them, Hebei, Anhui, Hubei, Hunan, Chongqing, Qinghai, and Xinjiang have a significant decline in TTU PI, and the level of HTID is significantly faster than the growth rate of the level of TTU.

(5) *Htech*, *Habsorb*, *HTIDL*, *cooper,* and *fina* have a significant role in promoting the coupling coordination of TTU-HTID. *Utech*, *TTAU*, *gover*, *interme*, and *insti* have no significant impact on TTU-HTID coupling coordination.

5.2. Policy Enlightenment.

(1) Based on the regional university resources and industries development, each region should highlight its characteristics, exploit the potential of coupling coordination between TTU and HTID, expand the ability to connect with innovative resources outside the region, and build a multiparticipant industry-university-research collaborative innovation platform. Besides, they should also change the unbalanced development of TTU-HTID coupling coordination and reduce the difference of regional TTU-HTID coupling coordination.

(2) All regions should focus on guiding universities to actively integrate into the regional technological innovation system, serving the regional technological innovation chain and industrial chain, and aiming at the common key technologies and cutting-edge leading technologies for industrial development, playing the role of "complement chain," "strong chain," and "chain extension." It is necessary to start from the source of innovation, transform technological achievements into high-tech industries, guide universities and industries to "go out" and "bring in," solve the difficult problem of industrialization of Technology in University, and promote the coupling coordination development of them.

(3) All regions should pay more attention to building a technological innovation system with enterprises as the main body, focus on improving *Htech* and *Habsorb*, vigorously broaden the channels for industry-university cooperation, and further strengthen the construction of the technology service system, especially the technology financial system, and give full play to the role of finance in promoting HTID and TTU.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

FH and LX conceived and designed the research. YQ put forward method and modified the manuscript. FH and WJ drafted the manuscript, prepared figures, and revised the manuscript. All authors have read and agreed to the published version of the manuscript.

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Research Article

The Signal Effect of New Energy Vehicles Promotion on Enterprise Innovation

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Entering the promotion catalogue is the basis for China's new energy vehicle (NEV) enterprises to obtain promotion subsidies. Using a multistage difference-in-differences (DID) model with a sample of listed NEV enterprises in China from 2008 to 2017, this paper empirically analyzes the impact of entering the promotion catalogue on the innovation of NEV enterprises. The results indicate that entering the promotion catalogue can significantly promote innovation of NEV enterprises from the perspective of radical innovation, incremental innovation, and external technology introduction of NEV enterprises. In the mediation mechanism examination, this study finds that entering the promotion catalogue promotes innovation in NEV enterprises by increasing corporate profits and easing financing constraints. Based on the conclusions above, this paper recommends to strengthen core technology breakthrough of NEVs, cultivate market demand of NEVs industry, and improve subsidy supervision system of NEVs.

1. Introduction

In the context of global climate change, the conflict between energy consumption and the ecological environment is arising. The development of new energy vehicles (NEVs) has become the strategic choice of coupling economic, social, and ecological objectives. Government investment in NEVs is of great significance for cultivating emerging industries, gaining future industrial competitiveness as well as alleviating environmental and ecological problems. As a key strategic emerging industry in China, the NEV industry is facing problems such as technology shortage and immature market development at the initial stage of development. Technological innovation is the main source of competitive advantage for the long-term survival of organizations [1]. However, the technological innovation of NEVs has the "dual externalities" of knowledge spillover and environmental improvement, which is difficult to be compensated in the market price of the product. This can easily cause the private income of enterprise innovation investment to be less than the social income, leading to insufficient willingness to invest in innovation. As a result, it is difficult to guarantee the technological innovation of enterprises, which is not conducive to their long-term development [2, 3]. In order to compensate for the "dual externalities" of enterprise innovation, it is necessary to provide government subsidies to NEV enterprises.

Government subsidies beforehand and government subsidies afterwards are two essential components of government subsidies. Government subsidies beforehand are usually provided in the budding period of the innovative activities. They can not only help reduce the innovation costs but also correct market failures in technological innovation. Thus, government subsidies beforehand can enhance the willingness of enterprises to invest in innovation [4]. However, in the absence of scientific evaluation and

monitoring, such subsidies may increase firms' dependence on the government and reduce innovation efficiency. Government subsidies afterwards, which usually take place after a firm innovation has met a specific standard, can avoid firms' dependence on government subsidies and facilitate firms' entry into a virtuous cycle of technological innovation [5]. Since 2009, China has been promoting NEVs to accelerate the proliferation of NEVs, linking the supply and market demand at both ends. In order to facilitate the implementation of the promotion policy, China's Ministry of Industry and Information Technology (MIIT) has formulated a NEV promotion catalogue based on certain performance and technical standards, and the models entering the promotion directory can receive corresponding promotion subsidies. With the development of the NEV industry, China continuously adjusts and optimizes the entry criteria and conditions of the NEV promotion catalogue, including vehicle usage, power, battery type, energy density, and mileage. In the "Catalogue of Recommended Vehicles for the Promotion and Application of New Energy Vehicles" in 2017, the number of catalogue models for special purpose motor vehicles and passenger cars increased by 291 and 81, respectively, compared with 2016, and the number of catalogue models for passenger cars decreased by 32, which puts forward higher requirements on the power, economy, safety, comfort, and other indicators of the selected models.

Driven by the promotion policy, China's NEV production and sales scale has achieved tremendous growth, ranking first in the world since 2015. However, China's NEV industry has been plagued by the problem of focusing on scale rather than technology. The promotion policy is a kind of government subsidies afterwards policy. Moreover, entering the NEV promotion catalogue is the basis for obtaining promotion subsidies. In China, few scholars have paid attention to the panel data of NEV enterprise under the policy of government subsidies, especially under government subsidies afterwards. Therefore, our study tries to fill this gap by taking China's NEV listed enterprises in the period of 2008–2017 as samples to investigate whether entering the NEV promotion catalogue can promote enterprise innovation, which provides a new perspective for the analysis and evaluation of NEV promotion policy and a new reference for the promotion of NEV technology progress.

The remainder of this paper is structured as follows: Section 2 summarizes the relevant literature and presents the research hypothesis. The data sources, the measurement of the variables, and the research methodology are discussed in Section 3. Section 4 provides the main empirical results. The conclusions and policy implications are provided in Section 5.

2. Literature Review and Research Hypothesis

As the essential part of the economic infrastructure, technical standards can drive technological innovation and economic growth [6, 7]. Among them, technical standards play a decisive role in determining the pace and direction of technological innovation and can systematize unstructured technological innovative activities [8]. Technical standards can provide information for the knowledge stock and functional requirements of small and medium enterprises (SMEs). It can not only guide SMEs' investment and management of innovation elements such as technology, equipment, capital, information, and employees but also guide the development of various stages of technological innovation such as conception, design, research and development (R&D), manufacturing, and marketing. For example, enterprises prefer to allow employees to have a high level of job flexibility because they are more creative and innovative in this condition [9]. Therefore, technical standards can directly affect the process and effects of SMEs' technological innovation [10]. The process of standardization of technologies involves the interaction of many organizations such as the market, government, and business alliances [11]. In the process of standardization of different technologies, the involvement of the above organizations and the degree of their role vary. In general, nonproduct standards related to quality, reliability, safety, health, and environmental content are best suited for government-led development [12]. The government promotion catalogue for NEVs has a certain technical threshold, which provides a direct target for NEV innovation. Only if NEV enterprises meet this target, they can be eligible to enter the promotion catalogue. The technical standards in the promotion catalogue can guide SMEs to choose suitable technologies for their own R&D and introduce corresponding copyrights and patents. In sum, technical standards can encourage new technologies to replace old ones and provide a higher technical platform for the innovative activities of NEV enterprises. Based on the above analysis, this paper proposes hypothesis 1:

> H1: entering the promotion catalogue can promote innovation in NEV enterprises

In a market economy, the fundamental goal of an enterprise's activities is to obtain its profit, which can be achieved by satisfying the market demand. The "demand-pull" theory asserts that demand leads to technological innovation, and that changes in the scale and direction of demand effectively promote enterprises' technological innovation [13]. Market demand reflects consumers' requirements for products. This requirement is a very important driving force for the use of new technologies [14]. Therefore, market demand can prompt enterprises to produce products that match it through technological innovation [15]. Among them, the expansion of the market demand scale helps enterprises to make full use of the larger market demand space, expand production scale, and achieve economies of scale [16]. It can not only share innovation costs and reduce innovation risks but also provide a reliable guarantee for the benefits obtained from successful innovation [17]. At the same time, the expansion of market demand increases the incentive to innovate by influencing the market structure and the "survival of the fittest" market competition mechanism [18]. Entering the NEV promotion catalogue means that enterprises can get corresponding

subsidies, thus directly increasing their income. At the same time, it sends a brand signal effect to the sales market of NEVs and expands the market. Therefore, the expansion of NEV companies into a wider market can help increase corporate profits, thus promoting corporate innovation. According to the above analysis, our study proposes hypothesis 2:

> H2: entering the promotion catalogue can promote innovation of NEV enterprises by increasing their profits

Lerner first proposed the idea that R&D subsidies have a signal effect based on empirical results from American SMEs that entered the Small Business Innovation Research (SBIR) program from 1983 to 1997 [19]. Taking samples of enterprises from their respective countries, scholars have a consistent attitude: R&D subsidies provide a positive signal for the quality and technological advantages of enterprise projects. This signal effect can increase the possibility of enterprises for external financing by compensating for the defects of information asymmetry in the capital market [20, 21]. External financing is an important source of corporate innovation [22]. However, enterprise innovation presents the characteristics of high investment, high risk, and information asymmetry. Therefore, it is often difficult for companies to obtain the necessary financial support for innovative activities [23]. Entering the promotion catalogue means that the company's brand is recognized by the state and society, and NEV companies will be expected to develop better. Since it is a listed company, this behavior will send positive signals to investors about the quality of the company, which will help to finance the company and thus provide reliable financial support for innovation. In summary, this paper proposes the following hypothesis:

> H3: entering the promotion catalogue can promote innovation in NEV enterprises by reducing financing constraints

We contribute to literature in these aspects. First, our study divides government subsidies into government subsidies beforehand and government subsidies afterwards, and focuses on the impact of government subsidies afterwards on the innovation of NEV enterprises. Second, NEV enterprises with vehicle production business are selected as overall samples and exclude the heterogeneity of the research samples. Third, a multistage DID method is used in this study to alleviate endogenous problems.

3. Data and Methodology

3.1. Sample and Data. This study selected A-shares listed NEV enterprises from 2008 to 2017 as research samples. In order to ensure the scientific validity of the study, we selected NEV enterprises with high industry representation and sound financial disclosure and obtained the data of 334 effective observation samples. The patent data were manually searched through the patent database of the China National Intellectual Property Administration. The data of promotion subsidy were obtained from the "Catalogue of Recommended Vehicles for the Promotion and Application of New Energy Vehicles" of the MIIT of the People's Republic of China. The other data were obtained from China Stock Market Accounting Research Database (CSMAR) and Wind Economic Database (WIND), and missing data were manually supplemented in the annual reports of the companies in Cninfo.

3.2. Definition of Variables

3.2.1. Dependent Variables. Innovation in NEV enterprises can be divided into internal independent R&D and external technology introduction. This study uses the number of different types of patents to measure internal independent R&D. China's patents are divided into three types: patents for invention, patents for utility model, and patents for industrial design. Among them, patents for invention have the highest degree of innovation and are used to measure the radical innovation (*Rad*) of an enterprise. Patents for utility model and industrial design have a relatively low degree of innovation and are used to measure the incremental innovation (*Inc*) of an enterprise. Due to the time lag in patent grants, the number of invention patent applications is used here to measure the internal independent R&D of the enterprise. For the external technology introduction (*Ext*) of NEVs, this study refers to the study of Xu et al. [24] and measures it by the increment of intangible assets and goodwill of the enterprise because intangible assets and goodwill can reflect the technology purchased by the enterprise and can bring excess economic benefits to the enterprise [25].

3.2.2. Independent Variables. Promotion subsidies may expand the market demand for NEVs and stimulate innovation efforts by increasing corporate profits and easing financing constraints. If the vehicle models in the catalogue recommended by the MIIT are qualified, NEV enterprises can enter the promotion catalogue and receive government subsidies. The promotion subsidy ($Treat * Post$), which is the focus of this study, is measured by an interaction term of two dummy variables. The coefficients of $Treat * Post$ indicate the changes in the innovation performance of the experimental group of NEV enterprises under the policy effect [26].

3.2.3. Intermediate Variables. The subsidies obtained as cash flow after the NEVs enter the "Catalogue of Recommended Vehicles for the Promotion and Application of New Energy Vehicles" may motivate the dual innovation and external technology introduction of NEV enterprises. These results may be achieved through two paths formed by corporate profit and financing constraints. Corporate profit (*Profit*) is an important indicator of profitability, which may provide favorable material conditions for the innovative behavior of NEV enterprises [27]. This study expresses corporate profit in terms of net profit. Financing constraint (*Fin*) is the response of corporate financing cost, measured by the ratio

of interest expenses to current liabilities [28]. Higher financing constraint implies higher financing cost, which may inhibit the internal independent R&D and external technology introduction of NEVs.

3.2.4. Control Variables. Control variables are used to control the impact of the NEV enterprises' own characteristics on their innovation. With reference to existing literature, this study controls the following five variables: (1) enterprise age (*Age*): the age of the enterprise is related to managerial efficiency and may affect the enterprise's ability to innovate [29, 30]. (2) Enterprise scale (*Size*): large enterprises can withstand stronger innovation risks and reduce innovation costs through scale effects [31]. (3) Debt to asset ratio (*Lev*): this variable reflects the ability of NEV enterprises to use creditors' funds to carry out business activities. A higher level of debt will increase the financial risk of the enterprise, which has an impact on innovation [32]. (4) Government subsidies (*Sub*): this variable represents the number of subsidies received by NEV enterprises from the government. Higher subsidies can promote the innovation of NEV enterprises [33]. (5) State ownership (*Sta*): in the Chinese stock market, the government directly controls the state-owned shares. The larger the share of state-owned shares in the total share capital, the more likely it is to benefit to the innovation of NEV enterprises [34, 35].

The definitions of the main variables in this paper are shown in Table 1.

3.3. Research Models

3.3.1. Multistage Difference-in-Differences Model. In our study, a quasinatural experiment is conducted to estimate the effect of the NEV promotion subsidy policy on enterprise innovation. We take the NEV enterprises that have entered the promotion catalogue as an experimental group and the NEV enterprises that have not entered the catalogue as a control group. Compared to the traditional regression method, the DID method can alleviate the endogeneity problem in a differential manner. For this purpose, this study uses the DID method to observe the effect of the policy. In addition, the Chinese government's promotion of subsidy policies for NEVs is gradually promoted, while the traditional DID method can only test the policy performance implemented at a single point. Therefore, in order to investigate the impact of the promotion of subsidy policies on the innovation of NEV enterprises, this study constructs the following multistage DID model:

$$Y_{i,t} = C + \alpha Treat_i Post_{i,t} + \beta_1 X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t}, \quad (1)$$

where Y is denoted by radical innovation (*Rad*), incremental innovation (*Inc*), and external technology introduction (*Ext*), respectively. $Treat_i$ is the dummy variable of the experimental group. The experimental group of enterprises is not fixed due to the different times of entry into the NEV promotion catalogue. Enterprises which have entered the NEV promotion catalogue will be included in to the experimental group, and control group otherwise. $Post_{i,t}$ denotes the time dummy variable, that is, $Post_{i,t} = \begin{cases} 1, t \geq t_0 \\ 0, t < t_0 \end{cases}$, where t_0 stands for the year of entering the promotion catalogue of NEVs. α, the coefficient of $Treat_i Post_{i,t}$, is the DID estimator illustrating the policy effect on innovation of NEV enterprises, which is one of the highlights of this paper. If α is positively significant, then entering the promotion catalogue exert positive effects on the innovation of NEV enterprises; if α is negative and significant, then this government's promotion subsidy policy restrains the innovation of NEV enterprises; if α is nonsignificant, then entering the promotion catalogue of NEVs does not exert a significant effect on the innovation of their enterprises. μ_i and λ_t, respectively, represents individual fixed effects and time fixed effects. $X_{i,t}$ is denoted by the control variables. $\varepsilon_{i,t}$ is the random perturbation error term.

3.3.2. Mediation Effect Model. In order to test whether the effects of the promotion subsidy policy on dual innovation and external technology importation by enterprises are realized through the paths described above, based on equation (1), this paper refers to Edwards and Lambert and constructs a mediation effect model for further testing [36]:

$$M_{i,t} = C + \beta Treat_i Post_{i,t} + \beta_2 X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t}, \quad (2)$$

$$Y_{i,t} = C + \alpha' Treat_i Post_{i,t} + \delta M_{i,t} + \beta_3 X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t}, \quad (3)$$

where M represents the intermediate variables, including the corporate profit (*Profit*) and financing constraint (*Fin*). The testing principle is as follows: the effects of the independent variable on the dependent variable and the independent variable on the intermediate variable are verified by equations (1) and (2), respectively. If both α and β are statistically significant, the intermediary variable is included in equation (1), and both the independent and intermediary variables are regressed on the dependent variable. That is, regression tests are performed on equation (3). In addition, if both coefficients β and δ are statistically significant, it refers to the existence of mediation effect. Furthermore, if the coefficient δ is statistically significant but the coefficient α' is statistically insignificant, it means that the intermediate variable demonstrates a perfect mediation effect, implying that only this mediating variable plays a role in the mechanism. Moreover, if both the coefficient δ and α' are statistically significant but the coefficient α' is less than the coefficient α, it means that the intermediate variable demonstrates a partial mediation effect, implying that there are other reasonable mechanisms of action. However, if either β or δ is not statistically significant, then a Sobel test or a Bootstrap method is needed to determine whether the mediating variable has a mediation effect.

4. Results

4.1. Descriptive Statistics. The mean, standard deviation, minimum and maximum values of the variables for the 334 samples are shown in Table 2.

Table 1: Definition of variables.

Type of variables	Variable	Definition
Dependent variables	Radical innovation (*Rad*)	The number of patent applications for inventions per year (10,000)
	Incremental innovation (*Inc*)	The number of annual utility model and design applications (10,000)
	External technology introduction (*Ext*)	The increase in intangible assets and goodwill (100,000,000)
Independent variables	Promotion of subsidies (*Treat* ∗ *Post*)	Equal to 1 if NEV enterprises enter the promotion catalogue and 0 otherwise
Intermediate variables	Corporate profits (*Profit*)	Net profit (100,000,000)
	Financing constraints (*Fin*)	Interest expenses/current liabilities
Control variables	Enterprise age (*Age*)	Ln (year of observation-year of establishment)
	Enterprise scale (*Size*)	Ln (total assets)
	Debt to asset ratio (*Lev*)	Ln (total liabilities/total assets ∗ 100)
	Government subsidy (*Sub*)	Ln (government subsidy/operating income ∗ 100)
	State ownership (*Sta*)	Ln (number of shares held by the state/total share capital ∗ 100)

Table 2: Descriptive statistics of the variables.

Variable	Obs	Mean	Std. dev.	Min	Max
Treat ∗ *Post*	334	0.55689	0.497499	0	1
Profit	334	3.05994	9.82459	−3.035234	72.51881
Fin	334	0.022331	0.021615	0	0.141911
Rad	334	0.008883	0.021269	0	0.1886
Inc	334	0.011962	0.027535	0	0.2446
Ext	334	0.544392	1.498973	−5.884992	17.52637
Age	334	2.763407	0.365151	1.609438	4.060443
Size	334	16.99343	4.37686	9.891342	24.77929
Sub	334	−0.618773	1.617142	−14.69064	3.024192
Lev	334	3.975222	0.393875	1.967371	4.574195
Sta	334	0.694190	1.540632	−5.124496	4.09601

4.2. Multistage Difference-in-Differences Estimation. This paper uses a DID model to estimate the impact of promotion subsidies on internal independent R&D and external technology introduction in NEV enterprises. The unbiased result of the multistage DID estimation requires the assumption of parallel trend to be established. That is, internal independent R&D and external technology introduction in the treatment and control groups should have a consistent trend of change before the implementation of the promotion subsidy policy. Otherwise, the multistage DID cannot accurately estimate the effects of the policy implementation. It is therefore necessary to perform a parallel trend test for equation (1).

Figures 1–3 provide the parallel trends of radical innovation, incremental innovation, and external technology introduction respectively. The results show that, before the implementation of the promotion subsidy policy, whether new energy vehicle companies enter the promotion catalogue has no significant difference in their innovation behavior, which is in line with the hypothesis of parallel trend. Furthermore, after the implementation of the policy of promotion subsidies, the level of internal independent R&D and the introduction of external technology have increased in the enterprises that have entered the NEV promotion catalogue. The results indicate that the multistage DID approach is applicable to the evaluation of subsidy policies for the promotion of NEVs.

Table 3 shows the estimated results of the multistage DID. In models 1–4, the regression coefficient of "*Treat* ∗ *Post*" is significantly positive at the level of $p < 1\%$. Furthermore, the regression coefficient of "*Treat* ∗ *Post*" is positive and significant at the level of $p < 5\%$ in model 5. This result indicates that the policy of promotion subsidies greatly stimulate both internal independent R&D and external technology introduction in NEV enterprises. This result is consistent with the existing literature. For instance, in Canada, Mohnen found the effectiveness of government R&D subsidies by comparing the innovation performance between enterprises that received only R&D tax credits and enterprises that received both R&D tax credits and R&D subsidies [37]. Bronzini and Piselli empirically tested that a R&D subsidy programme implemented in northern Italy had a positive influence on the innovative activities of beneficiary firms [38]. Kang and Park have found in the Korean biotechnology sector that government project funding can stimulate internal R&D and thus positively promote innovation in enterprises [39].

4.3. The Mediation Effects of Corporate Profits Test. First, we choose corporate profits as the intermediate variable to investigate whether government subsidies affect innovation in NEV enterprises by increasing corporate profits. The results in Table 4 show that the estimated coefficient of the

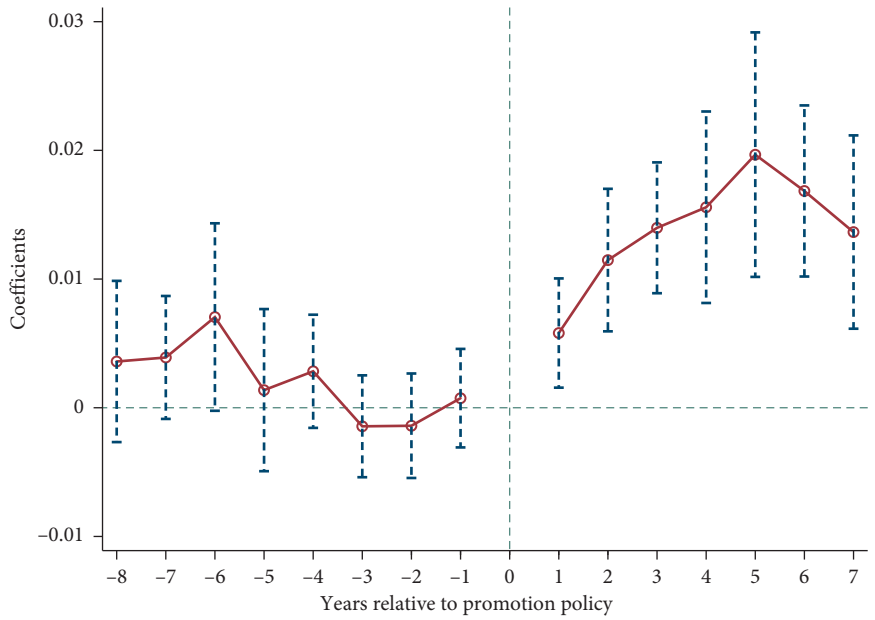

Figure 1: Parallel trend test for radical innovation.

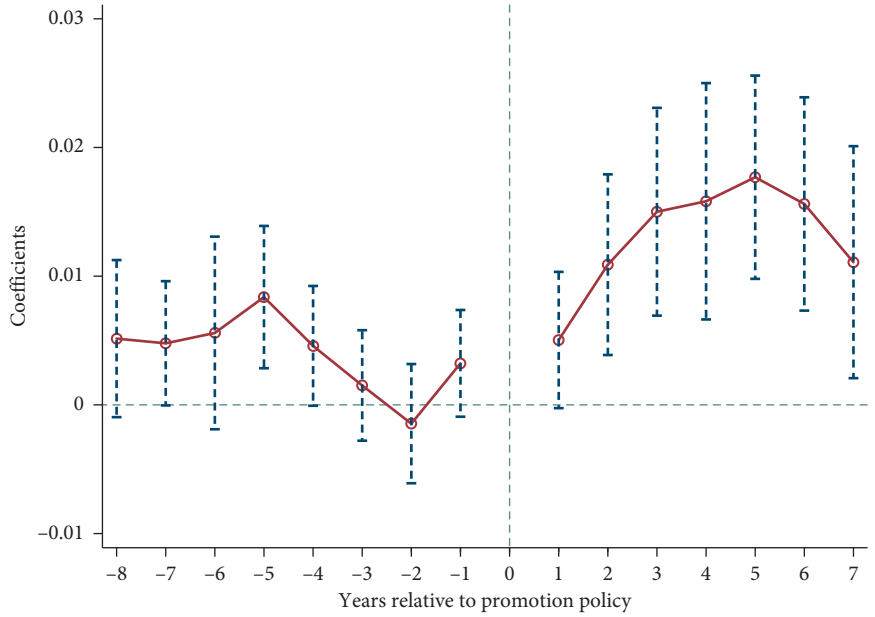

Figure 2: Parallel trend test for incremental innovation.

promotion subsidy in model 7 is significantly positive at the level of $p < 1\%$, indicating that the promotion subsidy significantly increases the profits of NEV enterprises. Based on model 7, the intermediate variable of enterprise profit is added. The results represent that the internal independent R&D of the enterprise in models 9 and 11 is significantly positive at the level of $p < 1\%$, and the external technology introduction of the enterprise in model 13 is significantly positive at the level of $p < 10\%$. The regression coefficients of promotion subsidies on enterprise innovation remain significantly positive after controlling for enterprise profits. These results prove that promotion subsidies can further promote enterprise innovation by increasing enterprise profits, and there is a partial mediation effect of enterprise profits in the relationship between promotion subsidies and enterprise innovation. Hence, hypothesis 2 is verified. After entering the promotion catalogue, government subsidies are effective in increasing enterprises' profitability [40, 41]. Therefore, the direct subsidies and indirectly enhanced profits from NEVs provide cash flow for innovative activities that require large amounts of capital. In addition, because profitable enterprises have a greater incentive to innovate

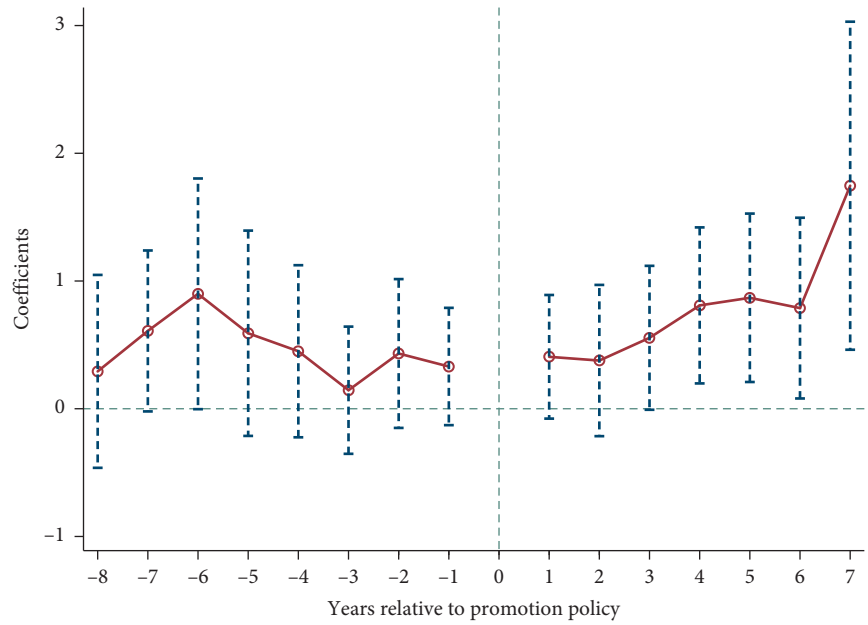

Figure 3: Parallel trend test for external technology introduction.

Table 3: The test of the effect of promotion subsidy policy.

Variables	*Rad*		*Inc*		*Ext*	
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Treat * *Post*	0.010519***	0.011056***	0.012537***	0.012348***	0.372542**	0.483211***
	(4.63)	(4.49)	(4.24)	(3.88)	(2.27)	(2.68)
Age		0.003807		0.001348		−0.356128
		(1.19)		(0.33)		(−1.51)
Size		0.000187		−0.000172		0.033943*
		(0.68)		(−0.49)		(1.69)
Sub		0.001136		0.000921		−0.002802
		(1.64)		(1.03)		(−0.06)
Lev		0.000311		0.002428		0.105016
		(0.10)		(0.59)		(0.45)
Sta		0.002611***		0.004092***		0.005842
		(3.50)		(4.25)		(0.11)
N	334	334	334	334	334	334
R-squared	0.0605	0.1048	0.0513	0.1098	0.0153	0.0313

Note: *, **, and *** represent significance at 10%, 5%, and 1% level, respectively.

Table 4: The mediation effects test of corporate profits.

Variables	*Profit*	*Rad*		*Inc*		*Ext*	
	Model 7	Model 8	Model 9	Model 10	Model 11	Model 12	Model 13
Treat * *Post*	3.211800***	0.011056***	0.009565***	0.012348***	0.011338***	0.483211***	0.318741*
	(2.72)	(4.49)	(3.93)	(3.88)	(3.55)	(2.68)	(1.85)
Profit			0.000464***		0.000314**		0.051208***
			(4.13)		(2.13)		(6.43)
Age	−1.131982	0.003807	0.004333	0.001348	0.001704	−0.356128	−0.298161
	(−0.73)	(1.19)	(1.38)	(0.33)	(0.41)	(−1.51)	(−1.34)
Size	0.150109	0.000187	0.000118	−0.000172	−0.000219	0.033943	0.026256
	(1.14)	(0.68)	(0.44)	(−0.49)	(−0.62)	(1.69)	(1.38)
Sub	−0.340113	0.001136	0.001294*	0.000921	0.001028	−0.002802	0.014615
	(−1.02)	(1.64)	(1.91)	(1.03)	(1.16)	(−0.06)	(0.31)
Lev	0.583723	0.000311	0.000040	0.002428	0.002244	0.105016	0.075176
	(0.38)	(0.10)	(0.01)	(0.59)	(0.55)	(0.45)	(0.34)

Table 4: Continued.

Variables	*Profit*	*Rad*		*Inc*		*Ext*	
	Model 7	Model 8	Model 9	Model 10	Model 11	Model 12	Model 13
Sta	0.382209	0.002611***	0.002433***	0.004092***	0.003972***	0.005842	−0.013730
	(1.07)	(3.50)	(3.34)	(4.25)	(4.14)	(0.11)	(−0.27)
N	334	334	334	334	334	334	334
R-squared	0.0316	0.1048	0.1493	0.1098	0.1220	0.0313	0.1404

Note: *, **, and *** represent significance at 10%, 5%, and 1% level, respectively.

Table 5: The mediation effects test of financing constraints.

Variables	*Fin*	*Rad*		*Inc*		*Ext*	
	Model 14	Model 15	Model 16	Model 17	Model 18	Model 19	Model 20
*Treat * Post*	−0.004541*	0.011056***	0.010246***	0.012348***	0.011223***	0.483211***	0.452091**
	(−1.85)	(4.49)	(4.20)	(3.88)	(3.57)	(2.68)	(2.50)
Fin			−0.178372***		−0.247538***		−6.852492*
			(−3.27)		(−3.52)		(−1.69)
Age	−0.000149	0.003807	0.003781	0.001348	0.001311	−0.356127	−0.357148
	(−0.05)	(1.19)	(1.19)	(0.33)	(0.32)	(−1.51)	(−1.52)
Size	0.000891***	0.000187	0.000346	−0.000172	0.000049	0.033943*	0.040050*
	(3.26)	(0.68)	(1.26)	(−0.49)	(0.14)	(1.69)	(1.97)
Sub	0.003289***	0.001136	0.001723**	0.000921	0.001735*	−0.002802	0.019738
	(4.76)	(1.64)	(2.44)	(1.03)	(1.91)	(−0.06)	(0.38)
Lev	−0.003606	0.000311	−0.000333	0.002428	0.001535	0.105016	0.080308
	(−1.13)	(0.10)	(−0.11)	(0.59)	(0.38)	(0.45)	(0.34)
Sta	−0.000508	0.002611***	0.002520***	0.004092***	0.003966***	0.005842	0.002361
	(−0.68)	(3.50)	(3.43)	(4.25)	(4.19)	(0.11)	(0.04)
N	334	334	334	334	334	334	334
R-squared	0.1360	0.1048	0.1331	0.1098	0.1424	0.0313	0.0397

Note: *, **, and *** represent significance at 10%, 5%, and 1% level, respectively.

[42, 43], the promotion of subsidies promotes innovation in NEV enterprises by boosting their profits.

4.4. The Mediation Effects Test of Financing Constraints. Second, we use the financing constraint as an intermediate variable to test whether government subsidies can affect the innovation of NEV enterprises by alleviating the financing constraint. From the results in Table 5, the estimated coefficient of the financing constraint in model 14 is negative and significant at the level of $p < 10\%$, indicating that the promotion subsidy reduces the financing constraint of the enterprise's NEVs. Furthermore, models 16, 18, and 20 add the intermediate variable financing constraint to model 14. The results indicate that internal independent R&D is positive and significant at the level of $p < 1\%$, while external technology introduction is significantly positive at the level of $p < 5\%$. After controlling for the financing constraint, the regression coefficient of the promotion subsidy on enterprise innovation is still positive and significant. Similarly, the regression coefficient of the financing constraint on enterprise innovation is significantly negative. This implies that the promotion subsidy can promote enterprise innovation by reducing the financing constraint, which plays a partial mediation effect in the relationship between the promotion subsidy and enterprise innovation. Therefore, our hypothesis 3 is verified. This is because the obtained government subsidies not only inject funds into the enterprise's R&D investment but also send positive signals to the investment institutions outside the enterprise [44]. As an important hidden mechanism for R&D subsidies to reduce the financing constraints of companies, the signal effect can weaken the information asymmetry between companies and investors and obtain more external financing for enterprises [45]. The innovation of NEV enterprises cannot be separated from a large amount of financial support. Therefore, after NEVs enter the promotion catalogue, promotion subsidies can promote innovation of NEV enterprises by easing financing constraints.

5. Conclusions and Policy Recommendations

Our study empirically examines the impact of government promotion subsidy policy on the innovation of NEV enterprises using a multistage DID model with 44 A-shares listed NEV enterprises from 2008 to 2017. The results show that, before entering the NEV promotion catalogue, the government's promotion subsidy policy did not promote innovation of NEV enterprises; after entering the NEV

promotion catalogue, the government's promotion subsidy policy stimulated innovation of NEV enterprises and significantly promoted radical innovation, incremental innovation, and external technology introduction. In the mediation mechanism examination, our study reveals that entering the promotion catalogue could provide material support for the innovation of NEV enterprises by increasing their profits and easing their financing constraints.

According to the above research findings, our study proposes the policy recommendations as follows:

Firstly, it is necessary to strengthen the breakthrough in core technologies of NEVs. On the basis of cultivating consumption and production capacity, the Chinese government's subsidies for NEVs should focus on the R&D of key technologies. At the same time, the Chinese government should raise the technical standards for NEVs to enter the promotion catalogue, so as to stimulate the innovative motivation and enthusiasm of NEV enterprises.

Secondly, market demand for the NEV industry should be nurtured. The government should stimulate the enthusiasm and purchasing power of the consumption of NEVs to promote the sustainable development of the market demand. This will guide more social funds into the NEV field and provide financial support for the innovation of enterprises.

Thirdly, the NEV subsidy regulatory system should be improved. The government should increase the intensity of information disclosure to reduce the possibility of financing constraints due to information asymmetry between the government and companies and improve the level of supervision and inspection to increase the illegal cost of enterprises cheating subsidies. At the same time, the government should establish a reasonable elimination mechanism, such as a subsidy rebate mechanism, to shift the main body of NEV development from the government to the market and force enterprises to improve their innovative drive.

Data Availability

The patent data were manually searched through the patent database of the China National Intellectual Property Administration. The data of promotion subsidy were obtained from the "Catalogue of Recommended Vehicles for the Promotion and Application of New Energy Vehicles" of the MIIT of the People's Republic of China. The other data were obtained from China Stock Market Accounting Research Database (CSMAR), Wind Economic Database (WIND), and missing data were manually supplemented in the annual reports of the companies in Cninfo.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

C. J. conceptualized the study; X. W. was responsible for data curation; X. W. provided software; X. W. was responsible for formal analysis; X. W. prepared the original draft; C. J. reviewed and edited the manuscript.

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