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Health and corporate/urban sustainability

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Health and corporate/urban sustainability

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Editorial: Health and corporate/urban sustainability

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health, corporate sustainability, urban sustainability, innovation, policy

Editorial on the Research Topic
Health and corporate/urban sustainability

The intersection of health, corporate practices, and urban development has emerged as a critical frontier in addressing global sustainability challenges. This Research Topic, Health and Corporate/Urban Sustainability, seeks to bridge these gaps by presenting interdisciplinary insights into how health—both at individual and community levels—shapes sustainable development trajectories. The 12 articles in this Research Topic underscore that prioritizing health is not merely a moral imperative but a strategic lever for fostering economic stability, environmental sustainability, and societal wellbeing. This research can potentially inspire transformative change in our approach to sustainability.

Health as a catalyst for corporate sustainability and innovation

Corporate sustainability is increasingly intertwined with employee health and safety, as evidenced by several contributions. Nawata reveals that physical and mental health conditions, such as hypertension, stress, and inadequate work-life balance, significantly correlate with long-term absenteeism, imposing financial burdens on firms. These findings reinforce the need for workplace interventions targeting preventive healthcare and mental wellbeing to enhance productivity. On the other hand, Wang and Yuan demonstrate how digital platforms amplify corporate social responsibility (CSR) by facilitating environmental innovation. Their study highlights a 55.31% improvement in policy enforcement when firms adopt digital tools, underscoring technology's role in aligning CSR with public health outcomes.

The nexus between policy and corporate innovation in biopharmaceutical industry is further explored by Xia and Jia, who identify industry-university-research (IUR) collaborations as a driver of biopharmaceutical innovation. Their nuanced analysis cautions that government subsidies, while boosting R&D inputs, may inadvertently stifle innovation quality—a paradox demanding policy recalibration. Meanwhile, Wu et al. illustrate how economic policy uncertainty spurs Chinese pharmaceutical firms' innovation, particularly through financialization and executive incentives. These studies advocate for adaptive governance frameworks that balance risk, innovation, and corporate stakeholder welfare.

Urban health: resilience, equity, and recovery

Urban sustainability hinges on equitable health systems and resilient infrastructure. Zhang and Deng emphasize this by linking internal migrants' health to economic resilience in the Yangtze River Delta, China. Their analysis reveals that migrants' health boosts labor participation, enhancing cities' capacity to withstand crises—a relationship moderated by access to public health services. This aligns with Makoni et al.'s advocacy for community-led monitoring, whereby Zimbabwe leverages local engagement to reduce HIV's stigmas and improve service delivery. Such grassroots approaches exemplify how decentralizing health governance can strengthen urban resilience.

The COVID-19 pandemic laid bare systemic vulnerabilities in the healthcare system, prompting Zhang et al. to propose a loosely coupled process management framework for epidemic prevention. By integrating digital systems with adaptable workflows, their model mitigates healthcare strain—a lesson critical for future pandemic preparedness. Further, Linghu et al. demonstrate that information and communication technology (ICT) development in China enhances carbon emission efficiency by 0.11% per 10% increase in internet penetration, yielding public health co-benefits through cleaner energy and innovation. These articles collectively argue for technology-driven, inclusive urban planning to harmonize environmental and health goals, empowering our readers with the knowledge and tools they need.

Policy, innovation, and regional pathways

Regional case studies offer valuable lessons for global sustainability. Lin et al. uncover that income inequality in rural China exacerbates health disparities, mitigated by education and health awareness. Their work underscores the need for targeted policies to address socio-economic determinants of health. Similarly, Meng et al. analyse Guangxi's post-pandemic tourism-urbanization-environment nexus, advocating for digital transformation and green practices to revive tourism sector while safeguarding environmental health.

At the macro-economic level, Fan et al. resolve longstanding debates through a meta-analysis of 479 studies, confirming a strong positive correlation ($r = 0.429$) between health insurance and economic performance. Their findings reveal that public insurance systems in developed nations yield greater economic returns, urging policymakers to tailor healthcare financing to local contexts. Complementing this, Li and Ma attribute 3.9% growth in comprehensive total factor productivity to digital economy advancements in China, driven by technological innovation and education—a blueprint for emerging economies.

Toward integrated sustainability

This Research Topic has advocated for a paradigm shift: viewing health not as a siloed sector but as a linchpin of holistic sustainability. Corporate strategies must integrate employees' wellbeing with environmental and governance goals, while urban policies should prioritize equitable health access to bolster economic resilience. Technological innovation—from digital platforms to green ICT—emerges as a cross-cutting enabler, yet its success hinges on contextual adaptation and inclusive designs.

As nations navigate post-pandemic recovery and climate challenges, this Research Topic emphasizes the urgency of embedding health into the sustainability framework. Policymakers, corporate leaders, and urban planners are urged to adopt synergistic approaches that recognize health as both a driver and outcome of sustainable development. The practical implications of this research can empower these stakeholders to make informed decisions that will shape the future of our world.

This editorial synthesizes contributions to the Research Topic "*Health and Corporate/Urban Sustainability*." We extend gratitude to all authors and reviewers for advancing this critical dialogue. Their collaborative efforts have created a community of scholars and practitioners dedicated to advancing health and sustainability.

Author contributions

JS: Investigation, Validation, Writing – review & editing, Writing – original draft, Conceptualization. XS: Validation, Conceptualization, Writing – review & editing. EH: Conceptualization, Validation, Writing – review & editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Addressing unforeseen public health risks via the use of sustainable system and process management

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During the coronavirus disease 2019 (COVID-19) pandemic, the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which was designated by the World Health Organization in January 2020 as a newly emerging coronavirus in 2019, and its variants have placed unbearable strain on the healthcare systems of various countries, with serious implications for sustainable development worldwide. Researchers have proposed several solutions, such as the use of digital technologies to improve prevention systems. However, the challenges of epidemic prevention and control failures have not been addressed fundamentally, as the key causes of epidemic failures (i.e., outbreaks) and strategies for process management have been neglected. The purpose of the current study is to address these issues by exploring the causes of epidemic prevention and control failure and targeting improvement strategies that combine system structure of epidemic prevention and process management. Specifically, following an exploration of the main reasons for COVID-19 prevention and control failures through a case study of two tertiary hospitals, this paper outlines a targeted prevention and control system based on triangular validation and a loosely coupled process management framework and verifies the expected results using simulation methods together with statistical data on the spread of SARS-CoV-2 in Wuhan, China. The findings not only advance the development of epidemic risk prevention and control theory, especially the complementary nature of IT applications and process management in the field of epidemic risk prevention and control, but also provide guidance on the innovation and implementation of epidemic prevention and control systems and process management and recommendations for countries to promote sustainable development from a health-focused perspective.

KEYWORDS

epidemics, unknown risk, prevention system, loose coupling, sustainability

1. Introduction

Since early 2020, the sudden onslaught and rapid spread of severe acute respiratory syndrome-coronavirus 2 (SARS-CoV-2) and the subsequent coronavirus 2019 (COVID-19) pandemic have paralyzed the world and temporarily caused global sustainable development to come to a standstill. According to the 2021 United Nations Sustainable Development Goals

report[1], COVID-19 has had a catastrophic global impact. For example, the number of people living in poverty has increased from 119 million to 124 million, 255 million full-time jobs have been destroyed, and the basic survival of 1.6 billion informal workers have been jeopardized. The global COVID-19 pandemic has spread to more than 170 countries, infecting more than 651 million people and causing approximately 6.6 million deaths until 23 of December, 2022.

The rapid escalation of the COVID-19 pandemic has clearly exposed the inability of some countries to respond to epidemic risks, especially in terms of the responsiveness of their outbreak prevention and control systems and corresponding process management. For example, although early cases of SARS-CoV-2 infection were reported in Wuhan, China, the city was not closed until January 24, 2023, causing the government to miss a 14-day golden period for epidemic prevention and control. Accordingly, this delay led to a geometric increase in patients with COVID-19. India faced a similarly desperate situation associated with an outbreak of infection with the Alpha variant of SARS-CoV-2, and South Africa's prevention and control system was unable to cope with the spread of the Beta variant. However, these countries had previously implemented effective early warning systems in response to sudden outbreaks of H1N1 influenza, Middle East respiratory syndrome (MERS) and Ebola hemorrhagic fever (EBHF). Therefore, countries around the world are focusing on the reasons underlying the failure of COVID-19 prevention and control measures and making corresponding changes to strengthen their capacity to respond to similar pandemic risks in future emergency situations and further promote sustainable development.

One fundamental reason that has been proposed to explain the observed failures in pandemic control is the pathogenic features of SARS-CoV-2, which vary from those of viruses associated with prior epidemics. These differences in pathogenic features have led to distinct virus risk profiles. The origins of risk may be traced back to research reported by Knight (1), in which risk was found to be coupled with uncertainty. Risk can be divided into known and unknown risks according to the knowledge hierarchy (i.e., level of understanding) (2). Statistical estimation indicates that approximately 4,000 viruses exist in nature, 95% of which are unknown to humans. Among the 5% of viruses known to humans, coronaviruses received little attention until the late 1990s and have remained the focus of a vaguely localized area of study for nearly 20 years. In other words, the study of viruses is rife with unknowns, which may enable outbreaks of epidemic diseases that cannot be anticipated by existing knowledge governing prevention systems (3). According to Hagigi and Sivakumar (4), risk can be classified as born or unborn, depending on whether the risk is associated with an outbreak or widespread transmission. For example, India regarded the original strain of SARS-CoV-2 as a born risk but the Alpha variant as an unborn risk. Thus, unknown or known risk was much related to the time which means that risk has been happened in the same area or not; while born or unborn was much related to area, means that a risk has been happened in other area during the same period Most existing epidemiological methods for outbreak control are well suited to cope with born-known, unborn-known, and born-unknown risks but struggle to handle unborn-unknown risks. In addition, although studies have plausibly explained the risk factors for epidemic disease outbreaks, they have not provided precise methods for controlling each factor.

Lisa Gralinski, an associate researcher in Ralph Baric's laboratory in North Carolina, United States, emphasized the importance of preventive technology in countering epidemic outbreaks. However, clinical presentations are heterogeneous, and the early diagnosis of epidemic diseases is uncertain; consequently, reliable information must be extracted from both structured and unstructured data, and this need has increased the requirement for analytical skill with digital technologies (5, 6). The use of new digital technologies, such as big data and artificial intelligence, has been proposed to expand the scope of surveillance in prevention systems, unify data structures to facilitate information sharing, and connect internal pathways within healthcare systems to facilitate information transfer (7–9). Additionally, some experts have stressed the value of combining digital technologies with social media data to enhance predictive information (10, 11). Although these studies have successfully fostered the enhancement of outbreak prevention technology, several flaws remain. For instance, data collection in the context of prevention has been limited to social media users, and data from third parties such as academic research institutes have been neglected. Furthermore, SARS-CoV-2 has spread more rapidly and behaved more unpredictably than other pathogens that have caused epidemic outbreaks and thus requires a capacity for rapid process reaction. To date, however, research has not provided comprehensive suggestions for strengthening prevention systems while simultaneously increasing response capabilities.

A few scholars have suggested that hospitals' established process management are characterized by features such as cascading reports, centralized aggregation, and centralized surveys; these lead to an inherent path dependency and make it difficult for prevention systems or countries to implement timely reassessment strategies or resilient responses to rapidly control the spread of unborn-unknown risks (12, 13). Others have suggested that the low probability of an outbreak (14) frequently results in a disregard for prevention management, especially process management, due to the low urgency associated with the risk probability, and this disregard can lead to a deficiency in process management. Additionally, the insufficient understanding, attitudes, and behaviors of healthcare workers with respect to the control systems used in prevention and control efforts might increase the risks (15). In summary, the research has highlighted the difficulties associated with process management practices and the elements that drive them but has not shed light on their bottom-up process management preventive strategies or presented solutions.

To address research issues in the failure of epidemic prevention and control, the study described in this paper uses theoretical risk types to investigate the causes of failure to prevent outbreaks of unborn-unknown risks in both the technical and process dimensions. A triangulated validation system based on big data and artificial intelligence technologies is proposed, and a loosely coupled process management framework is extended. This paper also includes an analysis of the expected results. Conclusions can be drawn via simulation analysis and interview-based case studies, with great theoretical and practical significance for countries aiming to strengthen their risk prevention systems and emergency management processes.

1 The Sustainable Development Goals (SDGs). 2021. https://unstats.un.org/sdgs/report/2021/.

2. Literature review

The fundamental academic rationale of this study is set on the following premises: first, the prevention and control of epidemic outbreaks are crucial elements of sustainable development; second, the causes for, and preventative measures against, varying risk categories of epidemics must be differentiated; third, tackling epidemic outbreaks involves enhancing the direct reporting system, particularly through data structure adjustments and improvements; fourth, adaptive process management forms the core of an organization's ability to respond swiftly to rapid environmental changes, thereby better equipping them to handle pandemic situations. Consequently, our literature review is structured into four key sections: Sustainability and Health; Uncertainty and Health Risk; Systems Technology and Adaptive Process Management and Loose Coupling; and Decision-Making Frameworks.

Our study specifically dwells on the terms "Sustainability," "Uncertainty," "Risk," "Systems Technology," "Health Risk," "Adaptive Process Management," and "Decision-Making." We identified literature pertinent to our research by using these keywords in Web of Science searches. Given that our paper fundamentally pertains to the fields of management and preventative medicine, we streamlined the disciplines to "Preventive and Control Medicine" and "Management." Also, we confined our selection to articles published between 2012 and 2022. An initial selection yielded 1,044 articles. Following preliminary analysis of the titles and profiles of these papers, we hand-picked 68 of the most relevant for further reference.

2.1. Sustainability and health

The term "sustainable development" has gained prominence in the last decade (16). Sustainable development encompasses economic, societal, and environmental considerations. However, it has been proposed (17) that sustainable development extends into health, drawing particular attention to how health improvements are integrally connected to at least ten of the Sustainable Development Goals (SDGs). These include eradicating poverty and inequality, promoting health and well-being, and safeguarding the environment to ensure sustainable growth. Hence, sustainable health progress is an integral international public policy issue for achieving sustainable development (18).

China has underscored its most considerable health sustainability challenges, including increasing epidemics (19). It has been noted that pandemic responses are the most crucial types of health interventions in programs relating to disease prevention and health promotion (20). A sustainable health system capable of responding to a pandemic should possess three key attributes: affordability for patients and families, employers, and governments; acceptability for key populations such as patients and health professionals; and an adaptive response to an unexpected pandemic (21).

Enhancing the efficiency of health case prevention and control systems may not be an easy task. Some research has delved into enhancing the efficiency of these systems from a technological angle (22, 23). However, such research usually targets a single dimension, namely the effectiveness of the prevention and control systems, with scant attention given to the merging of process management and systemic change dimensions. Therefore, it becomes pivotal to amalgamate both administrative and systemic perspectives to ramp up disease prevention odds.

2.2. Uncertainty and health risk

Research on uncertainty can be traced back as far as 1921, when (1) categorized uncertainty into quantifiable and non-quantifiable forms. A quantifiable form was identified as a type of uncertainty that can be reduced to a finite probability distribution with sufficient information and knowledge; i.e., it can be transformed into a known risk. A non-quantifiable form was identified as uncertainty that cannot be quantified in advance and is difficult to transform into a manageable risk through data analysis and knowledge acquisition due to its unknown nature.

Known risks have always been central to risk prevention and management concerns related to the prevention and control of pandemic outbreaks (24). In contrast, unknown risks frequently present challenges and become weak points in prevention and control efforts due to the variability of disease symptoms, diversity of causes, extent of spread, and complexity of related hazards (25). First, unknown risks often exhibit irregular clinical variation because of their low prevalence and spread and thus are difficult to identify in the early stage based on patients' symptoms. Healthcare workers are constrained by time and attention (5) and frequently find it difficult to deduce novel causal relationships in the short term, instead relying on established knowledge and experience to produce unclear explanations (14). Second, the initial clinical features of an unknown risk are often similar to those of a known risk. For example, COVID-19 has a median incubation period of 3 days (26), and its initial symptoms include malaise, cough, mild fever, and even changes in blood count in certain individuals, making it difficult to detect a sudden outbreaks at the early stage. Third, the range of possible causes hinders healthcare personnel's ability to determine the source of illness. This makes it difficult to characterize epidemic diseases and their transmission routes (27).

If epidemic breakouts or transmission networks at the national or regional level are evaluated as a system, the risk of an epidemic may be classified as born or unborn (4). For example, in China, SARS and SARS-CoV-2 were initially concentrated and widely spread within the nation, necessitating a proactive response in terms the nation's own attitudes, systems, and technologies for epidemic preparedness, and thus were regarded as unborn risks. For other external parties, such risks are regarded as born risks, as the outbreak is known but has not yet spread to their system. For example, the initial outbreak of the Alpha variant of SARS-CoV-2 occurred in India, and hence was considered an unborn risk for that country, whereas it was a born risk for other nations such as China, the United States, and Italy.

In summary, risks can be classified as known or unknown according to the level of relevant knowledge, or as born or unborn according to differences in the outbreak circumstances. These classifications yield a 2×2 classification framework to describe four types of risk, namely unborn-known, born-known, born-unknown, and unborn-unknown. For example, in China, unborn-known risks include diseases such as hepatitis B or tuberculosis; born-known risks include, for example, EBHF; born-unknown risks include diseases

such as MERS; and unborn-unknown risks include, for example, SARS and COVID-19.

2.3. Systems technology

Compared with known risks for which the pathogen, transmission routes, and outbreak conditions are known, an unknown risk is associated with uncertainty; such a risk is difficult to translate into a controllable risk and thus resembles a "black swan" event (28). Currently, there are two primary strategies for dealing with such unknown risks. First, technological advancements can increase the availability of knowledge about the risk to enable early prediction and judgment (2). This strategy entails the examination of system and media data. For example, multidimensional big data, such as personal sleep and body temperature, population movement tracking, and social media sentiment, can be leveraged (29). Second, institutional change can maximize the separation of risks from unknown risks. This type of strategy involves a quick and flexible response to the risk components that can be isolated and controlled during the dynamic process of a sudden epidemic. Such a strategy entails altering the associated management procedures.

Integrated information technology (IT) applications are crucial for predicting, diagnosing, and controlling epidemic disease outbreaks (30) through techniques such as time series analysis, simulation modeling, social network analysis, and geographic visualization of epidemic diseases in conjunction with their transmission characteristics to detect and determine disease development trends in real or near-real time. This information may be used to guide public health decisions for prevention and control (6). "Prevention system" is a broad term that refers to the establishment of an information monitoring and transfer platform to collect, process, store, retrieve, analyze, research, and make decisions on behalf of regional health prevention and control administrative departments at all levels (31). The fundamental information system "Web-based Direct Reporting System for Infectious Disease Outbreaks and Public Health Emergencies" for disease prevention and control consists of six subsystems, including a statutory epidemic disease system, an emergency public health event reporting system, a statutory epidemic disease surveillance system, and a statutory epidemic disease surveillance system (32). As a result, the system can establish a quick response model based on an epidemic illness and public health emergency case database. Ideally, an effective response from the Center for Disease Control (CDC) in China would be generated only 4 h after the detection of an epidemic disease at the grassroots level (33).

However, this strategy is contingent upon the comprehensive reporting of threat cases by a local health facility or the CDC: specifically, the categorization of an epidemic and the case descriptions supplied by a local health facility or the CDC serve as the foundation for a quick reaction. Generally, local health institutions or the CDC can properly categorize or completely characterize the known risks and offer enough new case data to enable the prevention system to react effectively. However, local health institutions or the CDC may be unable to precisely categorize or adequately characterize an unborn-unknown risk, thus hindering the prevention and control system's ability to generate an effective response. There is a tremendous need to alter the data structures of current systems by utilizing IT to control such unborn-unknown risks (6).

2.4. Adaptive process management and loose coupling decision-making frameworks

Apart from digital technology, an information system's value is decided by its supporting procedures (34, 35). That is, to realize value, the managers and technology users must develop trust in the information systems technology itself, while members of the organization must develop a whole process response solution driven by data, information, and the system. The following theoretical explanation has been put forth to explain the failure of systems and process management to perform as expected with respect to the prevention and control of COVID-19 in Wuhan, China: when an organization lacks awareness of the applications and extended functions of information systems, as well as the process management of their applications, data analysis can only guide managers' decision-making as the true determinants continue to be based on individual experience (36). In an outbreak epidemic scenario, this explanation is demonstrated by the fact that although a prevention and control system exists and is equipped with special channels for a rapid response, the system is not fully triggered during the 20-day period between the concentration of an unborn-unknown epidemic and the wide spread of disease. The implemented measures are still cascaded, evaluated, and investigated centrally, demonstrating a remaining distinction between technological innovation and application management.

Research has shown that this fragmentation between information systems applications and management processes is key to a country's inability to mount an agile response to an unborn-unknown risk. Addressing the issue of independence between technological innovation and application management in the context of risk prevention and control will require changes to management processes or organizational practices. Organizational practices are interconnected, repeatable, and recognizable norms of action and patterns of behavior that are carried out by several actors (37); one example is the process of increasing the identification of certain diseases. Organizational practices provide a crucial foundation for not only organizational activity but also everyday operations.

However, the diversity of diseases and causes makes it difficult for a control system to establish uniform diagnostic criteria for various epidemic diseases, and new organizational practices are required to integrate data and information into decision-making systems to proactively identify and rapidly search diseases through practice updates and thus adapt to rapidly changing circumstances (38). For instance, the "Koch Rule," which requires the isolation of a pathogen or viral strain before identifying the pathogen responsible for an epidemic, may result in delayed preventive measures (39). Avoiding or mitigating the costs associated with such a situation will require both technological and process changes (40), such as the adoption of next-generation sequencing (NGS) to determine viral genome sequences and modification of the process of reporting, aggregating, and analyzing data in control systems. It is essential to understand that simply improving technology without changing process management is insufficient in terms of handling unborn-unknown or even existing born-unknown risk shocks, as IT embedded in an organization can only fully enhance the efficiency of the organization's rapid response when its use transitions from exploratory to institutionalized (41, 42).

Adaptability is the ability to adapt effectively in response to changing conditions, with a focus on quicker and more effective

iteration (43, 44). "Adaptive management" refers to organizations that overcome organizational inertia by coordinating resource allocation in response to changing demands in the external environment (45). Organizational inertia develops because of the process and institutionalization of organizational operations; excessive inertia can render an organization incapable of adapting, leading it to face survival issues (46). In this paper, "adaptive process management" refers to management processes that are dynamically aligned with an organization's or system's intended reactions and adjustments to four distinct types of unforeseen pandemic threats.

Adaptive process management is a proactive form of adaptive management that focuses on two critical adaptive decision-making issues: (1) how to accurately distinguish adequate prevention from overreaction, and (2) how to handle the complementarity of collective and individual decision-making to organically unify democracy and centralization in risk assessment and decision-making. Theoretically, a loose coupling decision-making framework is required for proactive adaptive management decisions. "Coupling" refers to the existence of interconnected elements within a system that maintain a degree of certainty and stability in the overall system. "Loose" means that the individual, team, subsystem, and other elements of the system have some capacity to change independently to adapt quickly to changes in the external environment (47). One example of a loosely coupled decision-making structure in China involves the Meteorological Office's forecasts of typhoons and the government's decisions to suspend work: the Meteorological Office makes a professional judgment about the level of warning to issue and provides risk warnings, while the government makes decisions about collective risk control actions within a multi-objective framework, which inform individuals' or groups' risk control actions. Using a sub-delegation strategy, this loosely connected decision-making structure preserves the basic responsiveness of forecasting while avoiding the loss of risk warning capacity through its integration into governmental multi-objective decision-making (48, 49).

Unlike known risks, unknown risks are not only defined by variability and widespread transmission but also have extremely short lead times for adaptive management. All above unknown risks are the key focal points of decisions in a loosely coupled decision-making architecture. In a situation such as the COVID-19 pandemic, misleading surveillance data, such as false negative results in certain patients, may result in misclassification and increase the risk of viral propagation. In the early stage, multiple inconsistent judgments are unavoidable and frontline healthcare workers, while intuitively equipped with field experience, struggle to collect large amounts of data or information that cannot be presented in a structured manner in the short term (50); these limitations create a decision support dilemma, with incomplete information and data provided by at the grassroots level to higher-level but non-frontline decision makers (5). Addressing the information asymmetries between decision makers and frontline workers has long been a key area for improvement in the context of loosely coupled decision-making for pandemic planning and containment (6, 51).

2.5. Concluding comments

In summary, the prevention and process management systems developed in response to SARS and other types of risks can generate agile responses to born-known, unborn-known, and born-unknown risks; however, such systems have not functioned as expected in the face of SARS-CoV-2 and its mutated strains and variants. From the perspective of responsiveness to the unknown risks of a pandemic outbreak, the main reasons for these failure of system function can be found mainly in the structure of the network data and the design of process management.

To address this problem, this study proposes a research framework for managing change in prevention and control systems and processes for dealing with the unknown risks of pandemic outbreaks, as shown in Figure 1. The fundamental academic premise of this framework is that reacting to unknown risks enables organizations to avoid and manage changes in the unexpected environment and respond in an agile manner; accordingly, the organizations must be better prepared to cope with unknown threats (52, 53). Especially given the difficulty of predicting when unknown risks will occur and the trends and scope of impact of such risks, an agile response data structure and loosely coupled management process are effective ways to reduce information asymmetry between the decision-makers and frontline workers and represents a key direction for changes in emergency management (see Figure 2).

3. Method

This study is focused on changes in prevention technology and process management made to handle unborn-unknown risks. It is important to both propose changes to improve prevention and control and statically analyze the expected effects of the improvements. In particular, this study aims to, first, explore the root causes of epidemic prevention and control failures, second, base the analysis of these causes on targeted theoretical change models, and third, conduct a comparative analysis of the enhancements' effectiveness via simulation.

Case study methodology is a highly effective tool for investigating the underlying causes of epidemic prevention and control failures due to its ability to explore key "events" impacting these failures. It allows for probing the root reasons behind these failures, bearing in mind these causes are multifaceted, encompassing both subjective and objective elements. Moreover, given the realities of prevention and control failures in China, this method offers comprehensive insight with its rich, in-depth analyses.

Following this, the study capitalizes on simulation analyses to gage the efficacy of systemic improvements in epidemic prevention and control, and in process management. Epidemic prevention and control management represents a unique area in comparison to traditional business management. It pertains to a situational entity characterized by the complexity of diverse participant interactions and is the fruition of collective societal actions, either conscious or unconscious. Given this backdrop of multi-actor interactions and collective actions, simulation analyses render meticulously detailed portrayals of expected enhancement outcomes.

In summation, the amalgamation of simulation analysis and case study methodology is a fulsome research approach for this study. Firstly, it traces the failure of epidemic prevention and control to the dual dimensions of system and process management. Secondly, targeted remedial measures are identified for these failures, underscored by detailed explanations of the triangular validation system and loosely coupled process management system designs.

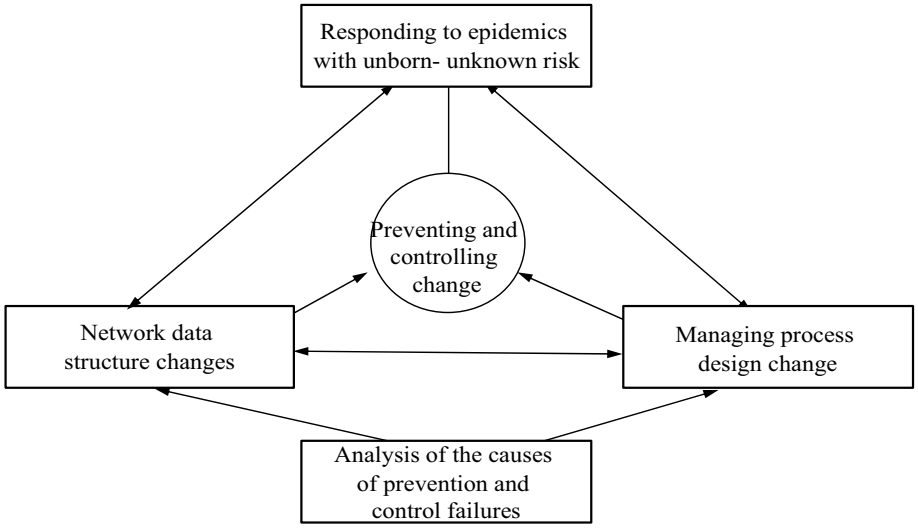

FIGURE 1
Proposed framework of a prevention system in response to an unknown risk (Source: authors' summary).

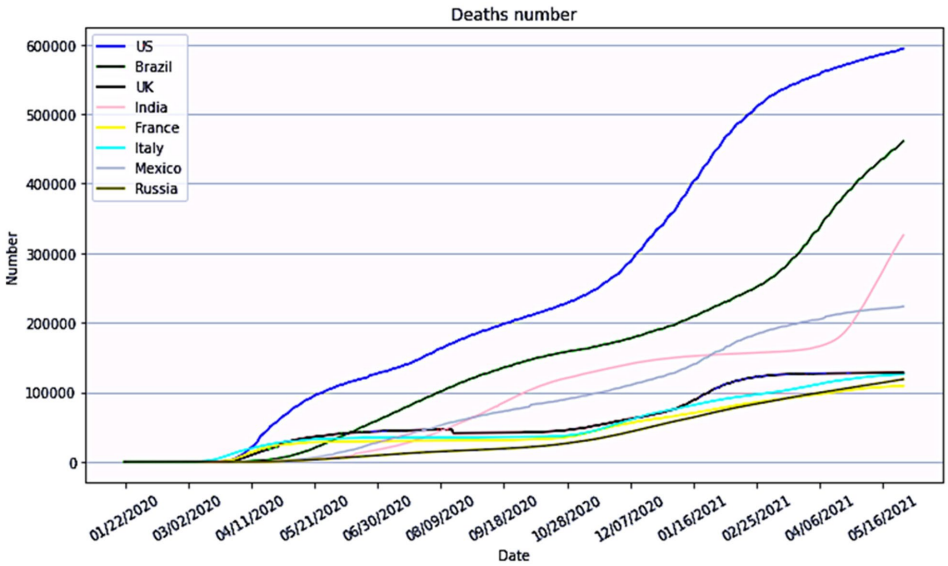

FIGURE 2
Global situation of unknown risk of major outbreaks of epidemic diseases (Source: World Health Organization).

Lastly, the applicability of proposed improvement strategies is examined through simulation analysis.

3.1. Case study

3.1.1. Sampling principles and data collection

H7N9 avian influenza A, MERS, EBHF, and COVID-19 were selected as the unborn-known, born-unknown, born-known risk, and unborn-unknown risks, respectively. The chosen diseases are characteristically the best representatives of the four risk types in terms of answering the research questions posed in this paper. First, there are similarities and differences between the four typical risks: EBHF and MERS are born risks, and H7N9 avian influenza A and COVID-19 are unborn risks; MERS and COVID-19 are unknown risks, while EBHF and H7N9 avian influenza A are known risks; accordingly, these four diseases fit well with the research questions in this paper (as shown in Figure 3). Second, the failures of prevention and control systems and process management, and the items causing these failures, differ between the four risk types, providing a basis for comparative analysis. For the purposes of this paper, "failure" refers to a failure of a system and its process management to complete measures such as monitoring, alerting, and reporting within a predetermined or prescribed time cycle in the face of an outbreak of epidemic disease.

Two hospitals in China were selected for interviews as part of this study, focusing on the four sample events illustrated in

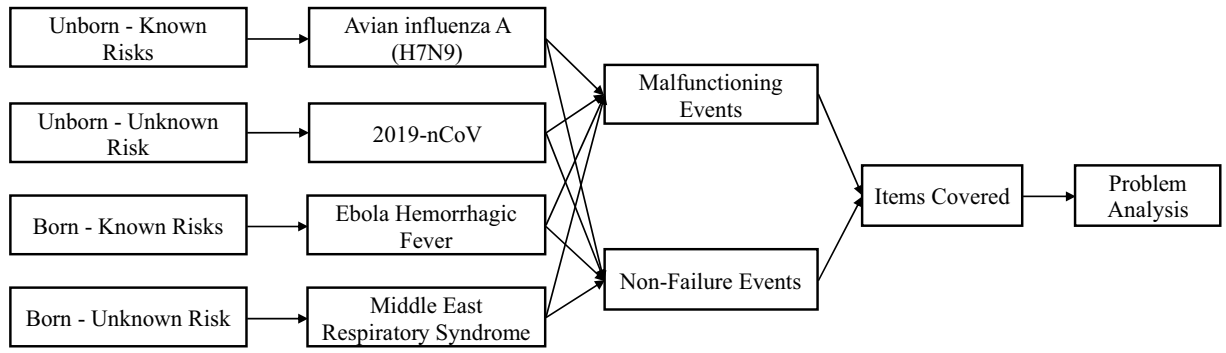

FIGURE 3
Four risk types and the key event analysis framework of this study (Source: authors' summary).

TABLE 1 Descriptive statistics of the interviewees in the two hospitals.

Local-level hospitals	Number of interviews	Numbers and affiliations of subjects		Length (hours)
Grade IIA hospital (α)	1	Infection department	4	2.17
		Other departments	7	3.89
		Prevention and Protection Section	2	0.85
		Management	5	2.44
Total	1	18		9.35
Grade IIIA hospital (β)	1	Infection department	5	3.04
		Other departments	6	3.52
		Prevention and Protection Section	3	1.49
		Management	5	2.71
Total	1	19		10.76
Total	2	37		20.11

Figure 3. Both hospitals had prior experience in the prevention and control of four infectious diseases, which aligned with the research objectives of our study. The interview outline was designed to address the research question of analyzing the causes of failure in direct reporting systems while incorporating the value realization theory of information systems. In-depth interviews were conducted at the two hospitals in January and June 2020; a total of 37 interviews spanning roughly 20 h were completed (see Table 1 for details). The interview procedure was standardized to ensure the data quality and usefulness. The interviews were held in mid-2020. Due to COVID-19 restrictions, most interviews were performed via telephone. To solicit comprehensive information, the interviews covered interviewees in various departments, including Infection department, other departments, prevention and protection section, and management. Each interview was performed by a single researcher, and the methodology was semi-structured, with questions based on the interview outline and follow-up questions based on the interviewees' responses and views to elicit more complete and in-depth information. Each interview was audio-recorded. To ensure the adequacy of the interview data and material, interview highlights were collated shortly after each interview, and the two researchers discussed the material internally to flag any inaccuracies, which would be improved and supplemented during follow-up interviews.

The research team sent a letter to each hospital prior to the interviews, which read as follows:

Dear XX Hospital,

Hello!

In order to gain a deeper understanding of the existing risk prevention and control system for major public health emergencies in China, and to develop a more reasonable and proactive response strategy, XXX has initiated and implemented personal interviews with hospitals as individual units.

These interviews will cover the responsibilities of your healthcare and management staff in the Prevention and Protection Section, Information Section, and Management Section, as well as the related workflow and personal responses to health incidents. If any of your personnel feel that certain interview questions infringe upon their privacy or are unwilling to answer, they can raise their concerns at any point during the interview. We will skip those questions and move on to the next. Additionally, your personnel have the right to request termination of the interview at any time. We fully understand and respect your decision in this regard.

Please be assured that your responses will be used solely for interview analysis by the researcher. Your organization and personal information will be treated with the utmost confidentiality, and all data will be handled anonymously to ensure the complete protection of your organization's privacy.

Thank you very much for your organization's participation!
Best regards,
XXX
The following is a concise outline of the interview:

1. In your opinion, how would you assess the preventive and control measures for COVID-19 at your facility? Are there any areas of improvement or challenges?
2. Has your facility established a system specifically designed to prevent and control outbreaks of infectious diseases similar to COVID-19? Could you provide a brief overview of how this system operates?
3. Does your facility have process management guidelines in place for the utilization of this system? If so, could you briefly describe these guidelines?
4. What are the responsibilities and actions expected from your department in terms of participating in the prevention and control of COVID-19? How do you currently fulfill these duties?
5. Do you believe that the rights and obligations of your department align effectively?
6. Have you encountered any situations where you were unable to carry out your duties or express your opinions regarding the prevention and control of COVID-19?
7. In your view, what measures do you believe should be taken in the future to enhance the prevention and control of infectious diseases like COVID-19?

In addition to telephone interviews, pertinent data were gathered from government agencies and relevant departments such as the Chinese Center for Disease Control; information on industry sales and business characteristics was collected from medical industry associations; and mass media data were collected from platforms such as social media and websites (see Table 2 and Supplementary Appendix for details). The inclusion of data from diverse sources increases the likelihood that the data will complement each another and can be cross-validated to increase the sample's validity (54). In summary, this study relied on telephone interviews and several data sources to assure the sufficiency, quality, and relevance of the data.

TABLE 2 Table of data sources and event types.

Data source	Event type	Number
National Health Commission and other relevant guidelines, policies, decrees, economic bulletins, statistical bulletins, etc.	Ebola hemorrhagic fever	31
	Middle East respiratory syndrome	14
	H7N9 avian influenza A	56
	COVID-19	63
Information from social media reports, websites, etc.	Ebola hemorrhagic fever	55
	Middle East respiratory syndrome	43
	H7N9 avian influenza A	79
	COVID-19	87
Information from industry associations on industry sales, business characteristics, trends, etc.	Ebola hemorrhagic fever	7
	Middle East respiratory syndrome	1
	H7N9 avian influenza A	13
	COVID-19	6
Public information, such as libraries and professional databases	Ebola hemorrhagic fever	1
	Middle East respiratory syndrome	3
	H7N9 avian influenza A	4
	COVID-19	7

3.1.2. Data coding and analysis

Data were coded and analyzed in three stages: reduction, presentation, and conclusion and validation. Data reduction entails the selection and simplification of qualitative textual information, the construction of coding tables, and the conversion of data to codes. Presentation entails a comparative analysis of the reduced data coding tables to establish initial connections between the theoretical findings and case data. Conclusion and validation entail the formulation of a theoretical framework supported by data, as well as the ideas for changes to prevention methods that arise from the framework.

The data were gathered into textual documents and classified using known case study procedures. The classified documents were inspected and tagged, and content analysis was used to analyze significant events. The key events were manually coded with the user's description and attribution of the key event. Back-to-back coding occurred separately, with team members collaborating prior to coding to establish the coding scheme, which included ideas, critical procedures, and the basic logic that connected concepts. The primary processes were as follows. First, the data were coded at a source level to identify the characteristics of the four risk types. Second, failure and non-failure events were subjected to collective coding using an information collation index to form a secondary library of entries on unknown risks, the inability to consult, system selection, system filling, too many layers, different calibers, data silos, early warning dissemination, social notification, resource allocation, the centralization of authority, single study and judgment, the independence of prevention and control, hierarchical reporting, and training practices. Third, the results of the secondary coding were coded at three levels according to the initial diagnosis, reporting system selection, system data reporting, early warning notification, organizational centralization, expert judgment, and organizational practice. These stages yielded the coding sources and data classification shown in Table 3.

This article follows the qualitative research approach of ensuring credibility and validity by analyzing the criteria from four perspectives to control and evaluate the data collection and analysis: construct validity, intrinsic validity, extrinsic validity, and reliability.

Correlational features were found to exist between risk classes, prevention and control systems, and process management reactions to failure events (or comparable descriptions of failures) during the early examination of the textual material. The largest proportion of failure events, 83.62%, was identified among COVID-19 events, and this value was much greater than those for the other three types of risk class events (see Table 4). The dysfunctional events alluded to in Table 4 are the statistical frequencies of event reactions spanning the entire pandemics and clearly demonstrate proclivities for dysfunctional and non-dysfunctional behavior. To establish independence, statistical analysis was applied to the primary event reported in secondary sources if two events were addressed in the same article.

TABLE 3 Table of coding sources and data classification.

Data sources	Data classification	Codification			
		Ebola hemorrhagic fever	H7N9 avian influenza A	Middle East respiratory syndrome	COVID-19
First-hand data	Information obtained through in-depth interviews	A1	B1	C1	D1
	Information obtained through informal interviews	A2	B2	C2	D2
Second-hand data	Relevant guidelines, policies, decrees, economic bulletins, and statistical bulletins of the National Health Council	a1	b1	c1	d1
	Information on sales, business characteristics, and industry trends published and maintained by industry associations	a2	b2	c2	d2
	Information obtained through social media reports and websites	a3	b3	c3	d3
	Public information obtained from local libraries, etc.	a4	b4	c4	d4

TABLE 4 Frequency of failure and non-failure responses to critical events for four types of risk.

	Failure events		Non-failure events		Total	
	Number	% of	Number	% of	Number	% of
Ebola hemorrhagic fever	11	10.48%	94	89.52%	105	100%
Middle East respiratory syndrome	7	10.29%	61	89.71%	68	100%
H7N9 avian influenza A	34	21.38%	125	80.50%	159	100%
COVID-19	229	83.62%	37	16.37%	266	100%

Due to the unusually high proportion of events describing failures, this paper separately codes the key event causes underlying the failures and non-failures of the direct reporting system and its prevention and control system in response to emergent risks for the COVID-19 pandemic, an unborn-unknown risk security event.

3.2. Simulation analysis

A determination of the value of prevention and control system modification necessitates a retrospective review of the degree to which the failure of such systems and process management systems to react to a pandemic disease outbreak would jeopardize public safety. In this study, the described situation is examined through a retrospective simulation utilizing available data on the Wuhan and national outbreaks in China, along with a basic sensitivity test. The focus is on modeling the effects of alterations in the direct reporting system and process management on the Hubei provincial and national outbreaks. It investigates how changes in the direct reporting system and processes impact the timing of closure measures and subsequently influence the progression and control of the outbreak.

Epidemics of infectious illnesses capable of interpersonal transmission have become increasingly dangerous due to the rapid expansion of transportation networks and substantial increases in the ease of travel. Since the first case of pneumonia with an unknown etiology was reported in Wuhan on December 8, 2019, the number of infections associated with the COVID-19 pandemic has increased at a breakneck pace. As of December 1, 2021, the total numbers of confirmed cases and related fatalities worldwide were 127,398 and 5,697, respectively, and cases had been confirmed in all 34 provinces, municipalities, and autonomous areas in China. In Hubei province (excepting the Shennongjia Forestry District), all 12 prefecture-level cities, one autonomous prefecture, and three county-level cities under provincial control have enacted city closure measures, as shown in Figure 4A. Figure 4B depicts the Chinese national data during the initial outbreak from January 15 to February 12, 2020, providing a visual representation of the widespread transmission of an epidemic outbreak.

The Susceptible Infectious Recovered Model (SIR) model is a foundational model for studying the pace, geographical extent, and pathways of transmission of an infectious illness, and variations such as the Susceptible Infectious Recovered Susceptible (SIRS) and Susceptible Exposed Infectious Recovered (SEIR) models have been developed. Given the latent nature of SARS-CoV-2 infection, the SEIR model provides a more accurate description than the other models (55). Therefore, the SEIR model was used in this study to investigate the spread of SARS-CoV-2. The simulations were implemented using MTALAB software.

The simulation analysis consists of three steps. Firstly, this study simulated the number of confirmed cases in Wuhan, taking into account the actual situation of the city (e.g., quarantine and lockdown policies), and conducted a coincident analysis with the real situation to confirm the feasibility and validity of this simulation model. Secondly, it applies a C-SEIR model that includes governmental quarantine measures (C) and simulates the possible confirmed cases by changing the implementation date of the city closure measures. A comparative analysis with retrospective results was conducted to show that the implementation of government quarantine measures can be accelerated by changing the direct reporting system of infectious diseases. Lastly, it carried out a simulation of the implementation of loosely coupled process management to assess the effectiveness of the method in improving the timeliness of the government response.

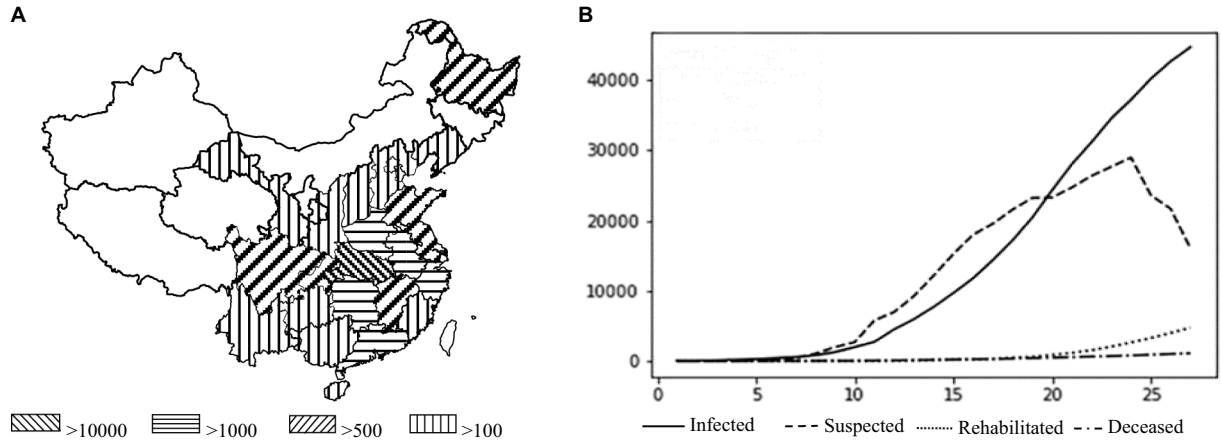

FIGURE 4
(A) Geographical distribution of the national epidemic (Source: the Chinese Center for Disease Control and Prevention). **(B)** Actual national outbreak data from January 15 to February 12, 2020 (Source: the Chinese Center for Disease Control and Prevention).

The settings of the SEIR model are as follows: S (Susceptible) represents a healthy person lacking immunocompetence and susceptible to infection after contact with an infected person; E (Exposed) refers to a person who has been in contact with an infected individual but is not yet infectious; I (Infectious) refers to a patient with an infectious condition that can transmit the disease to susceptible individuals, turning them into E or I; R (Recovered) represents a person who has recovered from the illness and is immune. In the case of a lifelong immune infectious disease, recovered individuals may not be re-transmitted to S, E, or I. In summary, susceptible individuals become exposed when they have effective contact with an infected person, exposed individuals become infected after an average incubation period, infected individuals can recover and become immune, and recovered individuals are immune for life and no longer susceptible.

In the first simulation, we selected 2% of the total household population in Wuhan, as the initial vulnerable population base. The initial values of each parameter in the model are as follows: the number of contacts of infected people (r) = 21; the probability of infection for susceptible individuals (b) = 0.048; the probability of illness for exposed individuals (a) = 0.13; the number of contacts for exposed individuals (r^2) = 21; the transmission probability for exposed individuals (b^2) = 0.048; recovery probability (y) = 0.04; time (T) = i [for i in the range (0, 160)]. The transmission period began on December 30, 2019, when Li Wenliang and other physicians published seven verified cases on social media, leading to Wuhan's implementation of a city closure on January 23. We calculated the number of people in each of the four groups on each day based on an iterative formula.

In the second simulation, we considered the effect of government measure C by adding the parameters: the newly diagnosed number of people with an exponential growth rate ($r0$) of 0.16 and the basic contagion number (R0) of 3.1. The highest number of confirmed cases in Wuhan was anticipated to reach 53,768, peaking on the 39th day after the emergence of SARS-CoV-2 when considering the actual scenario of city closure and quarantine. The change in the number of diagnosed people nationwide was simulated, assuming T is two days ahead and two days behind the actual date of the city closure. It's important to note that the primary objective of this article is to establish an environment for analyzing the focal issue, rather than assessing the precision of this prediction. Figure 4 presents the actual situations of geographic distribution of the epidemic and the numbers of infected and recovered cases in China.

In the third simulation, we considered the impact of process management and the timeliness of government response on the number of confirmed cases. More details are provided in Section 5.4.

4. Result analysis

4.1. Result of simulation analysis

The major objective of a control system is to allow a quick reaction through real-time epidemic monitoring, transmission, and analysis, with the goal of treating patients with untreated or primary illness rather than those with severe illness. The quarantine measures implemented in Wuhan and numerous other locations during the COVID-19 pandemic were shown to effectively "treat the serious illness." We applied the C-SEIR model, which includes government quarantine measures (C), and stimulated the national COVID-19 situation in China (e.g., Figure 5A). The basic reproducibility coefficient (R0) of SARS-CoV-2 was found to vary over time and is depicted in Figure 5A as having a realistic fit to the SARS-CoV-2 transmission curve. In sensitivity experiments, the date of implementation of the city closure measures was changed. No significant linear association was found between an earlier or later closure and the transmission inflection point; however, this analysis did reveal a significant correlation of the closure date with the number of confirmed cases. As seen in Figure 5B, advancing the closure by 2 days was associated with an estimated reduction in the cumulative number of infections by nearly a third, while delaying it by another 2 days would have doubled the cumulative number of infections. As posited by Wu et al. (56) and others, the number of infections was estimated to theoretically exceed 200,000 (R0 = 3.1) if effective prevention and control measures had not been taken during the early stages of the outbreak.

The above retrospective simulations of measures for the treatment of serious illness, such as city closures, at various points in time

demonstrate that the introduction of these measures at various points had significant effects on the number of infections and the control of infectious disease spread. However, the risks to life, high socioeconomic expenses, and reduced quality of life of the population yielded two results that fell short of the management systems' goals. Thus, this paper addresses the question of how to avoid the scenario depicted in Figure 4 and mitigate the severity of the scenario depicted in Figure 5 by transforming the prevention and control system into a multi-stage hierarchical warning and response mechanism with different risk control actions at various points in time. Thus, Figures 4, 5 serve as the baseline for an ongoing study that includes a comparative static analysis of the improvement options.

4.2. Results of case study

The analysis of case data in this paper reveals two major reasons for risk prevention and control failures. First, when the prevention and control system was applied, the data were primarily based on manual declarations and a lack of risk communication functions. Second, in process management, the organizational practices were null and void, the decision-makers were disconnected from the COVID-19 epidemic data, and epidemiology was over-centralized.

4.2.1. Analysis of the key issues in the application of the prevention system

4.2.1.1. Heavy reliance of data on manual reporting

As previously stated, the existing prevention and control system is managed locally and hierarchically, and the response model is based on the comprehensive entry of instances of danger by local health facilities or CDCs, as stated by an employee of a Shanghai hospital's Infection Control Department (ICD): "Regardless of whatever department's physicians detect an epidemic illness, they must complete an epidemic disease report card and submit it to the hospital's Prevention and Protection Department, which will forward it to the appropriate authorities. The current national epidemic illness report card is based on ICD-10 diagnostic codes and contains information on 39 identified epidemic diseases. Most current hospitals and local disease control centers transmit fundamental data through manual reporting, while some hospitals link to the epidemic illness system via an Application Programming Interface (API) interface. Other data sources and functionalities only serve to supplement analyses or aid decisions and cannot serve as a trigger for illness reporting. Completion by individuals is subject to opportunistic motivations such as under-reporting by the person making the entry and cannot exclude subjective bias (57). Clearly, the data structure, which is dependent on individual completion, does not enable the system to respond agilely to unforeseen risk shocks.

Data standardization is required for automated reporting and analysis to be successful. Standardization at the data level refers to the use of uniform statistical techniques, procedures, and calibrations across data-collecting entities (58) to guarantee the generalizability of data and the efficacy of centralized analysis. In this study, the analysis of significant events revealed that variations in data quality and statistical content occurred across various healthcare facilities in the system's reporting process. Using the COVID-19 prevention and control process as an example, small healthcare facilities and local communities concentrated on screening potential patients and identifying key observation targets when implementing the system and collected only personal information, whereas fever clinics required detailed symptoms to establish suspicion about individual

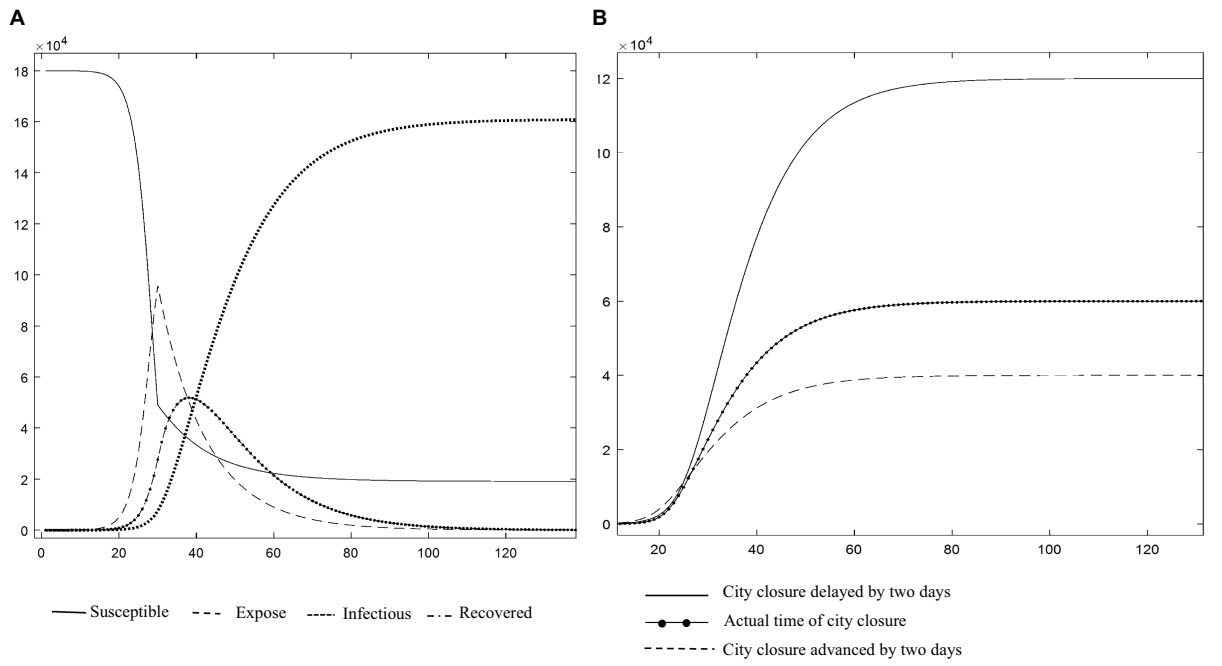

FIGURE 5
(A) Changes in the infection rate curves for China (Source: authors' calculations). **(B)** Description of the impact of implementing city closure measures at different points from January 30 to February 7, 2020 (Source: authors' calculations).

cases. These differences in the purpose and scope of data gathering between units resulted in a lack of data sharing.

"Consistency in the statistical caliber, the quickness with which an unknown illness may get a correct diagnosis, and the ease with which patients can obtain [a diagnosis] all have a significant influence on statistics. And COVID-19 fails to address this issue." Data standardization clearly has a direct influence on the prevention and control of an epidemic outbreak. For example, the COVID-19 outbreak prevention and control system included a "pneumonia self-reporting" feature; however, missing unique personal identifiers, such as ID numbers, resulted in the passive redundancy of a considerable quantity of data due to its rarity. As another example, a deficiency in the collection of crucial epidemiological history data adds to the difficulty of diagnosing and treating individual patients. Obviously, in medical diagnostics, the availability of vast volumes of unstructured data precludes the instant exploitation of the value of these data (6). A typical example from existing control systems is the direct reporting of pneumonia unspecified (PUE), which relies on both symptom descriptions entered in natural language and standard indicators such as the body temperature and white blood cell and lymphocyte counts, which require manual processing before being integrated into the database and thereby reduce the amount of data collected. Such non-standard language must be manually processed prior to integration into the database, thus lowering the data use efficiency.

4.2.1.2. Lack of a risk communication function

The massive spread of an unexpected epidemic illness not only jeopardizes people's health but also creates widespread fear throughout a society. Information on widespread diseases may be promptly transmitted via borderless information exchange routes on the Internet, such as between official media outlets, self-published media outlets, and the public.

However, the current prevention and control system is a data-driven information system that connects medical institutions with the CDC; it lacks a response function for risk communication to the general public. Official information on COVID prevention and control has frequently been communicated through press conferences or public notifications issued by the Health and Welfare Commission, whereas interactive communications between public entities regarding the COVID-19 risks in different regions, population flow tracking, personal health guidance, hotspot tracking, real information and disinformation, and other related topics have primarily been transmitted by Ding Xiang Doctor, Baidu, and other Internet platforms. As a result, there has been a dearth of broad information exchange between the government and the people, as exemplified by the following: "Article 18 of the Communicable Disease Prevention and Control Law specifies the CDC's detailed responsibilities but does not specify whether the CDC has the authority to release information about epidemics as opposed to direct disposal," and "I, as a local government, do not have the authority to communicate information about epidemics." The legislation and remarks from government officials are ambiguous and indicate a dearth of government services tasked with informing the public about hazards.

A situation wherein the public does not have adequate access to official information and alternative channels (e.g., self-published media) continue to publish "false news" or "rumors" inevitably will result in a great deal of unconscious behavior among the public, making it more difficult to prevent and control risks such as mass shootings, the exodus of inhabitants from areas like Wuhan, and the frenzy over mask purchases. We proceeded to host the dinner this year as we deemed the epidemic's propagation to be restricted to person-to-person, and so did not have adequate notice. This vividly shows how the absence of risk communication channels between the government and the public may contribute to the escalation of an unexpected epidemic crisis and result in additional harmful outbreaks. Accordingly, this article argues that creating effective risk communication channels between the government and the public is crucial for coping with unanticipated risk shocks.

Table 5 summarizes the textual analysis and provides typical instances of referenced evidence of failures in response to risk shocks at the level of prevention and control systems.

Table 5 and the preceding analysis and findings demonstrate that non-automatic data generation and the non-standardized formation of data structures at multiple levels have made it difficult for the existing prevention and control system to achieve a true, timely, accurate, and complete presentation of data during the COVID-19 risk prevention and control process, and have made it even more difficult to share and apply information efficiently. This disjointed and uneven approach to data gathering, sharing, and processing has impeded the prevention and control process, making it harder to react to unforeseeable risk shocks. Simultaneously, this data structure has made it more difficult for the prevention and control system to serve as a platform for critical risk communication to the public, hence lowering the impact of government information sources on society. Thus, development efforts should be directed toward making the data structure systematically responsive to unforeseen risk shocks and allowing continuous and high-frequency risk communication between the government and the public after a sudden pandemic outbreak.

4.2.2. Analyses of critical concerns in process management

4.2.2.1. Process practices are deficient

A prevention system connects epidemic disease surveillance efforts with informational exchanges between health and disease control administrations at the commune, district, municipal, provincial, and national levels, enabling an agile systemic patterned response to structured data on born-known or unborn-known risks. Due to the temporal latency associated with data propagation, nimble model responses may also be developed. However, for unborn-unknown epidemic diseases, the reporting process of the prevention and control system is highly susceptible to routine formality, as expressed by a CDC system physician during an interview: "It has not happened [in epidemic diseases] in so many years that medical institutions have generally not taken it selves." Due to such evolution and solidification of practices via repetition, epidemic disease underreporting, late reporting, misreporting, and underreporting continue to occur even when the prevention and control system is equipped with technical functions such as data storage, structured form entry, data analysis, and standardized report presentation (30).

Fearing that the incorrect assessment of an unborn-unknown risk may result in overreaction and negative consequences, such as a social panic and economic decline, local hospitals and even CDCs tend to take the most cautious approach possible by avoiding responsibility as much as possible and adhering to the traditional practice of reporting

TABLE 5 Classification of prevention and control system failure events and examples of evidence.

Dimension	Main constructs	Coding entries	Examples of evidence (typical citation)
Choose and complete the reporting system (45)	System selection (44)	12	"Direct reporting of PUEs is one of the CDC's tasks and is activated by specific situations." (d3) "Prior to January 20, new coronavirus pneumonia was not recognized as a 'legal infectious illness' and hence could not be utilized for the national Web-based prevention and control direct reporting system's 2-h direct reporting window." (d3) "Normally, we avoid the direct reporting system, especially if we are unsure whether or not it is an epidemic, and the system will not allow us to enter the PUE." (D1)
	System reports (23)		"The direct reporting method is complicated, and many physicians are unfamiliar with how to use it." (d3) "If you are unable to use the direct reporting method, you will be sent to the hospital's prevention and protection department." (D1) "Although I'm in the prevention and protection section, I'm actually an administrator, and it's especially difficult to fill in epidemics that are not in the system." (D1) "The communication of suspected patients is still done by telephone to inform the health committee and the CDC." (d3)
System data reporting (53)	Excessive layers (17)	21	"There are many levels of data reporting, including national, provincial, municipal, and district, and there is a procedure for data reporting that begins with the agency responsible for epidemic disease surveys at the district level." (d3)
	Numerous calibers (31)		"Epidemiological statistics are also highly reliant on two critical variables: the statistical quality and the diagnostic technique. The consistency of statistical calibration, the capacity to rapidly identify the correct diagnosis for an unknown condition, and the access of patients to a prompt diagnosis may all have a significant effect on statistics. This is where the reaction to COVID-19 fell short." (d3)
	Silos of data (14)		"The majority of hospitals no longer communicate patient data in a timely and synchronized manner. This results in hospitals grossly underestimating the devastation and effect of unknown diseases when they strike, and it is detrimental to bottom-up oversight of decision-making and growth within organizations." (d3)
Early warning bulletin (54)	Early warning issuance (31)	22	"This year's continuance of the Vanguard Banquet was based on our earlier assessment that the spread of this virus was restricted to human-to-human transmission, implying that there was inadequate notice of the incident." (d3)
	Social bulletin (46)		"While Article 18 of the Communicable Disease Control Law delineates the CDC's precise tasks, it does not provide the CDC the authority to release information on epidemic illnesses with direct disposal authority." (d4)
	Resource allocation (19)		"Patients must be diagnosed using nucleic acid testing, and the shortage of nucleic acid testing reagents in the previous period resulted in some delays in risk prevention and management." (d3)

The response frequencies in the "Main constructs" column are shown in brackets.

at each level, centralized aggregation, and centralized research. As one clinician at Wuhan Zhong Nan Hospital stated, "Previously, clinicians reported unexplained pneumonia to the director, who then reported to the director, who then reported upward." In other words, a hospital would use the system to report at the municipal or provincial level rather than the national level.

Additionally, a clinical judgment manifests as a diagnosis requiring further research, which the computer system cannot identify immediately and hence cannot report directly. Taken together, the above information shows that the current process management system is deficient in terms of effective organizational practices that enable rapid information exchange and efficient decision support in response to unforeseeable risk shocks. Furthermore, the existing division of authority and responsibility, organizational practices, and other factors have precluded the effective application of information systems.

4.2.2.2. Disconnected frontline decision-makers

Theoretically, given the widespread effects of disease outbreaks with unknown risks, the process management system's local response sensitivity is crucial to the success of early prevention and control efforts. However, the development of local early response sensitivity in process management systems has raised concerns about procedural legitimacy, including the rights to make decisions about outbreak epidemics, to diagnose and characterize diseases, and to disseminate information.

Currently, only the national CDC has the authority to diagnose and characterize illnesses. During the early stage of the COVID-19 pandemic, clinical detection of the causative factors (e.g., mycoplasma, bacteria, viruses) using imaging in combination with conventional methods, such as viral nucleic acid testing of blood samples, during diagnosis and treatment had not yet been determined; accordingly, process management required centralized reporting to local CDCs

and health committees. At the micro level, while the causative agents of epidemic outbreaks with unknown risks exhibit characteristics that distinguish them from previously identified causative agents, information about these agents' potential for harm, transmission routes, viral characteristics, and effective treatments is uncertain, thus hindering prevention and control systems' ability to develop plans. For instance, the nucleic acid test kit for SARS-CoV-2 was not available until 76 days after the first confirmed case. In another example, SARS-CoV-2 was not discovered as the seventh to infect people until it had already caused a substantial epidemic.

Simultaneously, standardized epidemic reporting using deterministic indicators within the prevention and control system might create uncertainty for non-frontline healthcare staff reacting to an outbreak (59). This uncertainty, combined with the fact that the incubation time for SARS-CoV-2 varies by individual, caused the first clustering of COVID-19 outbreaks to be poorly defined, which complicated centralized reporting and decision-making. For instance, the first universally generalized history of exposure to South China seafood markets in the context of unknown epidemic illnesses associated with feverish symptoms and positive viral testing revealed a huge number of hidden dangers during later prevention and management efforts. The previously discussed procedural legality concerns have led departments such as the Health and Wellness Commission to passively choose a strategy wherein decisions are deferred in favor of conducting research. As a staff member responsible for epidemic disease reporting card review at the Wuhan Jiang Han District CDC stated in an interview, "While the reporting of sudden epidemic diseases is bottom-up, these new diseases must first be reported." Considering the rapid and widespread transmission of an unexpected epidemic disease, this reaction technique objectively has become a component of the rapid amplification of unborn-unknown risks.

4.2.2.3. High concentration of information power

Currently, only the government health agency can provide information about unexpected epidemic illnesses. According to the Prevention and Control of Infectious Diseases Law, the Emergency Response to Public Health Emergencies Regulations, and the Ministry of Health's Information Release Program on Statutory Infectious Diseases and Public Health Emergencies, the State Council's health administrative department is responsible for informing the public when an infectious disease outbreak or epidemic occurs. In response, a lawyer from the Beijing Jing Law Firm provided the following representative quote: "The current laws and regulations place an unreasonable burden on the publication of information on sudden epidemic diseases, which, combined with the lengthy and inefficient pre-reporting procedure, tends to delay information publication." These statements imply that the concentration of all power for distributing information about a breakout epidemic within government health departments has made it impossible to react swiftly to the effects of endogenous unknown risks.

Table 6 summarizes typical instances of reported data on the management of risk processes that have resulted in failures to prevent and control unborn-unknown risks.

From Table 6 and the study findings, it can be inferred that the centralization of the authority to diagnose and characterize illness and distribute information within the CDC and government health departments has resulted in a closely integrated and centralized decision-making system. Although a benefit of this decision-making structure is that the components of the prevention and control system are tightly coupled and work cooperatively (60), the drawback is that the sensitivity of local frontline healthcare professionals is diminished. Although the intuitive judgments made by these professionals are not based on substantial research, they serve as a locally sensitive early warning method for the control system. Thus, the path of changes in management should be determined by the ability to integrate democratic and centralized decision-making, and by the ability to combine consistent action in the prevention and control system with improved sensitivity in local responses.

5. Improvements and verification

Based on the analysis and findings presented above, a conclusion can be drawn that increasing the local sensitivity of data, establishing risk communication channels, implementing adaptive process management changes, and establishing a loosely coupled decision-making structure are three areas for improvement intended to help the prevention and control system cope with unborn-unknown risk shocks.

5.1. Triangulated validated risk communication system

As mentioned previously, the absence of a response function for risk communication in the prevention and control system means that the government frequently has lacked sufficient information sources for studying and making decisions about sudden major epidemics with unknown risks; in addition, the public often struggles to obtain effective information protection, which frequently has resulted in the escalation of negative situations. The purpose of change is to expand the application models of existing prevention and control systems to address the lack of existing prevention and control systems and risk communication functions in the population. Such expansion should include the development of risk warning models, risk control models, and risk communication models. In the event of a large-scale epidemic involving unknown risks, the prevention and control system should shift from management to risk communication mode by, for example, providing a transparent information sharing channel between medical institutions and the public to avoid widespread panic caused by rumors and speculation, or by providing public information for guidance and official actions. In another example, online psychological assistance could be provided to individuals to prepare them for early warnings and changes due to unexpected risk shocks.

This application is referred to as a triangulated risk communication system in this study. This triangulated risk communication paradigm has been verified and can differentiate between an epidemic alert, warning, and reaction. An alert is a source of early warning information, and alerts and reactions are connected but not synonymous. Specifically, big data platforms and official media outlets serve separately as "social whistle blowers," while the prevention and control system serves as an "internal whistle blower," thus constituting a triangulated verification system. Accordingly, the prevention and control system can more effectively communicate the risk of a major epidemic and provide sufficient information to guide

TABLE 6 Examples of evidence of prevention system failure at the process management level.

Dimension	Main constructs	Coding entries	Examples of evidence (typical citation)
Organizational centralization (37)	Concentration of power (37)	31	"Due to the complexity of characterizing big epidemic outbreaks, after the data model has identified the infectious virus, openness and open access are often not in the hands of local governments, and choices are made by the National Center for Disease Control (NCDC). Following the receipt of the data, the NCDC is required to send specialists to verify and validate the data. The whole process may be significantly delayed, which is detrimental to the prompt disclosure, prevention, and control of hazardous new major epidemic disease strains." (d3)
Expert assertion (33)	Single study (27)	32	"Detection of a sudden significant epidemic, of course, necessitates waiting for a professional consultation, but that is much too difficult at present; everyone is busy, and it is still mostly up to one expert." (D1)
	Immunization independence (14)		"Our outbreak of major epidemic disease prevention and control is all about minding our own business; how can we possibly care about others? It's impossible to handle difficulties with multi-sectoral communication; there's a chasm between the operational and administrative sectors." (D1)
Organizational practices (21)	Layers of reporting (19)	33	"The decision-making behavior and administrative procedures necessary for several levels of approval are expensive to society, time-consuming, and may not follow the normal pattern of abrupt significant epidemic development." (d3) "Without substantial external action, a newly recognized breakout of a severe epidemic, such as (novel coronavirus pneumonia), may only increase in lockstep with the threat's severity." (3d)
	Training practices (21)		"The surveillance reporting process is too complicated, necessitating cascading, sample surveillance, and so on, and the pressure to report and process is intense. Additionally, this system was supposed to monitor SARS and human avian influenza, which have not occurred (sudden major pandemic disease) in so many years that medical institutions have generally ignored them, even though the CDC also conducts annual training for subordinate CDC staff and hospitals, which is almost always a walk in the park." (d3)

the government's response decisions, while considering multiple objectives such as political, economic, and diplomatic considerations (see Figure 6).

Unconfirmed news is widely disseminated via channels such as social media platforms, in which the truth is likely to be distorted, leading to unconscious group behavior (26). For example, misinformation or true/false seeking information about a sudden major epidemic disease garners 41% public attention and 35% retweets (26). Figure 6 disinformation drew considerable attention. The validation of risk misinformation is classified in Figure 6 as risk over-prompting validation, risk under-prompting validation, and unprompted risk validation. The purpose of over-prompting verification is to ensure that the stated risk is accurate and not exaggerated. The purpose of under-prompting verification is to ensure that the stated risk is accurate and that the degree of risk is fully described in accordance with the facts. The purpose of unprompted verification is to ensure that the stated risk is accurate and not exaggerated. In terms of rumor detection and insight, artificial intelligence (AI) can be used to efficiently and rapidly evaluate whether a piece of material is a headline, incorrect information, or rumor by aggregating and analyzing data on sources, sensitive words, and authors (61, 62). Throughout the COVID-19 outbreak, Tencent Medical Dictionary and Ding Xiang Yuan used data mining and sentiment analysis to monitor and disprove hot rumors, providing over 100 million individuals with expert responses and official facts. AI-based risk warning verification may substantially enhance verification speeds and accuracy. As AI applications gain traction and as prevention and control systems, media systems, and social big data platforms develop AI models for mutual information verification, this triangular verification mechanism is expected to yield a systematic and agile mode of response to the impacts of unborn-unknown risks.

Figure 6 implies that all subjects communicated via the triangular risk alert system can be independently self-validated, followed by triangular validation of the required information and, eventually, a risk warning created via full analysis. During the self-validation stage, the initial information source is identified, and the publisher's qualifications are determined by analyzing the user's professional field, registration time, activity pattern, and other portraits; the credibility of the information is calculated by summing the proportions of people with various attitudes, their respective levels of credibility, and other information. Next, all information sources within the subject are analyzed. After self-validation is complete, the information moves into the triangular validation stage, where the "social whistleblower" and "internal whistleblower" are assigned to distinct risk alert topics, and all risk alerts are subject to a risk warning by the prevention and control system. After completing the triangulation of danger alarms, the system executes the associated risk alert. Thus, the triangulation process shown in Figure 6 will enhance the CDC's ability to issue early warnings about major epidemics while providing the government with strong information support to minimize uncertainty in making predictions and increase the sensitivity of reactions to major epidemics.

5.2. Change of data structure in the prevention system

Although a triangulation verification system can address the issue of risk communication, the application of the prevention and control system relies heavily on manual declarations, which is substantially impeded by the system's lack of risk communication functionality. With the application of digital technologies such as 5G networks, big data, and AI, the prevention and control system's data structure can

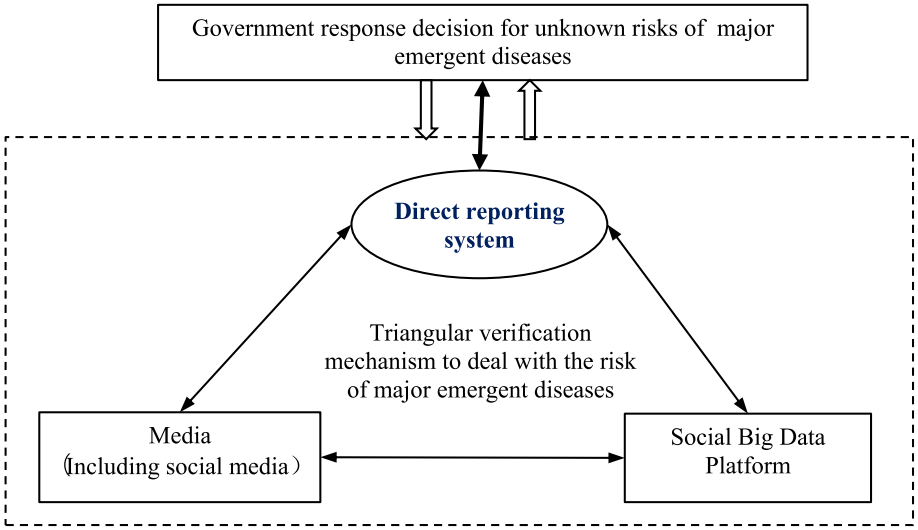

FIGURE 6
Triangulated validated risk communication system (Source: authors' summary).

be further optimized to improve information monitoring, data exchange, and multi-dimensional analysis capabilities in response to unforeseeable risk shocks. While it remains impossible to predict with certainty when and where a major epidemic disease with unborn-unknown risks will occur, it is possible to remove some of the uncertainties and transform them into manageable risks during the process of bearing risk shocks, thereby transforming passivity into activity, by increasing the local sensitivity of data and establishing an agile, big data- and AI-powered system for the initial transmission paths and regional unknown risks. As such, the purpose of this study is to change the prevention and control system's core automated data gathering function to a risk communication function that uses AI and big data analysis technologies.

One path forward may involve connecting hospital information systems (HIS) above the township level to the direct reporting system to achieve the underlying data; this would include the automatic collection, exchange, and storage of basic data such as test results, electronic medical records, and clinicians' diagnostic reports of suspected patients in epidemic disease departments. AI technologies then can extract the data for full analysis, detect aberrant values, and prompt the reporting of possible dangers, therefore displacing the data production system that depends heavily on spontaneous reporting by physicians before triggering alarms. Changes in data sharing between HIS and direct reporting systems may begin at third-tier hospitals in provincial capitals, followed by progressive expansion to medical institutions at all levels, including townships and counties. Simultaneously, healthcare personnel generate a considerable quantity of unstructured data when diagnosing cases of infectious illness, and thus it is difficult to totally remove the use of manual entry. In this regard, the direction of change involves introducing blockchain technology based on big data to establish a private chain within China's disease control system, connect each hospital system to a blockchain node, and synchronously enter personal reporting information, HIS, electronic medical records, test reports, and other contents into the blockchain.

As a second path forward, we advocate for adjusting data standardization in three areas of the prevention and control system: method standardization, process standardization, and caliber standardization. Method standardization involves creating and implementing a set of uniform report card formats across all healthcare institutions to standardize and unify the electronic medical record paradigm used by each hospital and thus improve data structuring. Extracting more commonalities from sudden major epidemics, incorporating these into a unified questioning framework, and using techniques such as deep learning in AI to improve the efficiency of natural language processing could reduce the cost of data collection. Process standardization can reduce errors in the underlying data and the impacts of complex environments on an organization (50). For example, variations in examination procedures and the questioning of suspected patients may introduce systematic bias at the lowest levels of the underlying data process. By using structured big data to construct data calibrations, we can ensure that data from disparate sources can be legitimately included in an aggregate analysis.

5.3. Creation of loosely coupled adaptive process management

The objective of a change in adaptive process management is to ensure an organic combination of democracy and centralization of research and decision-making authority, as well as the combination of consistent action by the prevention and control system and improved sensitivity of local responses. Adaptive process management, i.e., changes in loosely coupled process management, can be used to deal with the high level of uncertainty associated with the initial phase of an outbreak of an unknown major epidemic disease and to address how the direct reporting system's response to unknown risks evolves into organizational inertia (see Figure 7).

Figure 6 illustrates a sample architecture of loosely coupled processes based on tandem IT, with an emphasis on management that fosters complementarity between collective and individual decision

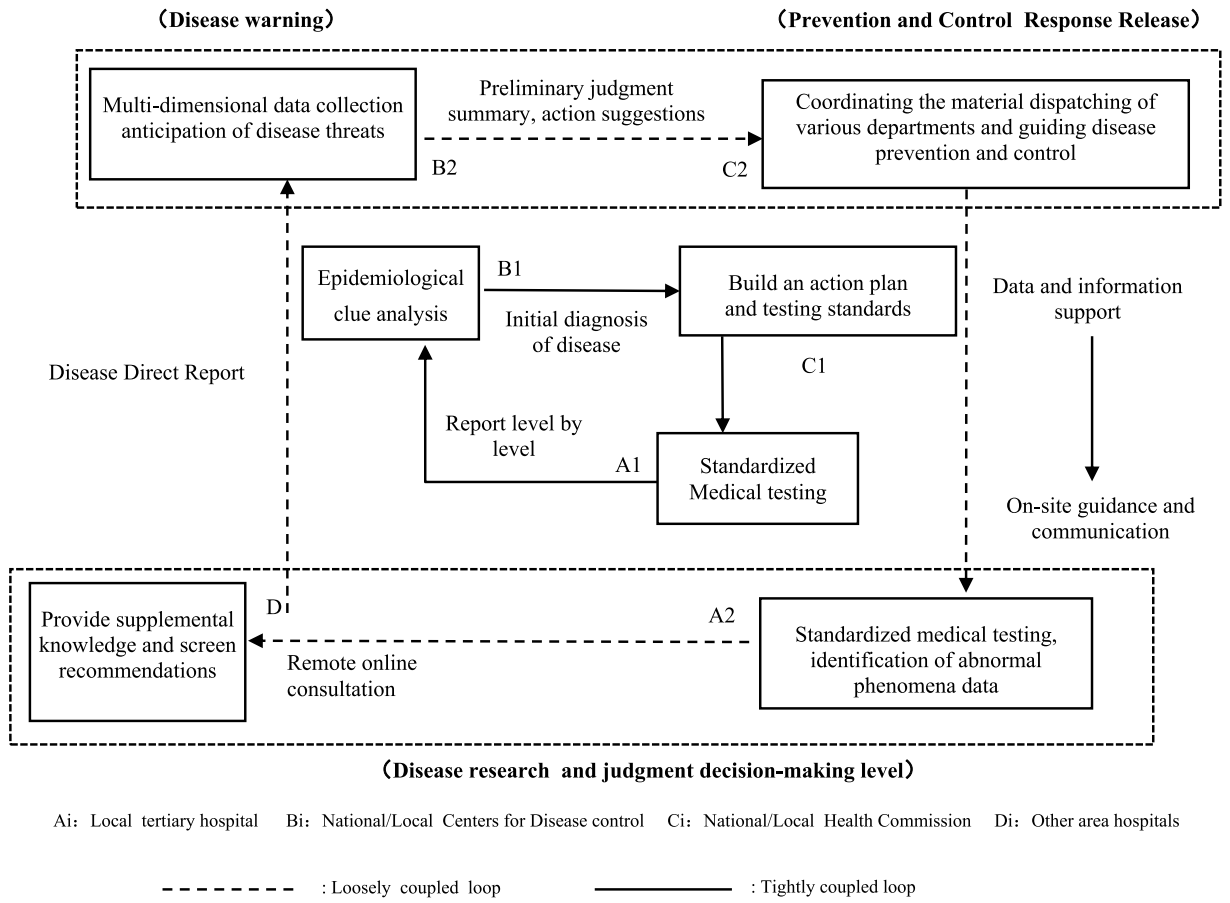

FIGURE 7
Main architecture of loosely coupled processes for adaptive process management change (Source: authors' summary).

making, thereby establishing an organic union of democracy and centralization in the study and analysis of unborn-unknown risks and associated decision-making. The inner cycle in Figure 7 represents the operational flow of a tightly integrated prevention and control system during risk responses and the generation of synergies and responses to born or unborn known hazards and born-unknown risk shocks. Synergies and responses are established when reacting to unborn-unknown risks that have not yet been created by compensating for the absence of a tightly connected inner circle with a loosely coupled outside cycle composed of A2–B2–C2–D based on tandem IT, as shown in Figure 7. The inner and outer cycles of the main process during the adaptive process management of the prevention and control system aim to avoid the rigidity of processes and practices associated with a single coupling pattern within the system, as well as degradation of the system caused by decentralization (63), by combining consistency of action within the prevention and control system with increased sensitivity to local responses.

Process optimization can be viewed through three lenses to produce complementary communal and individual decision-making in the outer circle, thus establishing the democratic centralization of research, analysis, and decision-making regarding unborn-unknown risks. First, epidemiological judgment is completed via remote consultations with representative medical institutions and CDCs in the region to avoid bias in judgments and analyses caused by regional differences in experience and the limitations of individuals' knowledge (64). If irreconcilable differences in the assessment of the epidemic arise, other healthcare providers may be asked to conduct studies and analyses, but the final judgment of the local healthcare provider is retained. Simultaneously, information on individual cases is shared transparently in real time via the direct reporting system between local tertiary hospitals and the National Health Commission, as directed by authorized management. Second, frontline healthcare workers typically collect a large amount of information that is difficult to present in a structured manner in the short term, and medical diagnostic capacity is limited at the township level. Third, to prevent local governments from engaging in opportunistic behavior, such as the selective reporting or whitewashing of material for various reasons, it is essential to evaluate the legislation governing public health crises. The Emergency Response to Public Health Emergencies Regulations and the Measures for the Administration of Information Reporting on Public Health Emergencies and Infectious Diseases have optimized information publication by, for example, granting the authority to publish information on epidemic disease warnings (e.g., the Meteorological Bureau's disaster warnings) to the CDC in collaboration with the government and the Health and Welfare Commission. Thus, the government has retained the competency in multi-objective decision-making needed to face unknown risks, while the CDC has acquired the loosely linked reaction capabilities necessary to cope with unknown risk shocks.

Thus, four possible outcomes can be predicted from the combination of CDC warnings and the government's response to a major unanticipated risk: accurate CDC warning and timely government response, accurate CDC warning and untimely government response, false CDC alarm and timely government response, and false CDC alarm and untimely government response. Ideally, the CDC would issue an accurate warning and the government would respond promptly; in the second-best scenario, the CDC would issue a false alarm and the government would respond prematurely. The other two eventualities must be assessed on a case-by-case basis. As with weather predictions, which are not always accurate or timely, precise pandemic warnings and false alarms coexist in this loosely coupled management process. Adaptive process management strategies for dealing with unknown risk shocks also include modifying how epidemic warnings are perceived and building a loosely connected system for managing public opinion regarding an epidemic.

5.4. Simulation analysis of changes in prevention system

Will the three modifications outlined above result in improvements? In the following sections, data on the COVID-19 pandemic presented in Figures 4, 5 are used as a baseline for simulating the implementation of improvement strategies to assess the effectiveness of measures intended to change the prevention and control of unborn-unknown risks with respect to response timeliness. The simulations are based on the SEIR model, which approximates reality by considering the asymptomatic post-infection latency period (i.e., exposure) in the population. To address the effect of unborn-unknown hazards, a multi-stage, hierarchical system of warnings and government reactions is established according to the separation of information warnings and the prevention and control response distribution authority as suggested in the preceding management change approach. First, based on the R0 deduced by Cole et al. (18), Wu et al. (56) and others, the R0 for a new epidemic is assumed to be unknown information during the early period of an unknown risk shock. Second, based on the studies of Wu et al. (56) and Cai et al. (57) additional parameters such as the number of initial infections, contacts of infected people within a population, transmission Both risk communications from the CDC and the government's reactions, such as the dissemination of warning materials and travel prohibitions, can significantly reduce the frequency of interpersonal exposure in the community.

Figure 8A illustrates the effect on epidemic illness transmission of a travel restriction that is issued or adopted at time $T = 7$, according to the SEIR model. In the figure, the vertical coordinates indicate the numbers of infected patients. The tighter the restrictions on human contact, the more effective the overall outbreak control, assuming that the patients are not re-infected after recovery and the epidemic transmission area is closed. When the interpersonal contact restriction is set to three people (i.e., fellow household members), the peak number of infected patients is less than half of what it would be when the risk is present. This finding shows that, first, the CDC's risk warnings and the government's response actions must complement one another. This finding is consistent with empirical research in the literature (35, 65) that considers risk warnings and governments' response actions to be information systems and management processes, respectively. Second, when dealing with unknown risk shocks, separating epidemic disease risk alerts from the issuance of government prevention and control responses results in more timely responses than are achieved when these measures are combined. The former is a loosely coupled decision-making framework that incorporates expert judgment and multi-objective decision-making.

During the early phases of an unknown risk shock, decision-making is hindered most by the paradox of overreaction and

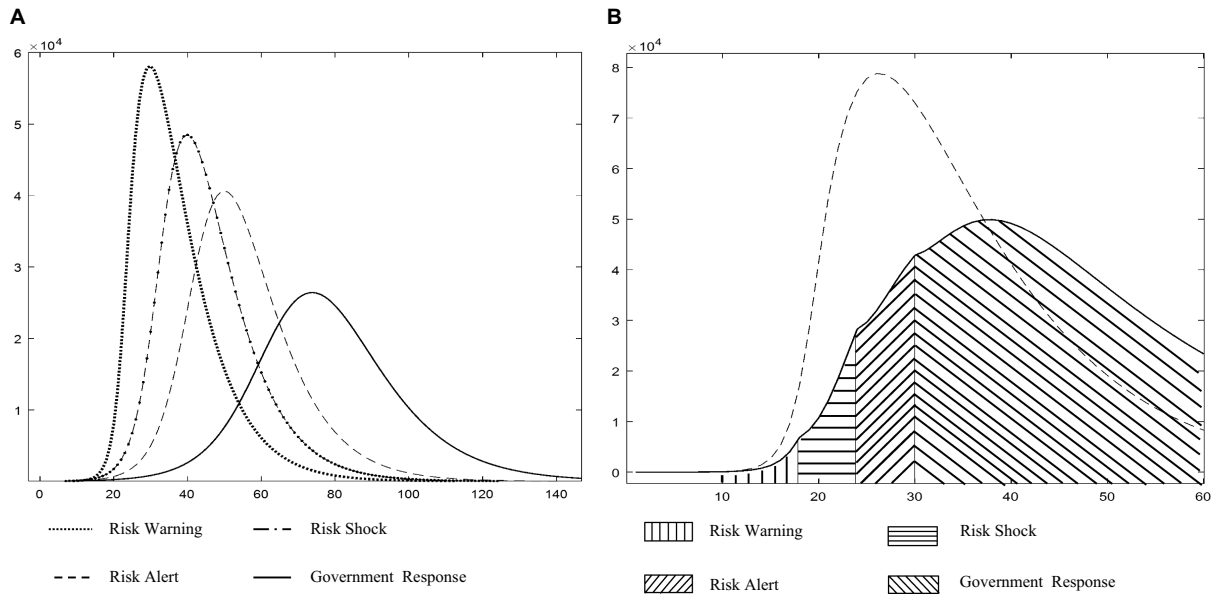

FIGURE 8
(A) Comparison of the impact on the epidemic of releasing information and imposing bans at the same time (Source: authors' calculations). **(B)** Phased release of information and imposition of bans on the impact of the epidemic, phased versus reality (Source: authors' calculations).

lagging response. An unborn-unknown risk is considered to be of unpredictable intensity, with the potential for quick and extensive spread. To achieve epidemic control while avoiding a social panic and economic downturn due to an overreaction, an improved strategy based on the information presented in Figures 6, 7 must assume that different information sharing, risk communication, and action measures will be implemented during the four early stages of an emerging epidemic by various entities such as local tertiary hospitals, the CDC, and the National Health Commission. In the first stage, risk alerting occurs at $T = 7$, i.e., when an unknown disease emerges and non-infectiousness cannot be ruled out; at this point, the population makes its own reference and travel planning decisions. In the second stage, if the rate of suspected case generation continues to rise for more than a week, the CDC is required to issue a risk alert and social risk communications even if the suspected epidemic remains undiagnosed. This stage can be considered as the strategic command center. After one week, if the growth rate of the epidemic is not accompanied by a decrease in population travel, the CDC increases its risk warning. This third phase may be considered as the tactical command center. In the fourth stage, if the number of individuals infected with the unknown disease continues to increase, the government reaction must intervene to avert a significant epidemic even if the disease has not yet been fully described and identified. This is the period during which danger is contained. During this stage, the prevention and control system switches to risk communication mode, wherein professional medical institutions such as the CDC take actions ranging from risk level assessment to risk downgrading and risk removal, and provide professional assistance to the government in making decisions on the resumption of work, mass production, and other aspects. Undoubtedly, a change in any of the aforementioned variables may result in an appropriate upgrade or downgrade of the risk warning and response level to avoid an overreaction related to epidemic prevention and control.

Figure 8B illustrates a simulation of a COVID-19 outbreak according to the four stages discussed above. The results in Figure 8B demonstrate that while the overall development of an epidemic cannot be reversed during first three phases beyond temporarily slowing the increase in patient numbers, theoretically, the multi-stage, hierarchical early warning and government response mechanism based on the improved strategies proposed in Figures 6, 7 can substantially reduce the peak number of infections in comparison with the real scenario, while gaining valuable time for disease diagnosis, analysis, and decision-making. These gains would enable a society to develop a short-term prevention and control plan for unknown risk shocks. According to the findings in Figure 8B, a multi-stage, hierarchical warning and response mechanism is a manifestation of the idea of integrating the governance, and is a potential direction for exploring the reform of risk prevention and control measures in response to sudden major epidemics.

6. Discussion and conclusion

6.1. Main conclusion

Ultimately, the aspiration of all nations is sustainable development. Epidemic prevention and control serve as a critical orthodoxy of sustainable health development, offering a strategic bulwark for the continuance of economic and social growth. Success in this domain can catalyze further supportive resources for diversified sustainable development arenas. Hence, epidemic prevention and control hold a pivotal position in the sphere of sustainable health development.

Through simulations and case studies, this article examines the successes and failures of a prevention and control system in responding to four types of risk shocks and analyzes the primary reasons for the system's failure to respond to unborn-unknown risk shocks in terms of its data structure and management processes. First, the data structure and supporting management procedures of the prevention and control system are nimble and adaptable to known and unknown risks, but the system inability to adapt to new risks was found to be the primary reason for its failure to deal with the COVID-19 pandemic. Second, to ensure that the prevention and control system remains agile and adaptive in the face of an unknown risk shock, its data structure should be generated automatically using underlying data from healthcare institutions nationwide and a private blockchain, and a triangularly validated risk communication system should be established. The management process should be proactive and adaptive (i.e., a loosely coupled decision-making process). Third, the establishment of a good loosely coupled decision-making framework to address unborn-unknown risk shocks does not imply that the current tightly linked decision-making structure should be disregarded or abandoned. The closely connected structure remains relevant for known risks that have not yet shown themselves, as well as for unknown risks that have manifested themselves, and is a regular decision-making structure in risk prevention and control management.

6.2. Creative contributions

This article introduces the concept of loosely coupled adaptive process management and explores the theory of adaptive management systems built around a loosely coupled process and a triangulated validated risk communication architecture to address two critical scientific issues: how to deal with the complementarity of collective and individual decision-making in the context of a disease epidemic, and how to define the fuzzy boundary between adequate prevention and overreaction. Accordingly, it provides sound advice to advance sustainable development from the perspective of the prevention and control of pandemic outbreaks.

First, this article proposes complementary theories of tightly and loosely coupled decision-making architectures via adaptive prevention and control management within the 2×2 category framework of born-known risks, unborn-known risks, born-unknown risks, and unborn-unknown risks, elucidates the primary reasons why the prevention and control system failed to function as expected when faced with the shock of COVID-19, and theoretically revealing the realization mechanism.

Second, a multi-stage, hierarchical warning and government response mechanism, including a risk alert, decentralized decision-making, a strategic control window involving risk warning and communication, a tactical control window involving risk alert escalation and enhanced communication, and risk proliferation containment and government action responses, is proposed by

drawing on the concept of integrating the governance of untreated, primary, and serious diseases. Theoretically, the operational mechanism for responding to major public health events is explained, and the article expands on the theoretical approach to defining the blurred line between adequate prevention and overreaction in the field of prevention and emergency management through the study and assessment of major public health risks and related decision-making.

Third, the integration of the theory of information systems value realization into the study of changes in prevention and control systems intended to cope with the unknown risks posed by major disease outbreaks has established complementarity between the application of information systems and changes in the management processes of prevention and control systems. This demonstrates that it is possible for multiple actors to implement prevention and control measures by interacting and collaborating with each other even in the context of a national public health crisis (34). That is, the principle of complementarity between information systems and management processes holds and enriches the context of research on the value of information systems.

6.3. Limitations and further research

The main limitations of this study are threefold. First, it was difficult to conduct in-depth face-to-face interviews due to the COVID-19 pandemic; instead, this research relied on telephone interviews, which have limitations that are difficult to circumvent, and a few direct interviews with CDC administrators. Second, the chain-of-evidence analysis mainly focused on a case study of the failures to respond to an unborn-unknown risk, with little discussion of the variables underlying failures to respond to risks of the other three types. Third, this study mainly explored problems in the management of epidemic outbreak prevention and control systems and processes in the Chinese context (66) and proposed relevant solutions, whereas the situations in other countries were not researched. Taken together, the first two limitations have no substantial impact on the stability of the results and policy recommendations in this paper. Future research should focus on conducting in-depth interviews with personnel from various management sectors to identify complementarities and synergies between local governments, healthcare commissioners, CDCs, and healthcare providers. In addition, epidemic outbreak prevention and control systems and process management in other countries should be explored, and experimental comparisons should be made to ensure that research on global sustainable health development is up to date.

6.4. Policy recommendations

Additionally, this article sets forth the following policy suggestions for advancing prevention and control management paradigms via innovation.

First, strategic needs for reforming and upgrading the disease prevention and control system should be met, including implementation of the prevention gateway and promotion of deep integration of the Internet, big data, artificial intelligence, and direct reporting systems. Recommendations: (1) The prevention and control system should integrate seamlessly with electronic medical record systems, HIS, laboratory information management systems, medical image archiving and communication systems, radiology information systems, and other systems at all levels of hospitals across countries and should standardize the API interfacing ports. Blockchain technology should be used at all levels, beginning with community hospitals, to create a private blockchain for the CDC system. Thus, the diagnosis and treatment process of frontline physicians will involve the automatic collection of disease information and thus truly create underlying data that are tamper-proof and traceable from bottom to top and horizontally throughout the prevention and control system, establishing a platform and set of data for the complete visualization and hierarchical authorization of data sharing systems from the local to the central level. (2) A standardized report card format should be created for clinicians to use and apply concurrently from top to bottom. In addition, top-down deployment to hospitals should be synchronized, and a query language database for self-consultation by patients should be developed rapidly to lower the cost of information exchange. (3) An early warning mode and a switchable prevention and control mode should be added to the current prevention and control system's application mode. (4) The current system's information sharing channels should be extended, with communication channels between official healthcare institutions and the general public, and the channels should be enabled to perform various application scenario tasks in a variety of modes. To accomplish these recommended changes, the prevention and control system must undertake specific technical work in three areas: expanding data generation methods to diversify the data source channels, promoting data standardization to increase the possibility and richness of data sharing, and establishing a risk communication channel to improve information symmetry between the government and society.

Second, comprehensive integration of the Internet, big data, AI, and public health management systems should be advocated. An adaptive process management system for responding to sudden major epidemics should be established, and an organic balance between democracy and centralization in the authority over decisions regarding research and judgment should be promoted along with an organic balance of consistent action within the prevention and control process with increasingly sensitive local responses. Recommendations: (1) Empowerment of the prevention and control system with the ability to warn and notify about hazards should be considered. The Health Care Commission's risk warning authority should be transferred to local tertiary institutions, with initial judgments based on information from frontline healthcare professionals. When the initial judgments are discordant, the prevention and control system may be utilized to facilitate data exchange between several hospitals and consultation with distant experts while maintaining the ultimate judgment of the local healthcare institution. For instance, the networked CDC and local medical institutions should be tasked with creating an organic balance between democracy and centralization in significant risk research, assessment, and decision-making, which would systematically enhance the capacity to study, evaluate, and make risk-related choices. (2) The public health management system's multi-stage and hierarchical early warning and response mechanism should be established and enhanced. The CDC is responsible for risk distribution and communication at three levels, namely danger alert, and risk warning, while the government determines whether and how

to react using measures such as restriction, quarantine, and city closure. At various phases, the risk alert and risk response levels are correlated differently, and the CDC risk alerts and government action responses function in a complementary manner to aid in risk prevention and management. (3) A loosely connected decision-making system should be created to address the effects of unforeseeable future hazards. A big data, AI-driven agile response model of the initial transmission paths and regional risks of unborn-unknown risks should be developed to provide powerful risk information for joint prevention and control mechanisms at the central and local levels, as well as decision support for the government in delineating the fuzzy boundary between adequate prevention and overreaction and alleviating the pressure of limited rationality in government.

Third, the CDC's professional management should be strengthened to enable it to handle tasks such as expanding the prevention measures, boosting risk awareness, and enhancing its capacity to investigate, appraise, and make decisions about important hazards. This article recommends strengthening the CDC's professional management capacity in three areas: (1) adoption of a personnel management system that balances mobility and stability and establishment of a system of transparency and procedures and a system of rotation for the primary person in charge (e.g., rotation from one location to another every 3 years and promotion from one location to another); (2) strengthening of the funding guarantee mechanism, improving the rate of funding allocation, directing funds toward improvement of the prevention and control system, and promoting organizational reform in the prevention and control of epidemic diseases; and (3) at the legal level and procedures to establish a mechanism for budgeting and allocating special funds, and arranging for an independent body to budget and control funds and disclose financial information in a timely manner.

Fourth, preventive management science and effective synergies between public health and medical services should be established and developed, and prevention and control, joint prevention and control, mass prevention and treatment, and other adaptive preventive management knowledge systems should be integrated effectively. Although emergency management science is reasonably well established, the theoretical community lacks a concept of preventive management and a relevant knowledge structure. Preventive management is needed for reforming and strengthening disease prevention and control systems and appropriate risk emergency response mechanisms in terms of disciplinary development, knowledge systems, and education and training. Recommendations: (1) a sub-discipline of preventive management should be established on par with emergency management in a disciplinary management system. Preventive management is a new multidisciplinary field of study that focuses on the theory and practice of adaptive preventive management. Its basic competencies include preventive medicine, systems engineering, information systems management, and public health management. Preventive management focuses on achieving an organic balance between democracy and centralization in terms of the authority to make decisions regarding preventive research and judgment, as well as an organic balance of consistent action in the prevention and control system with increased local response sensitivity. Research in this area addresses the management theory of preventive research and judgment, assessment, and decision-making in response to the impacts of major public security events. (2) Prevention management concepts and knowledge systems should be integrated into the national public health emergency management knowledge system; prevention management research teams, academic groups, and scientific research groups should be established and developed; the declaration and establishment of prevention management topics should be encouraged and promoted; and the exploration of frontier theories in prevention management should be encouraged. (3) The integration of theoretical research into prevention management should be promoted. Simultaneously, preventive management should be included in fundamental knowledge training provided to general practitioners, frontline medical and nursing staff, and others.

Author's note

1. Bain & Company, "Beating the Epidemic, Grateful to Move Forward - Is New Crown Pneumonia Trapping the Chinese Economy? Report, 8 February 2020, Sohu.com, https://www.sohu.com/a/371485904_282725.
2. Bluedot Canada issued its first alert for COVID-19 on 31 December 2019 with the help of an AI model, nearly a week ahead of the US Centers for Disease Control and Prevention's (CDC) alert on 6 January 2020.
3. Even though the scientific community disagrees on the true origin of COVID-19 based on genetic data analysis, the first confirmed COVID-19 patient in Wuhan and the first widespread spread of the COVID-19 epidemic, COVID-19 remains as an endogenous unknown risk in terms of the form in which the risk occurs.
4. Considering that the epidemic is still on-going, and the number of new confirmed, suspected, and fatal cases is still dynamic, this paper does not aim to give an accurate calculation of the number of people affected or economic losses.
5. The Prevention and Control of Infectious Diseases Law in Article 38, the Emergency Regulations for Public Health Emergencies in Article 25 and the Ministry of Health's Information Dissemination Program for Statutory Infectious Diseases and Public Health Emergencies together specify that the State establishes an information dissemination system for emergencies. The competent health administrative department of the State Council is responsible for releasing information on emergencies to the public. If necessary, the competent health administrative departments of the people's governments of provinces, autonomous regions, and municipalities directly under the central government may be "authorized" to release information on emergencies within their administrative regions.
6. Research Report on Public Awareness and Information Dissemination on Novel Coronavirus Pneumonia in 2020, 26 February 2020, China.org, http://www.chinanews.com/zwad/2020/02-26/8664390.html.

The variables, action processes, and strategy function settings of the simulation model in this paper are available upon request. Interested readers are encouraged to request this information directly from the authors. Ethics approval was obtained for the study.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

YZ led and conceived the study, performed the literature review analysis, conducted the case study and simulation analysis, and prepared the manuscript. PF assisted with literature collection, analysis, and writing, and also contributed to the case analysis. JS revised the manuscript and secured funding for the project. YY provided valuable input during the manuscript revision process. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2023.1249277/full#supplementary-material

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The impact of industry-university-research projects on biopharmaceutical companies' innovation performance: moderating roles of government subsidies for innovation

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Innovation holds paramount importance for both nations and businesses. This article presents a panel regression model designed to assess the fixed effects of industry-university-research (IUR) cooperation projects on innovation performance. Furthermore, it examines the moderating impact of government innovation subsidies by utilizing data spanning from 2007 to 2021, encompassing 326 listed Chinese biopharmaceutical firms. Our findings reveal that industry-university-research-cooperation projects have the potential to significantly enhance innovation performance across three key metrics: input, output, and quality for firms. The presence of government innovation subsidies as a moderator is found to have a positive influence on IUR-cooperation projects and their innovative inputs. However, it can yield adverse effects on IUR-cooperation projects with respect to innovation outputs and quality. The insights presented in this paper introduce innovative recommendations for elevating corporate innovation quality and refining the policies governing IUR cooperation.

KEYWORDS

industry-university-research cooperation, innovation, quality, inputs, innovation subsidies

1. Introduction

The biopharmaceutical industry is one of the high-tech sectors that showcase the strength of the national economy and is closely tied to the population's health. The innovation performance of the biopharmaceutical industry not only yields economic benefits but also contributes to long-term health advantages. The widely adopted approach known as industrial-university-research (IUR) cooperation involves establishing robust partnerships with universities, research institutes, and companies. This strategy is particularly notable within the biopharmaceutical industry, which operates in a highly competitive and increasingly complex environment (1). In the context of an economy's innovation system, universities and research institutes play a pivotal role as pioneers in knowledge advancement, serving as the primary source of technological innovation and talent cultivation (2). Firms bridge the gap between

technology development and market demand, converting scientific knowledge into practical productivity (3).

China's growing emphasis on science and technology innovation has led to remarkable progress in the development of breakthroughs, with the number of patent applications ranking at the top globally. Industry-university-research, as a novel approach to fostering innovation (4, 5), has also been progressively integrated into policy. In our search for keywords related to IUR, we scoured the websites of various ministries and commissions, including the Chinese government website, the Ministry of Science and Technology, the Ministry of Education, and the Ministry of Industry and Information Technology, as well as Peking University's Legal Information Network. To date, there have been approximately 2,000 or more policy documents on IUR-cooperation and cooperative innovation at the national level, including the Central Committee of the Communist Party of China, the State Council, the National People's Congress, and the ministries and commissions under the State Council, until 2022. These policy documents come in 25 different forms, encompassing laws, rules, opinions, plans, notices, programs, and blueprints, among others. Based on our data, the number of cooperation projects established between listed companies in China's biopharmaceutical industry and universities, or research institutes is significantly higher than the average for all listed companies. Simultaneously, the Chinese government is keen on promoting the development of self-developed pharmaceuticals, leading to extensive policy support. Hence, it is reasonable to select the biopharmaceutical industry as the focus of this study.

According to the research objectives, the literature on the relationships between IUR-cooperation and innovation can be categorized into three main groups. The first category of literature takes a macro approach to evaluate the intensity, sustainability (6), participation of each subject (7), influencing factors (8), and regional innovation performance of IUR-cooperation, the first category of literature adopts a macro approach (9, 10). The second category of literature focuses on universities, aiming to assess their role, performance, and the influencing factors in industry-university cooperation (11, 12), suggests that researchers engaged in industry-university cooperation tend to produce more and higher-quality articles. Additionally, TurkBicakci et al. (13) examine the impact of university participation in industry-university cooperation, considering factors such as institutional status, the nature of the institution, and research intensity (14). The third category of literature concentrates on the performance of firms, exploring topics like the objectives and benefits of enterprise participation, the challenges they face, and the criteria they employ when selecting cooperation partners (15, 16). Numerous studies employ publications and patents as significant indicators of IUR-cooperation. However, it is important to note that innovation is a high-risk activity, where the intention to cooperation comes first, and the results are produced second. Within this context, several important and relevant questions deserve our attention. For example, what is the impact of IUR-cooperation projects on firms' innovation performance? As the government progressively promotes the cooperative innovation model, does it moderate IUR cooperation and the innovation performance of firms?

Bases on the knowledge-based theory of the firm (17, 18), firms integrate the specialist knowledge of their member. This entails a complex web of coordination both within and beyond the boundaries of these firms. This efficient integration is achieved through cross-learning among organizational members. Furthermore, universities and research institutions possess their unique reservoirs of specialized knowledge and can serve as crucial partners and coordinators in cooperation with these firms. Government can significantly enhance a company's knowledge and learning capabilities, fostering the creation, and sharing of organizational knowledge. Government intervention aids firms in better aligning their strategies. We have undertaken the manual collection of IUR-cooperation projects within the biopharmaceutical industry, and we employ three distinct criteria to characterize corporate innovation performance, namely inputs, outputs, and quality. This article presents a panel regression model designed to assess the impact of IUR-cooperation on innovation performance, while also evaluating the moderating effect of government innovation subsidies. The data used in our analysis is drawn from 326 publicly listed Chinese biopharmaceutical firms, spanning the years 2007 to 2021. Furthermore, our study investigates the influence of government innovation subsidies on the relationship between IUR-cooperation and innovation performance. To ensure the robustness of our findings, this research employs several rigorous checks, including variations in dependent variables and instrumental variable analysis.

Overall, this work contributes significantly to current research in four keyways. Firstly, it provides a formal and rigorous empirical analysis of IUR-cooperation, addressing the existing dearth of such studies. Much of the existing literature on IUR-cooperation relies on theoretical analysis or questionnaire-based results (19, 20), some of which are subjective in nature. Moreover, many articles discussing IUR primarily focus on the number of patents (21), often overlooking the fact that cooperative projects precede patent filings for publicly traded companies. Research and development processes are intricate and demanding; therefore, enterprises, whether in collaboration with universities or research institutes, embark on these projects with vital research objectives. Additionally, the innovation of Chinese pharmaceutical companies has been historically characterized by a focus on imitation over originality and a tendency to prioritize quantity over quality. When evaluating the innovation performance of the pharmaceutical industry, the quality of innovation, as reflected in the ratio of exploratory patents, emerges as a crucial metric. Lastly, prior studies examining the factors influencing IUR-cooperation have largely considered the perspectives of companies, research institutions, and the broader open environment (22). However, increased government emphasis on the significance of IUR-cooperation, a substantial portion of government involvement has become apparent. In previous literature, the government's perspective was notably absent.

The rest of this essay is organized as follows. Section 2 provides a literature review and outlines the research hypotheses. In Section 3, we describe the models, variables, and data. Section 4 covers the empirical findings, including several robustness tests, and presents descriptive statistics of the variables. Finally, Section 5 concludes the paper.

2. Theoretical background and hypotheses development

Based on the knowledge-based view, the stages of corporate knowledge generation do not solely rely on internal development but also necessitate cooperation with institutions such as universities and

research organizations to jointly develop commercial knowledge, share risks, and reap mutual benefits (23). IUR-cooperation represents a diverse integration of knowledge between firms and universities or research organizations (24). Within this cooperation, universities and research institutes focus on fundamental research, while businesses concentrate on product development (25). Universities and institutions bring forth extensive complementary and diverse expertise (26),much of which is tacit, requiring interpersonal communication for knowledge integration (27). China has several IUR projects, including cooperation between universities and research institutes through R&D institutions affiliated with enterprises and strategic alliances between universities and businesses (28). In these projects, professionals from firms, universities, and research institutions collaborate on various levels (29). Universities, research institutes, and firms act as the production and input sides of knowledge, respectively, applying this knowledge to various aspects of innovative activities within the industry community through the knowledge flow process (30). The dissemination of knowledge from universities and research institutions to businesses is facilitated by formal or informal interactions between firms and these institutions (31).

2.1. The impact of industry-university-research-cooperation projects on firms' innovation input

The innovation process involves strategic efforts aimed at acquiring a diverse range of knowledge necessary for fostering innovation (32). Companies often opt to engage in cooperative partnerships with universities and research institutes, harnessing their technical and academic expertise to advance cutting-edge technologies and ideas that align closely with the company's specific objectives, as opposed to pursuing independent development (33). This cooperative approach tends to yield significant benefits, prompting stakeholders to consider augmenting their investments in R&D (34). As a result, these companies can engage more effectively with research institutes to efficiently access novel products and technologies. Such cooperative initiatives also serve to underscore a company's robust R&D capabilities, which, in turn, can enhance their attractiveness to potential investors. This heightened investor interest can ameliorate the financing challenges faced by listed companies to a certain extent. Consequently, listed companies often demonstrate a proclivity for entering into cooperative agreements with universities and research institutes and disclosing these partnerships. This strategic cooperation not only provides access to a wider pool of capital for innovation investments but also bolsters their innovation efforts through enhanced resources and expertise. Thus, we propose the following hypothesis:

> *H1a*: Industry-university-research-cooperation projects lead to innovation inputs.

2.2. The impact of industry-university-research-cooperation projects on firms' innovation output

Acquiring knowledge and skills through cooperation have been effective and efficient means of successful innovation (35). In pursuit of optimizing their innovation investments and expediting the commercialization process, companies tend to accord precedence to research initiatives that are characterized by low levels of risk and complexity (36). In this regard, efforts within the sphere of IUR-cooperation offer a distinct advantage, being both cost-effective and less fraught with risk when compared to internal R&D. This cost-effectiveness stems from the capacity of companies to leverage the existing scientific expertise and equipment available within universities and research institutions, thus circumventing the substantial expenditures associated with personnel recruitment and equipment procurement (37). Moreover, knowledge sharing is a mechanism to convert tacit into explicit knowledge (38). Industry-university-research cooperation projects facilitate the acquisition and integration of inter-organizational resources, including research talent, equipment, and facilities (39). Universities and research institutions can offer valuable technical guidance to businesses (40). This approach not only aids companies in overcoming technical challenges and accelerating R&D but also assists in resolving a range of issues, thus fostering innovation. As a result, through IUR-cooperation, organizations can effectively reduce restrictions on R&D expenditure and mitigate innovation risks while simultaneously enhancing their innovation outputs. Consequently, we propose the following hypothesis:

> *H1b*: Industry-university-research-cooperation projects lead to innovation outputs.

2.3. The impact of industry-university-research-cooperation projects on firms' innovation quality

Open innovation represents an agile innovation process that involves the assimilation of both internal and external knowledge and technologies through cooperative relationships (41). IUR-cooperation projects confer a distinct advantage upon companies by harnessing their strengths in basic research, thereby fostering the development of groundbreaking and original innovations. Owing to differences in market orientations and resource constraints (42), businesses frequently channel their efforts toward realizing incremental advancements in low-risk, cost-effective applications (43). The overarching objective is to expedite the transformation of these innovations into tangible economic value (44). In contrast, universities and research institutes primarily focus on fundamental research with an emphasis on breakthrough-oriented innovation (45), leading to fundamentally rooted innovation outcomes (46). Universities and research organizations can provide businesses with well-qualified technical guidance (47). This approach supports companies in innovating, aiding them not only in addressing technical challenges but also in resolving a diverse range of issues. Industry-university-research cooperation projects can, therefore, divert businesses from their path of solely incremental innovation, empowering them to attain exploratory innovation performance by drawing upon the fundamental research of universities and research institutions. Based on this discussion, we propose the following hypothesis:

> *H1c*: Industry-university-research-cooperation projects lead to innovation quality.

2.4. The moderating role of government innovation subsidies

The government plays a crucial role by providing financial support, knowledge about cutting-edge technologies, and the latest industry policies. Incorporating this type of knowledge is of significant benefit to firms (48). Business and government ties lead to both economic and operational performance (49).

Government innovation subsidies, on one hand, by removing financial barriers to industry-university-research (IUR) cooperation projects, can enhance the innovative input performance of enterprise (50), but also confirm the direction of innovation. IUR-cooperation projects aim to mitigate the costs and risks of innovation to enhance innovation performance (51). Subsidies can serve as financial support for firms' innovation initiatives and signal a commitment to acquiring additional societal resources (52). As a result, government innovation subsidies can significantly alleviate the financial constraints faced by companies engaged in IUR-cooperation (53), enabling them to offer high-quality innovative inputs and contribute to the successful implementation of projects involving industry, academia, and research.

On the other hand, the existing innovation support strategy is primarily based on the assessment of firms' R&D and innovation investments, as well as patent applications (54). Government innovation subsidies encourage firms to pursue short-term goals in IUR-cooperation. However, high-quality innovation often requires longer periods of R&D investment. Still, government officials, under pressure for performance assessment, tend to select innovative projects with short timelines and quick outcomes for their innovation support policies (55). This can lead to firms' preference for short-term goals in IUR-cooperation. They may be more inclined to select cooperation projects that can yield rapid inventive outcomes, which can be detrimental to their innovation outputs and quality (22). Moreover, after receiving innovation subsidies, companies may focus on short-term innovation objectives (56). Larger government subsidies may encourage opportunistic behavior among firms (57). Since it is challenging for the government to effectively assess the genuine quality of innovation achievements when selecting funding recipients, when government subsidies are increased, firms are more likely to pursue low-complexity and low-level innovation projects in IUR-cooperation. These firms may prioritize low-quality innovative outputs to access subsidized funding (58). This effect, known as "bad money drives out good," results in the abandonment of genuinely beneficial IUR-cooperation initiatives, making it challenging for firms to gain government support. Consequently, this undermines the positive impact of IUR-cooperation projects on enhancing innovation output and quality.

The following competing hypotheses are put up for more empirical investigation in this work based on the analyses presented above:

> *H2*: Government innovation subsidy positively moderates the relationship between IUR-cooperation projects on firms' innovative input.

> *H3*: Government innovation subsidy negatively moderates the relationship between IUR-cooperation projects on firms' innovative output.

> *H4*: Government innovation subsidy negatively moderates the relationship between IUR-cooperation projects on firms' innovative quality.

Combining the above hypotheses, the conceptual framework of the study is shown in Figure 1.

3. Research methodology

3.1. Sample selection and data sources

To mitigate the impact of significant accounting standard revisions, this paper utilizes data from biopharmaceutical companies listed on A-shares. After excluding companies subjected to special treatment during the observation period, those operating in the financial and insurance sectors, companies issuing both B shares (foreign capital shares) and H shares (listed in Hong Kong), and companies with significant missing data, the final research sample comprised 326 companies. Financial data from these firms spanning the years 2007 to 2021 were sourced from the CSMAR database. The patent application data presented in this research were sourced from the website of the State Intellectual Property Office of China. By using the website's patent examination function, we collected data on nearly one million patent applications submitted by all listed companies during the sample period. Furthermore, we manually compiled information regarding IUR-cooperation projects from publicly traded company disclosures. To ensure comprehensive control over all macro and micro factors influencing firms' decisions on IUR-cooperation, this study encompasses not only enterprise-level variables, but also macro-level statistics derived from the WIND database specific to the regions where these enterprises are located. The variables have been scaled to the 1 and 99% percentiles to mitigate the influence of outliers.

3.2. Variables

3.2.1. Dependent variables

This article examines three aspects of Innovation: inputs, outputs and quality (59, 60). Innovation **input** is assessed using established practices outlined in prior literature. Two key indicators are employed: the ratio of annual R&D expenditure to total assets (RD1) and the ratio of annual R&D expenditure to operating revenue (RD2). Innovation **output**, on the other hand, is evaluated by considering the number of patent applications submitted by the applicant company. These patents can be categorized based on the China Patent Classification, including invention patents, utility model patents, and design patents. Utility model patents pertain to new technical solutions involving shapes, structures, or their combinations that are practically applicable. Design patents relate to novel designs encompassing shapes, patterns, or their combinations, along with combinations of colors and shapes or patterns that exhibit esthetic appeal and suitability for industrial use. Invention patents are considered the most innovative, followed by utility model patents and design patents. To measure innovation output, this paper adopts two indicators following the approach of Bereskin et al. (61). (1) Patent1 represents the natural logarithm of the sum of the three patent categories plus one. (2) Patent2 accounts

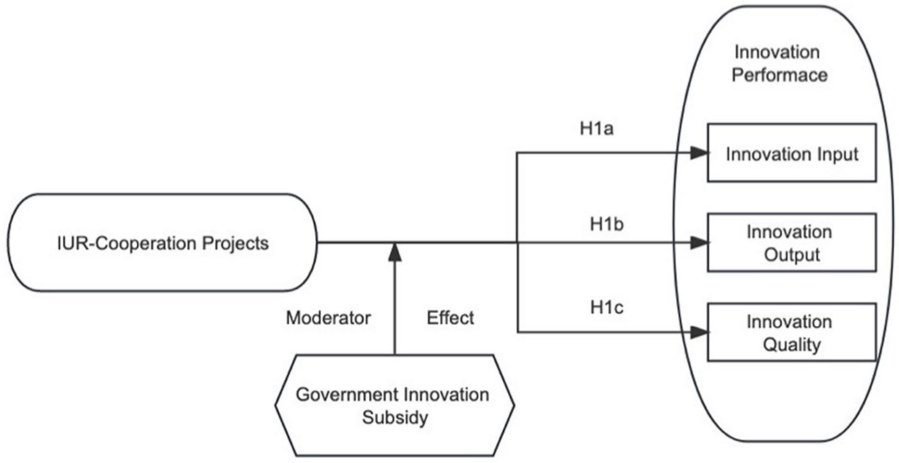

FIGURE 1
Conceptual framework.

for the varying contribution weights of the three types of patents, subjectively assigning a 3:2:1 weight distribution. It is expressed as the natural logarithm of the weighted total number of the three types of patents plus one (62, 63). Patent1 is used for the principal model evaluation, while patent2 is applied in the robust test. This research identifies invention patents, characterized by high R&D complexity and innovation levels, as indicative of high-quality innovation outcomes, in line with the insights of Rong, Wu and Boeing (64) and other studies. A greater number of invention patents acquired by a firm signifies a higher quality of innovation. We employ the proportion of exploratory patents as an indicator of a company's **quality**. The exploratory patent metric (65) defines a patent as exploratory if 60% or 80% of the patent classification numbers cited in the patent are unrelated to the firm's existing patent portfolio. The Qua1 is computed as the ratio of 60% unrelated patent citations to the total number of innovations and inventions. Qua2 represents the ratio of 80% of patent citations unrelated to existing patents to the total number of patent citations. If a company's Qua1 value is predictive, it suggests that its innovations are of higher quality. Qua1 is utilized in the primary regressions, while Qua2 is applied in the robust tests.

3.2.2. Independent variables

In this study, the primary method for collecting data on Industry-University-Research (IUR) cooperation projects is manual collection. We used various search terms such as "university," "research institute," "industry institute," "cooperation program," "cooperative research and development," and "joint research and development" to source documents from listed biopharmaceutical companies. These documents include the company's annual reports, public records of board meetings, social responsibility reports, and other disclosures. We then compiled statistics based on these disclosures. For instance, if publicly traded company A discloses IUR activities with university X, we count this as ONE IUR cooperation for company A in the current year. Some publicly traded companies disclose both the amount and number of projects, while others simply state that they are cooperating with a specific university or institute. Our data collection and statistical compilation follow the aforementioned method. In this research, we utilize an approach developed by Hong and Su (66) and Park, Hong and Leydesdorff (67), to assess the natural logarithm of the number of cooperative IUR projects. The larger this variable, the higher the proportion of businesses participating in IUR-cooperation projects, and the more substantial this cooperation is in the context of their overall innovation activities.

3.2.3. Moderators

The moderator is government innovation subsidies (GIS). In the notes to listed companies' annual reports, we look for government grants. Keywords for the screening criteria include: "first set," "science and technology support program," "standardization strategy," "research and development," "development," "innovation," "science and technology," "technology development," "technology project grant," "significant technology application," "productivity promotion centre," "incubator," and "Golden Sun." Following that, keywords are made as patents, copyrights, new products, and intellectual property rights. Novel cancer therapies, spores, antibiotics, and other forms of biological medical technology are studied as filters. Finally, we determine the total annual innovation subsidies granted to each listed company. We calculate as the natural logarithm of government innovation subsidies plus 1 (68).

3.2.4. Control variables

To control as much as possible for each contributing element of firm innovation quality and to prevent endogeneity difficulties caused by neglecting essential factors, we control for both firm-level and regional-level variables of the province where the firm's office is located. The firm-level control variables include Size (natural logarithm of assets), Lev (ratio of total debt to total assets), Roa (return of assets),ATO (Total Asset Turnover), Cash(Cash Flow Ratio), REC (Percentage of accounts receivable), Cur (Current Ratio), FIXED (ratio of fixed assets). The amount of control variables for the regional layer surface includes: col. (Number of high school projects in each province), Pgdp (gdp *per capita*), pop (Population size of each province) (69, 70).

3.3. Models

$$Innovation_{i,t} = \beta_0 + \beta_1 IUR_{i,t} + \beta Control_{i,t} + \alpha_i + \alpha_t + \varepsilon_{i,t} \quad (1)$$

where $Innovation_{i,t}$ is the degree of company innovation, $IUR_{i,t}$ is the level of IUR-cooperation projects, $Control_{i,t}$ is a set of firm-level and regional-level control variables presented in this study, α_i is an individual fixed effect, α_t is a period fixed effect, and $\varepsilon_{i,t}$ is a random error term.

$$Innovation_{i,t} = \beta_0 + \beta_1 IUR_{i,t} + \beta_2 GIS_{i,t} + \beta_3 IUR_{i,t} \times GIS_{i,t} + \beta Control_{i,t} + \alpha_i + \alpha_t + \varepsilon_{i,t} \quad (2)$$

Equation (2) displays the empirical model used to investigate the moderating influence of government innovation subsidies. $GIS_{i,t}$ is indicators of government innovation subsidies (71).The interaction term between the amount of IUR-cooperation projects and the government innovation subsidy is denoted by $IUR_{i,t} \times GIS_{i,t}$.

4. Empirical results

4.1. Descriptive statistics and correlations

The descriptive statistics for all relevant variables are shown in Table 1. The average value of the natural logarithm IUR is 1.861, and the standard deviation is 1.409. These statistics indicate that IUR-cooperation projects are still at a modest level but exhibit significant heterogeneity. RD1, Patent1 and Qua1 have respective means (medians) of 0.017(0.012), 2.246 (2.303), and 0.267(0.427). This result implies that the average inputs and outputs of innovation have increased over the sample period. Other variable distributions are identical to those reported in prior studies.

Table 2 illustrates the Pearson correlations among the variables, with the majority being significant but tiny. Industry-university-research-cooperation projects are strongly positively connected with RD1, Patent1 and Qua1, preliminarily indicating that IUR-cooperation projects can greatly boost innovation inputs and outputs. As a result of the fact that all VIFs are below the 10-point threshold (72, 73), there are no obvious correlations between variables. A Hausman test also shows that a fixed effect model should be employed in this investigation. The majority of indexes have been analyzed in accordance with existing research, and only significant variables have been integrated into our models as control variables (74).

4.2. Main regression analysis

The empirical results of the effect of IUR-cooperation projects on innovation performance can be found in Table 3. Column (1) shows the regression R&D inputs for model (1). The coefficient of the IUR-cooperation projects is 0.0002 which is highly significant at the 0.01 level ($t = 0.0000$). This finding demonstrates that IUR-cooperation projects have positive importance with R&D inputs. Column (2) displays the findings following the addition of several control factors, suggesting that IUR-cooperation projects remain significant despite considering the endogenous difficulties produced by the missing variables. The results of estimating innovation outputs without and with control variables are presented in columns (3) and (4), respectively. Industry-university-research-cooperation's principal coefficients are 0.0419 and 0.0149, which is statistically positive at the 0.01 and 0.1 level. The findings of evaluating innovation quality without and with control variables are presented in columns (5) and (6), respectively. Significantly positive at the 0.01 level are the coefficients 0.0029 and 0.0017 for the IUR-cooperation. This result suggests that IUR-cooperation projects can increase innovation inputs, outputs, and quality for businesses. These data thus support H1.

TABLE 1 Descriptive statistics.

Variable	N	Mean	SD	Median	Min	Max
RD1	2,941	0.0170	0.0190	0.0120	0	0.0920
Patent1	2,941	2.246	1.736	2.303	0	6.518
Qua1	2,941	0.227	0.267	0.427	0	0.916
GIS	2,941	1.627	4.177	0	0	15.66
IUR	2,941	1.861	1.049	2.079	0	3.738
Size	2,941	22.05	1.289	21.87	19.70	26.06
Lev	2,941	0.426	0.208	0.419	0.0500	0.894
ROA	2,941	0.0430	0.0640	0.0410	−0.230	0.220
ATO	2,941	0.662	0.454	0.560	0.0670	2.645
Cashflow	2,941	0.0460	0.0720	0.0460	−0.177	0.246
REC	2,941	0.116	0.102	0.0920	0	0.460
INV	2,941	0.149	0.139	0.114	0	0.719
FIXED	2,941	0.217	0.164	0.183	0.00200	0.710
col	2,941	10.53	0.872	10.69	0	11.71
pgdp	2,941	10.73	0.568	10.72	8.959	12.12
pop	2,941	17.76	0.673	17.91	14.88	18.65

TABLE 2 Pearson's correlation matrix for all variables.

	RD1	Patent1	Qua1	IUR	GIS	Size	Lev	ROA	ATO	Cashflow	REC	INV	FIXED	col	pgdp	pop	VIF
RD1	1																
Patent1	0.391***	1															
Qua1	0.416***	0.927***	1														
IUR	0.114***	0.184***	0.190***	1													
GIS	0.080***	0.114***	0.184***	0.190***	1												1.05
Size	−0.043***	−0.171***	0.292***	0.191***	0.012**	1											1.51
Lev	−0.084***	−0.271***	0.018***	−0.040***	−0.035***	0.482***	1										2.01
ROA	0.048***	0.156***	0.075***	0.071***	0.021***	−0.031***	−0.393***	1									1.51
ATO	−0.00600	0.074***	0.068***	0.038***	0.011**	0.033***	0.132***	0.176***	1								1.14
Cashflow	−0.012**	0.080***	0.035***	0.019***	−0.012**	0.058***	−0.150***	0.363***	0.121***	1							1.34
REC	0.144***	0.350***	0.273***	0.293***	0.102***	−0.183***	−0.008	−0.011**	0.152***	−0.191***	1						1.34
INV	−0.030***	−0.140***	−0.082***	−0.096***	−0.027***	0.106***	0.320***	−0.086***	0.032***	−0.229***	−0.098***	1					1.40
FIXED	−0.079***	−0.187***	−0.067***	−0.088***	−0.019***	0.098***	0.108***	−0.111***	0.00800	0.239***	−0.283***	−0.307***	1				1.44
col	0.029***	0.285***	0.225***	0.237***	0.051***	0.053***	−0.116***	0.049***	0.00100	0.021***	0.196***	−0.037***	−0.204***	1			1.64
pgdp	−0.042***	0.084***	0.026***	0.018***	−0.032***	0.071***	−0.023***	−0.00800	−0.028***	−0.00800	0.047***	−0.028***	−0.118***	0.237***	1		1.34
pop	0.099***	0.120***	0.138***	0.148***	0.080***	−0.079***	−0.059***	0.047***	0.060***	0.037***	0.092***	−0.026***	0.009*	0.424***	−0.301***	1	1.59

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

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TABLE 3 Empirical results of the impact of IUR-cooperation projects on innovation performance.

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	RD1	RD1	Patent1	Patent1	Qua1	Qua1
IUR	0.0002**	0.0002**	0.0419***	0.0149*	0.0029***	0.0017***
	(0.0000)	(0.0000)	(0.0079)	(0.0077)	(0.0005)	(0.0005)
Size		−0.0008***		0.502***		0.0217***
		(0.0001)		(0.0126)		(0.0008)
Lev		−0.0031***		−0.262***		−0.0123***
		(0.0005)		(0.0547)		(0.0033)
ROA		−0.0011		0.120		0.0168**
		(0.0011)		(0.118)		(0.0072)
ATO		0.0040***		−0.0651**		−0.0072***
		(0.0002)		(0.0257)		(0.0016)
Cashflow		0.0052***		0.0552		0.0000
		(0.0009)		(0.0884)		(0.0054)
REC		0.0184***		1.200***		0.0659***
		(0.0011)		(0.117)		(0.0071)
INV		0.0024***		0.0085		−0.0084*
		(0.0008)		(0.0825)		(0.0051)
FIXED		0.0044***		0.239***		0.0059
		(0.0006)		(0.0673)		(0.0041)
Col		−0.0002		0.0858***		0.0000
		(0.0002)		(0.0219)		(0.0014)
Pgdp		−0.0000		−0.0023		0.0000
		(0.0001)		(0.0128)		(0.0008)
Pop		0.0009		−0.0475		0.0036
		(0.0006)		(0.0654)		(0.0040)
Constant	0.0085***	0.0082***	0.952***	−9.671***	0.0285***	−0.491***
	(0.0013)	(0.0016)	(0.143)	(1.205)	(0.0087)	(0.0741)
Year fixed	Yes	Yes	Yes	Yes	Yes	Yes
Industry fixed	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.142	0.167	0.241	0.287	0.245	0.270
N	326	326	326	326	326	326

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

4.3. Moderating analysis

Our evidence so far implies that IUR-cooperation projects can effectively improve innovation performance. Table 4 displays the empirical estimation findings for testing the moderating influence of government innovation subsidies. In column (1), the coefficient of the key interaction term IUR*GIS is positive and significant. This result suggests that the effect of IUR-cooperation projects on innovation inputs is more pronounced in enterprises with higher government innovation subsidies. The results can also be shown in Figure 2. This finding supports H2. In columns (2) and (3), IUR is a variable with significantly positive coefficients. The components associated with GIS are significant, and the interaction term (IUR*GIS) is strongly negative. Thus, government innovation subsidies are not only inefficient at enhancing the outputs of company innovation, but they also have a negative moderating impact, diminishing the importance of IUR-cooperation projects in encouraging the outputs and quality of enterprise innovation. The results can also be shown in Figures 3, 4. Thus, H3 and H4 are also supported.

The empirical result that government innovation subsidies in this model do not increase enterprises' innovation output and efficiency is supported by a substantial empirical research as (75, 76). While China's industrial and innovation support policies can encourage enterprises to expand the number of innovation inputs, they are not successful in enhancing company innovation output and quality. None of the previous studies address the fact that government innovation subsidies have a negative moderating effect on the influence of IUR-cooperation projects on company innovation output. This study

TABLE 4 Empirical results of government innovation subsidies as moderator.

	(1)	(2)	(3)
Variables	RD1	Patent1	Qua1
IUR	0.0002**	0.0147**	0.0016***
	(0.0000)	(0.0077)	(0.0004)
GIS	0.0001***	0.0202***	0.0012***
	(0.0000)	(0.0016)	(0.0000)
IUR*GIS	−0.0000***	−0.0244***	−0.0012***
	(0.0000)	(0.0018)	(0.0001)
Size	−0.0008***	0.498***	0.0214***
	(0.0001)	(0.0126)	(0.0008)
Lev	−0.0031***	−0.254***	−0.0117***
	(0.0005)	(0.0545)	(0.0034)
ROA	−0.0011	0.130	0.0176**
	(0.0011)	(0.117)	(0.0072)
ATO	0.0040***	−0.0659***	−0.0073***
	(0.0002)	(0.0256)	(0.0016)
Cashflow	0.0052***	0.0659	0.0008
	(0.0009)	(0.0880)	(0.0054)
REC	0.0183***	1.192***	0.0651***
	(0.0011)	(0.116)	(0.0072)
INV	0.0024***	0.0183	−0.0079
	(0.0008)	(0.0822)	(0.0051)
FIXED	0.0043***	0.231***	0.0054
	(0.0006)	(0.0670)	(0.0041)
Col	−0.0002	0.0852***	0.0000
	(0.0002)	(0.0218)	(0.0013)
Pgdp	−0.0000	−0.0011	0.0001
	(0.0001)	(0.0128)	(0.0007)
Pop	0.0009	−0.0346	0.0043
	(0.0006)	(0.0651)	(0.0040)
Constant	0.0081	−9.841***	−0.500***
	(0.0116)	(1.200)	(0.0739)
Year fixed	Yes	Yes	Yes
Industry fixed	Yes	Yes	Yes
R-squared	0.168	0.292	0.275
N	326	326	326

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

has significant policy implications, including the inadequacy of present innovation support programs in encouraging the outputs and quality of enterprises' innovation.

4.4. Robustness tests

4.4.1. Replacing the dependent variables

This study will conduct robustness tests in the following areas to further assess the dependability of the results of the initial regression (77). RD2, Paten2, and Qua2 are substitutions for RD1, Paten1, and Qua1, respectively. As seen in Table 5, the outcomes are essentially consistent with the main regression.

4.4.2. Instrumental variable method

We carried out an instrumental variable analysis to allay the endogeneity worry brought on by omitted variables. As the instrumental variables (IV), designated by IUR_PRO and IUR _ PRO_IND, respectively, we selected the average IUR-cooperation projects of the other enterprises situated in the same province and the

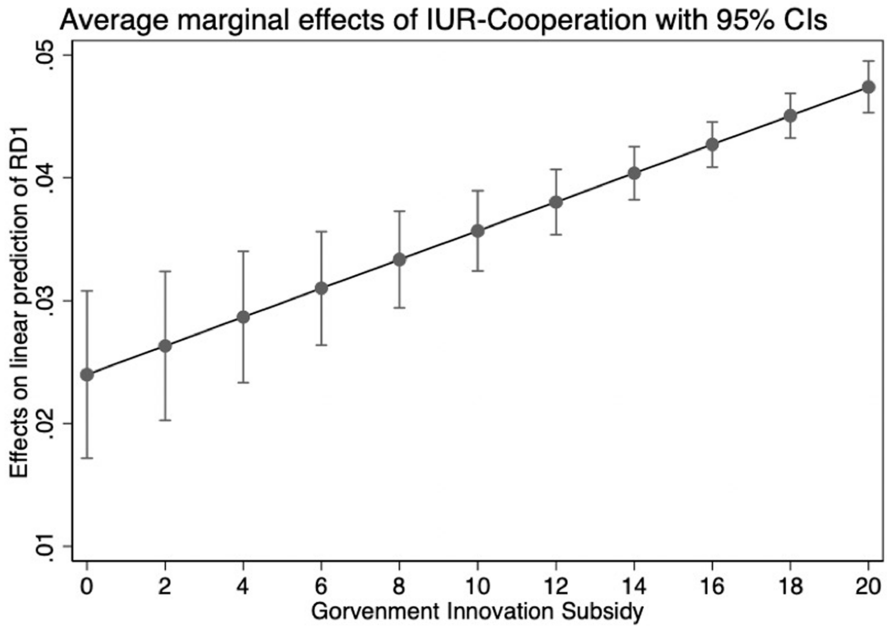

FIGURE 2
The moderating effect of GIS on RD.

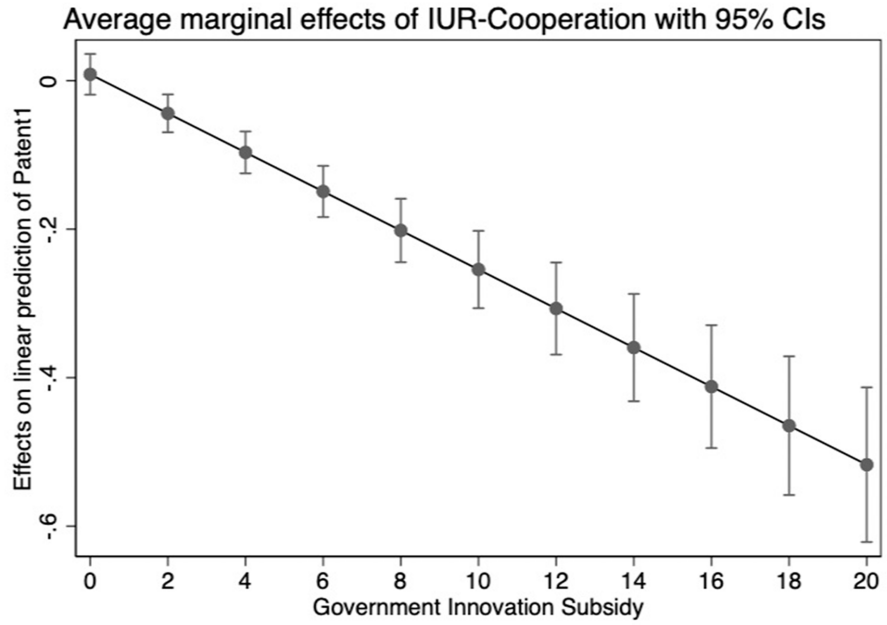

FIGURE 3
The moderating effect of GIS on patent.

average IUR-cooperation projects of the other firms located in the same province and belonging to the same industry. The method used as Zhou et al. (78) and Kanama and Nishikawa (79). The rationale behind establishing the number of tool variables in this manner is that the level of IUR-cooperation projects is obviously influenced by the features of regions and industries due to the various innovation resources and innovation requirements. Consequently, the total of industry-academic-research-cooperation variables at the regional and industry levels is anticipated to have a significant impact on the scope of enterprises' participation in IUR-cooperation. Regional and firm-level industry-university cooperation is unlikely to have a systematic effect on the innovation quality of individual enterprises. IUR _PRO and IUR _PRO_IND can therefore be used as the best instrumental variables for an industry-university partnership because they are consistent with the chosen standard of a valid instrumental variable.

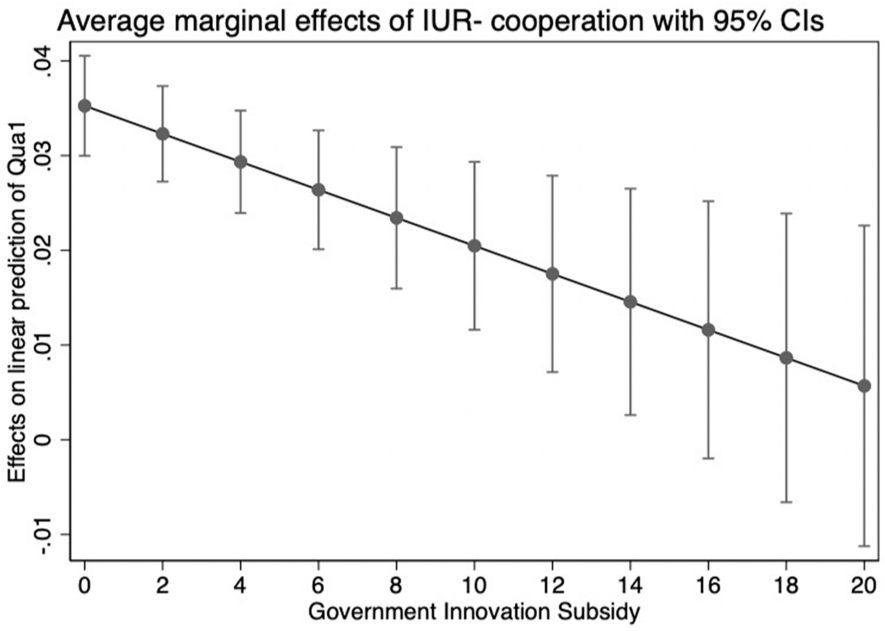

FIGURE 4
The moderating effect of GIS on quality.

Based on Jin and Wu's (80) method from 2021, we adopted a two-stage approach for this analysis. The results can be found in Table 6. In the first stage, we performed a regression of IUR-cooperation projects on IV. In the second stage, we replaced the IUR-cooperation projects index in the full model with the arithmetic mean of the fitted value from the first stage. Table 6 displays the estimated outcomes. In columns (1) and (5), the results of the first stage indicate that both instrumental variables have a significant positive correlation with IUR cooperation. The coefficients of IUR-cooperation projects in columns (2)–(4) and (6)–(8) are all positive and statistically significant. The outcomes are consistent with our initial findings.

5. Discussion

5.1. Discussion and conclusion

This study seeks to investigate whether and how Chinese biopharmaceutical firms leverage IUR-cooperation projects to enhance their innovation performance. To achieve this goal, we manually gathered data on IUR-cooperation projects from disclosures made by 326 listed Chinese biopharmaceutical firms between 2007 and 2021. We then applied a fixed effect model to assess the impact. Specifically, our findings reveal that IUR-cooperation projects have significantly improved the innovation performance of listed Chinese biopharmaceutical companies. They have led to a 0.002 percentage point increase in innovation inputs and a 0.0147 percentage point boost in innovation quality. These results indicate that IUR-cooperation projects not only augment the innovative input of biopharmaceutical enterprises but also contribute to the quality and quantity of their innovation. These findings extend empirical research on the influence of IUR-cooperation projects on the innovation performance of biopharmaceutical firms from the initial stages of collaboration, an aspect often overlooked in existing literature. Furthermore, our research demonstrates that government innovation subsidies positively impact the relationship between IUR-cooperation projects and innovative input, a finding consistent with Bozeman and Gaughan's (81). However, government innovation subsidies have a contrasting effect on the link between IUR-cooperation projects and innovation outputs and quality, leading to a negative moderation. This contrasts with the findings of Zhang, Yuan and Wang (82), who examined the diversity of partners involved in IUR-cooperation.

5.2. Theoretical implications of the study

In this article, the independent variables are quantified by assessing the corporative projects between listed companies and academia, unlike literature focus on paper and patents (21). These projects are the beginning of the inception of knowledge integrate with enterprises, universities, and research institutions. Thus, quantifying the cooperative aspect of the knowledge generation stage within the knowledge-based theory. The dependent variable under investigation pertains to the research and development performance of these listed companies, quantifying their knowledge utilization status. This provides evidence for the impact of IUR cooperation on knowledge theory. Furthermore, we introduce a consideration for the quality of innovation. The primary objective of IUR cooperation is to facilitate the integrate the cutting-edge technology and scientific advancements from universities and research institutes to enterprises, thus aiding them in achieving high-quality innovation. In line with the goals of IUR cooperation, we employ exploitation innovation (61) as a metric for evaluating innovation quality, a novel approach in the

TABLE 5 Empirical results of replacing the dependent variables.

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	RD2	Patent2	Qua2	RD2	Patent2	Qua2
IUR	0.0005***	0.0193**	0.00206***	0.0005***	0.0191**	0.0020***
	(0.0001)	(0.0091)	(0.0006)	(0.0002)	(0.0091)	(0.0006)
GIS				0.0000***	0.0233***	0.0014***
				(0.0000)	(0.0018)	(0.0001)
IUR*GIS				0.0000***	−0.0274***	−0.0014***
				0.0000	(0.0022)	(0.0001)
Size	0.0009***	0.577***	0.0244***	0.0008***	0.573***	0.0241***
	(0.0002)	(0.0149)	(0.0009)	(0.0003)	(0.0149)	(0.0009)
Lev	−0.0155***	−0.376***	−0.0180***	−0.0154***	−0.367***	−0.0173***
	(0.0011)	(0.0646)	(0.0040)	(0.0011)	(0.0644)	(0.0040)
ROA	−0.0455***	0.0993	0.0186**	−0.0454***	0.111	0.0195**
	(0.0025)	(0.139)	(0.0087)	(0.0025)	(0.139)	(0.0086)
ATO	−0.0106***	−0.0692**	−0.0084***	−0.0106***	−0.0702**	−0.0085***
	(0.0005)	(0.0303)	(0.0019)	(0.0005)	(0.0302)	(0.0019)
Cashflow	−0.0044**	0.0873	0.0011	−0.0043**	0.0997	0.0019
	(0.0018)	(0.104)	(0.0065)	(0.0018)	(0.104)	(0.0065)
REC	−0.0078***	1.402***	0.0768***	−0.0079***	1.392***	0.0758***
	(0.0024)	(0.138)	(0.0086)	(0.0024)	(0.137)	(0.0086)
INV	−0.0093***	−0.0220	−0.0125**	−0.0093***	−0.0111	−0.0119**
	(0.0017)	(0.0975)	(0.0061)	(0.0017)	(0.0971)	(0.0061)
FIXED	0.0019	0.219***	0.0037	0.0018	0.211***	0.0030
	(0.0014)	(0.0795)	(0.0050)	(0.0014)	(0.0792)	(0.0050)
Col	0.0011**	0.102***	−0.0000	0.0010**	0.101***	−0.0000
	(0.0005)	(0.0258)	(0.0016)	(0.0004)	(0.0257)	(0.0016)
Pgdp	−0.0001	−0.0073	−0.0001	−0.0001	−0.0060	−0.0000
	(0.0002)	(0.0152)	(0.0009)	(0.0003)	(0.0151)	(0.0009)
Pop	−0.00078	−0.0884	0.0028	−0.0007	−0.0737	0.0037
	(0.0014)	(0.0772)	(0.0048)	(0.0013)	(0.0769)	(0.0048)
Constant	0.0251	−10.33***	−0.522***	0.0247	−10.53***	−0.533***
	(0.0251)	(1.423)	(0.0888)	(0.0251)	(1.418)	(0.0886)
Year fixed	Yes	Yes	Yes	Yes	Yes	Yes
Industry fixed	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.166	0.278	0.263	0.166	0.283	0.268
N	326	326	326	326	326	326

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

field. Measuring innovation quality using the breadth-of-knowledge method is a seldom explored aspect in previous research. Notably, our study recognizes the government's pivotal role as a stakeholder in IUR cooperation, involving multiple parties. However, prior research often approaches the impact of policy trends from the perspective of universities. Zhang et al. (83) based on a novel sample of the China Academy of Sciences (CAS), collect data from 1978 to 2015 and test the government policy may have an influence on cooperation structures. In contrast, our analysis focuses on government subsidies for innovation as a conditional variable, providing a more targeted examination that accurately acknowledges the government's role in the context of cooperative innovation. This approach aligns with our objective to gain a deeper understanding of the government's influence in this arena.

5.3. Practical implication

For administrators, our study underscores the importance of fostering intensified interactions and cooperation between industries,

TABLE 6 Empirical results of instrumental variable method.

	IV = IUR _PRO				IV = IUR _PRO_IND			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Variables	IUR	RD1	Patent1	Qua1	IUR	RD1	Patent1	Qua1
IV	0.0981***				0.0985***			
	(0.0003)				(0.0015)			
IUR		0.0058***	0.368***	0.0172***		0.00213***	0.150***	0.0064***
		(0.0046)	(0.0401)	(0.0023)		(0.0002)	(0.0226)	(0.0013)
Size	0.0726***	−0.0117***	0.565***	0.0227***	0.0694***	−0.0009***	0.581***	0.0236***
	(0.0057)	(0.0058)	(0.0081)	(0.0005)	(0.0055)	(0.0000)	(0.0076)	(0.0004)
Lev	−0.3781***	−0.0643***	−0.348***	−0.0158***	−0.38231***	−0.0079***	−0.436***	−0.0201***
	(0.0065)	(0.0006)	(0.0529)	(0.0030)	(0.0012)	(0.0005)	(0.0502)	(0.0029)
ROA	−0.0006	0.0161***	0.596***	0.0396***	−0.0978	0.0159***	0.581***	0.0389***
	(0.1061)	(0.0019)	(0.141)	(0.0079)	(0.0016)	(0.0018)	(0.138)	(0.0078)
ATO	−0.1025***	0.0042***	0.138***	0.00334***	−0.0979***	0.0044***	0.118***	0.00235**
	(0.0140)	(0.0002)	(0.0205)	(0.0012)	(0.0131)	(0.0002)	(0.0198)	(0.0011)
Cashflow	−0.1652**	0.0186***	0.719***	0.0309***	−0.1422	0.0193***	0.756***	0.0327***
	(0.0869)	(0.0001)	(0.118)	(0.0066)	(0.0840)	(0.0013)	(0.115)	(0.0065)
REC	1.292***	0.0172***	1.742***	0.0996***	1.2272***	0.0222***	2.022***	0.113***
	(0.0661)	(0.0012)	(0.105)	(0.0059)	(0.0646)	(0.0011)	(0.0948)	(0.0053)
INV	−0.0020	0.026***	0.0152	−0.0013	−0.0231	0.0025***	0.0103	−0.00161
	(0.0554)	(0.0007)	(0.0730)	(0.0042)	(0.0534)	(0.0006)	(0.0713)	(0.0041)
FIXED	−0.2581***	−0.0043***	−0.672***	−0.0395***	−0.2121***	−0.0053***	−0.737***	−0.0427***
	(0.0437)	(0.0006)	(0.0603)	(0.0034)	(0.0352)	(0.00057)	(0.0583)	(0.0034)
Col	0.0104**	0.0102***	0.0719***	0.00280***	0.0094**	0.0016***	0.0834***	0.0834***
	(0.0053)	(0.0002)	(0.0136)	(0.0008)	(0.0045)	(0.0001)	(0.0024)	(0.0024)
Pgdp	−0.0282***	0.0027***	0.144***	0.00753***	−0.0192***	0.0010***	0.0648***	0.00245***
	(0.0046)	(0.0001)	(0.0126)	(0.0007)	(0.0099)	(0.0001)	(0.0132)	(0.0008)
Pop	−0.0161*	0.0004	0.3681***	0.0172***	0.0231*	0.0037	0.175***	0.0091***
	(0.0009)	(0.000)	(0.0401)	(0.0022)	(0.0009)	(0.0048)	(0.0115)	(0.0006)
Constant	0.2543**	−0.0193***	−0.522***	0.565***	0.2543**	−0.533***	−15.97***	−0.693***
	(0.0025)	(0.003)	(0.0888)	(0.0081)	(0.0025)	(0.0886)	(0.3115)	(0.0181)
Year fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.328	0.457	0.445	0.423	0.283	0.268	0.472	0.440
N	326	326	326	326	326	326	326	326

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

educational institutions, and other entities. Such cooperation should be structured to ensure that both parties can grow in alignment with the necessary supporting infrastructure and more. The synergy between businesses, academia, and research institutions plays a pivotal role in fostering innovation and development. Our findings also lead to the conclusion that government innovation policies cannot solely rely on government subsidies, as this approach may distort their effectiveness. In the realm of innovation policy, evaluation criteria such as "input but not output" and "quantity but not quality" should be reconsidered. Government innovation subsidies should aim to support the synergy between firms' innovation performance and IUR-cooperation while alleviating the costs associated with identifying collaborators, facilitating communication, and assessing potential risks. The government's role should encompass the establishment of a platform for IUR-cooperation initiatives, along with the optimization of the innovation market environment and legal framework.

5.4. Future research

The following outlines the potential avenues for future research: (1) Businesses aspire to cooperate and innovate, aiming to secure new

products and technologies and subsequently penetrate new markets. Our current preference for assessing innovation indicators involves the examination of patent data. However, in our future research, we may explore the adoption of more market-oriented indicators. (2) The majority of our research has concentrated on publicly traded pharmaceutical companies. These listed firms tend to be larger in size, yet their inclination and capacity for collaboration may not be as strong as that of smaller businesses. However, information about non-listed companies is often not readily accessible or transparent. In the future, should we gain access to suitable data, we could consider analyzing samples from SMEs.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YX: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft. YJ: Funding acquisition, Project administration, Supervision, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2023.1271364/full#supplementary-material

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Effects of information and communication technology on total-factor carbon emission efficiency and the health co-benefits

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Information and communication technology (ICT) has great potential to propel economic development toward a low-carbon direction. This study aims to investigate the effect of ICT development on total-factor carbon emission efficiency (TFCEE), as well as its public health co-benefits. We use dynamic (threshold) models and a panel of 30 Chinese provinces from 2008 to 2019. The results suggest that ICT significantly and positively impacts the TFCEE. Specifically, for every 10 per cent increase in the internet development index, the TFCEE increases by 0.11 per cent. Moreover, we find that ICT development indirectly improves the TFCEE by promoting green innovation and energy structure optimization. Furthermore, when green innovation (energy structure represented by the share of coal) switches from below to above (above to below) its threshold value, the promotion effect of ICT development on the TFCEE increases. Additionally, the results show that improving the TFCEE can lead to co-benefits in strengthening China's public health. This study delivers novel insights on promoting the TFCEE through the ICT channel and highlights its positive health-related externalities. Furthermore, we offer policy recommendations to Chinese decision-makers, which can apply to other emerging economies battling similar issues.

KEYWORDS

information and communication technology development, total-factor carbon emission efficiency, health, dynamic threshold model, moderating effect

1 Introduction

While China's economy has grown significantly during the past four decades, its carbon emissions have increased dramatically. Consequently, China is the world's leading greenhouse gas emitter (1). Ample empirical evidence indicates that carbon emissions are among the significant factors threatening public health (2–4). Thus, low-carbon transition has massive potential to bring public health co-benefits by directly reducing carbon dioxide inhalation, mitigating climate change, and reducing air pollutants that share emission sources with CO_2 (2, 5–7). Against the above backdrop, Chinese policymakers pledged to peak total CO_2 emissions by 2030 and to achieve carbon neutrality by 2060 (8) to maintain a balance between sustainability and carbon emissions. It is estimated that under the conditions of achieving the 1.5 C temperature goal and reaching the peak earlier than 2030, Chinese policymakers could prevent 118,000 (614,000) deaths by 2030 (2050) (9).

Notwithstanding, as an emerging economy, China needs to promote prolonged economic expansion. Thus, in the face of conflicting goals of carbon emissions reduction and continued economic growth, the key to resolving this dilemma is to improve the total-factor carbon emission efficiency (hereafter TFCEE) (10). TFCEE takes the GDP (carbon emissions) as the desired (undesired) output while considering the factor inputs of capital, labor and energy. As such, the TFCEE can effectively measure whether and to what extent regional development models meet the requirements of low-carbon transformation (11). Given the above backdrop, how to effectively improve the TFCEE has become a topical research question in recent environmental studies (10, 12).

Since the 21st century, the integration of information and communication technology (hereafter ICT) with various sectors of the economy has shown an unstoppable trend. Countries worldwide endeavor to develop and harness ICT, with internet technology being an essential part of it. China's public internet access started in 1994, while in August 2013, the State Council issued the Broadband China policy vigorously promoting ICT infrastructure construction. The recent 50th Statistical Report released by the China Internet Network Information Center (13) shows that, between 2008 and 2022, internet penetration in China has more than tripled from 22.6 to 75.6 per cent (see Figure 1).

Many studies investigate the effect of ICT or internet development on variables related to energy or carbon emissions, but the results remain inconclusive. Some scholars argue that ICT-related factors reduce carbon intensity (14). Others find that internet development increases enterprise energy efficiency (15) and improves the TFCEE (11, 16). On the contrary (17, 18), document that demand for ICT products increases carbon emissions and energy intensity. Overall, the existing literature has four important shortcomings. First, current studies ignore the suspected path dependence of TFCEE and use static regression models, which may yield estimation bias (11, 16). Second, the mediation and threshold effects between ICT development and TFCEE have not received adequate attention. Third, while limited studies show a positive (negative) association between ICT (carbon emissions) and public health in China (2, 9, 19), the health co-benefits from improving TFCEE remain unexplored.

Given the pivotal role of ICT in propelling China's economic development toward a low-carbon direction and the above-listed gaps in empirical research, our study has four main objectives. First, to investigate the relationship between ICT and TFCEE using a dynamic model. Second, to unveil how ICT impacts TFCEE through the mediation effect of green innovation and energy structure optimization and the threshold effect of ICT at different values of the two mediator variables. Finally, the study directly examines whether and how TFCEE improvement affects public health across 30 Chinese provinces.

Accordingly, the contributions of this study are as follows. We are the first to employ the dynamic model to identify the role of ICT in promoting TFCEE. Specifically, we use the two-step system generalized method of moments (hereafter 2SGMM), which accounts for the suspected path dependence (autoregressive process) of the TFCEE variable and mitigates the endogeneity problem. Moreover, we document nascent empirical evidence of the significantly beneficial effect of ICT on the TFCEE via its positive influence on green innovation and energy structure optimization. Additionally, we are the first to quantify the significantly different impact of ICT on the TFCEE concerning threshold levels of green innovation and energy structure. Finally, we deliver a novel contribution by documenting positive public health-related externalities associated with policies that improve the TFCEE through ICT development.

The remainder of this article is as follows: Section 2 presents a literature review. Section 3 develops the hypotheses, while Section 4 offers data and research methods. In Section 5, we outline and discuss the empirical results. We conclude the study and provide policy suggestions in Section 6.

2 Literature review

2.1 TFCEE measurements

One can measure carbon emission efficiency by single-factor indicators, which usually reflect the interaction between carbon emissions and GDP. For example, CO_2 emissions intensity is the ratio of carbon emissions to GDP (1). However, single-factor indicators do not consider all the key inputs in the production process, as well as the substitution effect among inputs. Thus, single-factor indicators are not capable of fully measuring CO_2 emission efficiency (10). Because of this limitation, some studies add capital and labor inputs into the analysis of carbon emission efficiency and propose the TFCEE as an alternative superior indicator (20).

Using TFCEE, we can estimate more accurately whether the development pattern meets the sustainable requirement of economic growth and carbon abatement. Data envelopment analysis methods are widely used to calculate the TFCEE (10). For instance, the directional distance function (hereafter DDF) captures the production process, including the undesired output of carbon emissions (21). However, the original DDF model is limited to increasing (reducing) desired (undesired) outputs (and/or inputs) with the same ratio, thereby leading to an overestimation of efficiency when non-zero slacks exist (22). Therefore, scholars propose the non-radial directional distance function (hereafter NDDF) based on slack variables to solve such an acute problem (23).

2.2 ICT development and TFCEE nexus

Scholars examining the multifaceted effects of ICT/internet advancements on energy usage or carbon emissions deliver conflicting evidence. On the one hand, some researchers find that ICT/internet development reduces carbon emissions (24), CO_2 per capita (25), carbon intensity (14), and energy consumption (26) while improving energy efficiency (27). On the other hand, others argue that the ICT/internet threatens the sustainability of resources and the environment by increasing CO_2 emissions (17) and energy intensity (18). Moreover (28), point out that the impact of ICT on carbon emissions per capita is uncertain by documenting a positive (negative) relationship in the short (long) term. It is worth noting

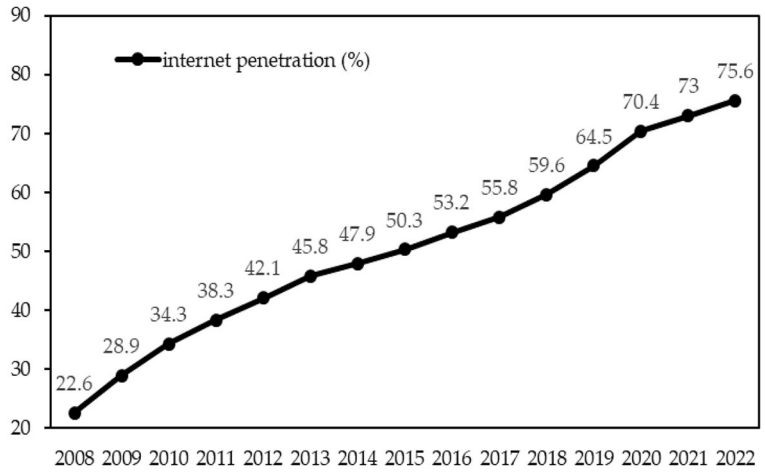

FIGURE 1
China's internet penetration growth in percentage terms from 2008 to 2022. Source: CNNIC, 2008-2022.

that the studies mentioned above use static models. However, the present value of the TFCEE is significantly influenced by its earlier values, which gives rise to a robust cumulative circularity (12, 29).

Two recent studies exploring the ICT and TFCEE nexus in China use static models and reveal a positive relationship (11, 16). Notwithstanding, some research suggests that there may be a threshold effect concerning the relationship between ICT progress and the environment or energy (30, 31). However, to our knowledge, no studies have investigated the threshold effects in the context of ICT effects on the TFCEE.[1] Instead, researchers primarily use simple multivariate linear models, neglecting the jumping character or structural breaks in the relationship between ICT development and the TFCEE caused by changes in other economic variables (11, 16).

Moreover, the relationship between the environment and health has long been one of the research hotspots (9, 32, 33). Studies examining China (1), the United States (2), and OECD countries (3) document the adverse effects of carbon dioxide on residents' health. However, there is a considerable lack of research on the impact of TFCEE on health. Additionally, pregnant women are an environmentally sensitive group (34), and health literature has found a strong correlation between air pollution and maternal complications and mortality risk factors (35). However, the maternal group is often overlooked in environmentally related studies.

2.3 Research gaps

Summing up, the following deficiencies are found in the relevant empirical literature: (1) Existing research has not considered that the TFCEE is usually path-dependent (autoregressive process) and has used static models for estimation. (2) Few studies focus on the mediation and threshold effects between ICT development and the TFCEE. (3) Health benefits of the TFCEE improvement remain under-explored. Our study attempts to fill the above research gaps.

3 Hypotheses development

3.1 The direct effect of ICT development on the TFCEE

ICT relies on electricity, and thus, its development may also decrease the TFCEE. With the operation of technologies, e.g., 5G, cloud computing, and data centers, there is a need for a growing number of energy-intensive infrastructures (17). Furthermore, applying ICT in various fields may create more demand for ICT-related products and services, exerting pressure on energy demand and increasing carbon emissions (24).

Notwithstanding, ICT advancement directly improves the TFCEE in two ways. First, ICT promotes the low-carbon transition of people's work and lifestyles. For instance, paperless transmission, e-commerce, remote offices, and the sharing economy are gaining ground along with the development of ICT. These approaches achieve more effective utilization of resources and reduce emissions of CO_2 caused by logistics, transportation, and the functioning of building space (36), thereby directly improving the TFCEE. Second, ICT improvement substantially boosts the level of informatization in other industries. Regarding production, ICT plays a fundamental role in the practical implementation of an energy management system (EMS) (37). The EMS, in turn, automatically controls, adapts, and optimizes the energy networks and orderly configures and schedules the multiple energy systems, thereby increasing the efficiency of the energy system.

Summing up, most studies suggest a generally beneficial influence of ICT development on the TFCEE. In other words, extant empirical evidence indicates that the positive impact of ICT tends to outweigh its adverse side effects on the TFCEE (24). Accordingly, we propose hypothesis 1, stated below.

1 Hao et al. (30) and Wu et al. (31) examine the threshold effects of ICT/internet development on electricity intensity or green total factor energy efficiency in China.

Hypothesis 1. ICT development positively affects the TFCEE.

3.2 The mediation effect of green innovation

ICT development is conducive to green innovation via the generation, acquisition, processing, and exchange of information (38). Specifically, ICT expansion drives the growth of information related to environmentally sound technologies while improving search efficiency and decreasing the acquisition cost. Moreover, ICT advances dramatically enhance the ability of individuals and organizations to process information and transform enterprises from experience- to data-driven (39). ICT also forms innovation clusters by linking various innovative entities (e.g., firms, universities, R&D institutions, and non-governmental organizations) together, thus facilitating communication, complementarity, and knowledge spillover among innovators (38). The mechanisms mentioned above increase the utilization of relevant information resources and the success rate of green innovation, thus promoting green innovation.

Green innovation, in turn, can significantly improve the TFCEE through the following mechanisms. First, some green technological advances (e.g., capturing and storing CO_2) directly contribute to energy savings and carbon reduction (10). Likewise, air quality management and energy storage technologies enable the same output with less energy input and fewer emissions, leading to a higher TFCEE. Second, environmental innovations can help renovate and upgrade pollution treatment equipment (40). As such, assuming it is effectively adopted, green technology innovation optimizes production processes and promotes the low-carbon transformation of energy-intensive enterprises, thereby improving the TFCEE (41). Given the above backdrop, we propose a second hypothesis as follows.

Hypothesis 2. ICT development significantly increases the TFCEE by promoting green innovation.

3.3 The mediation effect of energy structure optimization

ICT has motivated the so-called energy internet development (42), which uses cyberspace to identify, collect, analyse, transmit, and manage energy information. Furthermore, the energy internet integrates internet technology, multi-energy networks and technologies for renewable energy generation, enhancing system resilience and energy utilization efficiency and promoting renewable energy penetration (43). Additionally, the energy internet can overcome barriers to extraction, transmission, and control of large-scale clean energy projects and promote the transformation of economic development from traditional fossil fuels to a clean and efficient energy source (42). This process, in turn, drives the sustainable utilization of energy resources and promotes energy structure optimization. Moreover, with the growing popularity of the energy internet, clean energy usage is continuously expanding (e.g., electric vehicles), which further optimizes the energy structure.

Summing up, energy structure optimization increases the proportion of clean energy sources. Therefore, energy structure optimization can achieve the same economic output with fewer carbon emissions, improving the TFCEE (44). Given the above, we put forth hypothesis 3.

Hypothesis 3. ICT development significantly increases the TFCEE by promoting energy structure optimization.

4 Dataset, variables, and models

4.1 Benchmark regression model

The relationship between ICT development and the TFCEE can be represented by the basic model as follows.

$$TFCEE_{i,t} = \alpha_0 + \alpha_1 ICT_{i,t} + \beta\ Control_{i,t} + \mu_i + \delta_t + \varepsilon_{i,t} \quad (1)$$

Where $TFCEE_{i,t}$ is the total-factor carbon emission efficiency in Chinese province i and year t. The *ICT* term represents ICT development, while the *Control* term represents a vector of five control variables, including provincial population (*POP*), science and technology expenditure intensity (*TECH*), economic development (*GDP*), degree of economic openness (*OPEN*) and industrial structure (*IND*). μ_i and δ_t are the province and time-fixed effects, respectively. $\varepsilon_{i,t}$ is a random error term with zero mean, constant variance and is not serially correlated.

Given that the outcome variable *TFCEE* may be path-dependent (autoregressive process) (12, 29), we introduce a first lag of the dependent variable ($TFCEE_{i,t-1}$) into the right-hand side of Equation (1). However, dynamic models tend to suffer from endogeneity issues. In contrast, the OLS and the Fixed Effects (FE) estimators would yield biased results (45). Therefore, we use 2SGMM[2] (46) to estimate the dynamic model [see Equation (2)], which tests hypothesis 1.

$$TFCEE_{i,t} = \alpha_0 + \alpha_1 TFCEE_{i,t-1} + \alpha_2 ICT_{i,t} + \beta\ Control_{i,t} + \mu_i + \delta_t + \varepsilon_{i,t} \quad (2)$$

4.2 Mediation effects

Besides its direct effect, ICT development may also have two indirect effects on TFCEE, generally referred to as the mediation effects. To empirically examine such effects, Equation (3) is constructed as follows (47) to test hypotheses 2 and 3.

$$MED_{i,t} = \lambda_0 + \lambda_1 MED_{i,t-1} + \lambda_2 ICT_{i,t} + \theta\ Control_{i,t} + \mu_i + \delta_t + \varepsilon_{i,t} \quad (3)$$

Where *MED* represents two mediator variables: green innovation (*GINNO*) and energy structure (*ENER*). If the coefficient of $\lambda_1$is significant, a mediation effect exists, and vice versa (47).

2 2SGMM is a highly efficient estimation method in tackling the issue of endogeneity (1).

4.3 Dynamic threshold model

With changes in green innovation (*GINNO*) and energy structure (*ENER*), the impact mechanism between ICT development and the TFCEE may have a structural change—that is, there may be a threshold effect (30). To examine this issue, we construct a dynamic threshold model (30) and present it below in Equation (4).

$$TFCEE_{i,t} = \alpha_0 + \alpha_1 TFCEE_{i,t-1} + \alpha_2 ICT_{i,t}\left(q_{i,t} \le T\right) + \alpha_3 ICT_{i,t}\left(q_{i,t} > T\right) + \beta\, Control_{i,t} + \mu_i + \delta_t + \varepsilon_{i,t} \quad (4)$$

Where $q_{i,t}$ is the threshold variable, including green innovation (*GINNO*) and energy structure (*ENER*). T represents the threshold value to be estimated. $\alpha_2(\alpha_3)$ represents the effect of ICT development on the TFCEE when the threshold variable is below (above) the threshold value.

4.4 Data and variables

In line with prior studies (23, 48), we use the NDDF to estimate the *TFCEE* variable. We use a sample of 30 Chinese provinces ($n = 1, 2, \ldots, 30$). Each province includes inputs of capital stock (K), calculated by the perpetual inventory method; labor (L), measured by the total number of employees; and energy (E), expressed as the total energy consumption. Desired output GDP (Y) is proxied by provincial real GDP. In contrast, the undesired output of carbon emissions (C) is calculated according to the 2006 Intergovernmental Panel on Climate Change guidelines for national greenhouse gas inventories. Assuming that the optimal solution of each input and output obtained through the NDDF linear programming is $\beta_K^*, \beta_L^*, \beta_E^*, \beta_Y^*, \beta_C^*$. The dependent variable *TFCEE* can be formulated in Equation (6) (48).

$$TFCEE = \frac{\frac{1}{4}\left[(1-\beta_K^*)+(1-\beta_L^*)+(1-\beta_E^*)+(1-\beta_C^*)\right]}{1+\beta_Y^*} = \frac{1-\frac{1}{4}\left[\beta_K^*+\beta_L^*+\beta_E^*+\beta_C^*\right]}{1+\beta_Y^*} \quad (5)$$

TFCEE ranges from 0 to 1, such that a higher value of the *TFCEE* indicates higher production efficiency of the province. Consequently, if provincial *TFCEE* were equal to 1 (0), it would mean that the corresponding province was fully efficient (inefficient).

We construct a comprehensive index to measure ICT advancement, in line with recent studies (49), as shown in Table 1. Additionally, we employ the entropy method to evaluate the ICT development index (*ICT* variable), which ranges from 0 to 1.

Descriptions of all the variables are presented in Table 2. All variables are at the provincial level. The selection and measurement of the variables align with the prior research (6, 11, 16, 50, 51).

The sample ranges from 2008 to 2019. Due to limited data availability in Hong Kong, Macao, Taiwan, and Tibet, this study focuses on the other 30 provincial administrative regions as the sample. We obtained data from the National Bureau of Statistics, the China Statistical Yearbook, the Statistical Report on China's internet development, and the Chinese Research Data Services Platform. All the data are adjusted for inflation with 2008 as a base period to ensure comparability.

Table 3 presents descriptive statistics for variables. We can observe that the dependent variable *TFCEE* has the minimum (maximum) value of 0.177 (1), with a mean and standard deviation of 0.430 and 0.157, respectively. The leading explanatory variable, *ICT*, has a minimum (maximum) value of 0.018 (0.773), with a mean and standard deviation of 0.116 and 0.117. This result suggests substantial cross-provincial variability in the *TFCEE* and *ICT* during the sample period.

Figure 2 illustrates the trends of *TFCEE* (Figure 2A) and *ICT* (Figure 2B) in China from 2008 to 2019. We can observe that *TFCEE* and *ICT* follow a gradually increasing path over time.

5 Results and discussions

5.1 Benchmark regression results

Table 4 shows the estimated results of the dynamic panel regressions corresponding to the benchmark model in Equation (2). Columns (1) and (2) display the estimation results using the OLS and the FE methods. Column (3) shows the output from the 2SGMM estimation technique. The coefficient on the *LTFCEE* in column (3) is 0.9755 and larger (smaller) than the estimated coefficient from the FE (OLS) method. The results based on the 2SGMM model also pass the m1, m2, and Hansen tests. Due to the above, we can assume that our 2SGMM model is correctly specified. Furthermore, the coefficient on the *LTFCEE* term in column (3) is positive (within the range of zero to one) and statistically significant. This finding indicates that Chinese provincial-level *TFCEE* is path-dependent, in line with the recent study (12, 29). Such evidence could mean that because of the difficulty of changing the provincial-level production mode in the short term, the TFCEE changes slowly and exhibits path dependence.

Column (3) also shows that the *ICT* variable coefficient is statistically significant and positive. Specifically, the coefficient informs us that, on average, for every 10 per cent increase in the ICT development index, we expect the *TFCEE* to increase by 0.11 per cent, ceteris paribus.[3] Therefore, Table 4 implies that ICT development significantly promotes TFCEE improvement, which supports hypothesis 1. This finding supports the conclusions of Hao et al. (30) and Wu et al. (31) about the role of ICT development in driving low-carbon development. The estimated results can be associated with ICT accelerating the intelligent and exemplary management of the whole production process, improving the efficiency of resource allocation, reducing inefficient energy consumption and carbon emissions, and thus improving the TFCEE. China has entered a phase where the pace of economic growth has slowed down. In contrast, the task of carbon emission reduction is urgent due to the associated environmental and health damage, as well as policy commitments, thereby causing the TFCEE

3 Because the sample's mean values (see Table 3) of *TFCEE* (0.430) and *ICT* (0.116) and the coefficient on *ICT* (0.0404) in column (3) of Table 4, the average effect on the *TFCCE* associated with a 10 per cent increase in *ICT* variable is equal to 0.116*0.1*0.0404/0.430, or 0.11 per cent (52).

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TABLE 1 ICT development evaluation.

Variable	Dimension	Indicators	Unit
ICT development index	ICT basic resources	Netizen penetration rate	%
		Mobile phone ownership per 100 people	—
		IPv4 proportion[a]	%
	ICT information resources	Number of domain names per 10,000 people	—
		The average size of a webpage in kilobytes	KB
		The average number of websites per company	—
	ICT applications	The proportion of employment in ICT-related industries	%
		The ratio of e-commerce transactions to GDP	%
		Express service delivery (after placing an order online) volume per person	—

[a]IPv4 is the fourth version of the Internet Protocol (IP), and its proportion can reflect the ICT infrastructure construction level (43).

TABLE 2 Variable descriptions.

Variable type	Variable	Symbol	Variable measurement
Dependent variable	Total-factor carbon emission efficiency	*TFCEE*	As described in Section 4.4
Explanatory variable	Information and communication technology development	*ICT*	As described in Section 4.4
Control variable	Economic development	*GDP*	Natural logarithm of the per capita GDP
	Population	*POP*	Natural logarithm of the population
	Economic openness	*OPEN*	The ratio of the total value of imports and exports to GDP
	Industrial structure	*IND*	The ratio of secondary industries added value to GDP
	Urbanization level	*URBAN*	Urban population as a percentage of the total population
	Government financial autonomy	*GOVAU*	The ratio of government general budget expenditure to GDP
Mediator variable	Green innovation	*GINNO*	Number of green patent applications per capita
	Energy structure	*ENER*	Share of coal in total energy consumption
Public health measures	Inpatients	*INP*	The ratio of inpatients to the total population
	Mortality	*MOR*	Resident mortality (per 1,000 persons)
	Maternal Mortality	*MMOR*	Maternal mortality (per 1,000 live births)

improvement to encounter bottlenecks. As such, our findings could inspire strategic planning development in China and across other emerging economies with similar goals and problems.

5.2 The mediation effects of green innovation and energy structure

Environmental innovations promote continuous production process improvement, e.g., by avoiding high carbon emissions at source and fostering the development of end-of-pipe treatment technologies (carbon-storing and reusing) (41). Therefore, green innovation significantly reduces energy saving and carbon reduction costs, thus driving the TFCEE improvement.

Column (1) in Table 5 shows the estimated results from 2SGMM regression models testing for indirect ICT effects in the TFCEE using green innovation as a mediator variable from equation (3). The coefficient on the *ICT* variable is significant and carries a positive sign, meaning that ICT progress increases green innovation. This aligns with Tang et al. (38), who adopt China's broadband policy as a quasi-natural experiment. Columns (2) and (3) further distinguish between high-quality innovation represented by green inventions (*GINV*) and low-quality innovation represented by green utility models (*GUTI*), respectively. Estimated coefficients indicate that ICT advancement has a significantly stronger (statistically and economically) effect on promoting high-quality rather than low-quality green innovation. Such results can be associated with the ICT promoting digital ecology, thereby increasing research and development (38). This comparative advantage, in turn, makes it more likely for enterprises to receive long-term external financial support when conducting quality green innovation research characterized by higher difficulty levels, greater failure rates, and more extended periods (53). Such incentives motivate Chinese enterprises and significantly increase high-quality green innovation.

Because ICT affects green innovation, which, in turn, affects the TFCEE, we can assume that ICT development indirectly affects the TFCEE, which supports hypothesis 2. ICT is deeply integrated

TABLE 3 Descriptive statistics.

Variable type	Variable	Observations	Mean	Std. Dev.	Min	Max
Dependent variable	*TFCEE*	360	0.4399	0.1571	0.1766	1.000
Explanatory variable	*ICT*	360	0.1162	0.1167	0.0183	0.7728
Control variable	*GDP*	360	10.5173	0.5008	9.0812	11.7410
	POP	360	8.1924	0.7395	6.3172	9.3519
	OPEN	360	0.2711	0.2967	0.0114	1.5914
	IND	360	0.4507	0.0864	0.1620	0.6150
	URBAN	360	0.5639	0.1319	0.2911	0.8960
	GOVAU	360	0.2758	0.1266	0.0870	0.7724
Mediator variable	*GINNO*	360	1.3900	2.1483	0.0548	16.0956
	ENER	360	0.4145	0.1520	0.0121	0.7241
Public health measures	*INP*	360	0.1058	0.0340	0.0391	0.1922
	MOR	360	6.0423	0.7632	4.2100	7.5700
	MMOR	360	0.1624	0.1004	0.0110	0.6204

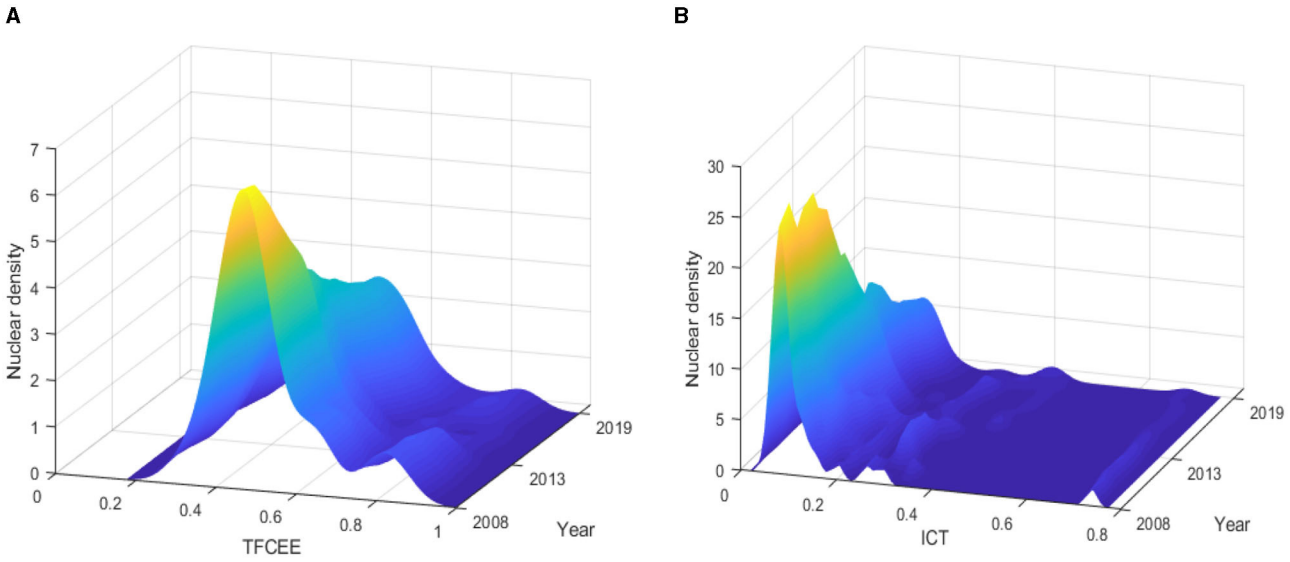

FIGURE 2
Trends of TFCEE **(A)** and ICT **(B)** in China from 2008 to 2019. Source: Authors' calculation.

into enterprises' production and operation activities, promoting their forward-looking technology research and significantly enhancing green innovation capabilities (54). At the same time, ICT development can enable firms to obtain knowledge and information at a lower marginal cost, break through barriers between industries, and further promote green innovation via the knowledge spillover effects (38). Green innovation, in turn, effectively increases energy efficiency and improves production processes (41), enhancing the TFCEE.

The optimization of the energy structure implies an increase (decrease) in the proportion of renewable energy (fossil fuels) in energy consumption. This can reduce carbon emissions, driving the TFCEE's improvement. The testing results for indirect ICT effects in the TFCEE using energy structure as a mediator variable from equation (3) are displayed in column (4) in Table 5. We can observe that the estimated coefficient on the *ICT* variable is negative and significant, which means that ICT development reduces coal's share in total energy consumption, i.e., optimizes the energy structure. This corroborates Xu et al. (55), who found that improving digitalization improves energy composition in a global study of 109 countries.

Again, because the ICT affects energy structure, which, in turn, promotes an improvement in the TFCEE, we can assume that the former indirectly affects TFCEE, in line with hypothesis 3. Specifically, ICT changes energy production and consumption patterns through knowledgeable information-based systems while accelerating energy transformation (27). Additionally, the ICT provides technological support for renewable

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TABLE 4 Benchmark regression results.

Method of estimation	OLS	FE	2SGMM
Variables	(1)	(2)	(3)
TFCEE	0.9926***	0.9075***	0.9755***
	(0.0161)	(0.0280)	(0.0107)
ICT	0.0299*	0.0794*	0.0404***
	(0.0162)	(0.0443)	(0.0097)
GDP	−0.0037	−0.0094	−0.0023
	(0.0062)	(0.0313)	(0.0066)
POP	0.0041	−0.0302	0.0054***
	(0.0026)	(0.0218)	(0.0018)
OPEN	0.0107*	0.0729	0.0121***
	(0.0056)	(0.0714)	(0.0032)
IND	−0.0109	0.0227	−0.0174
	(0.0143)	(0.0320)	(0.0111)
URBAN	0.0292	−0.1574	0.0281
	(0.0223)	(0.1542)	(0.0217)
GOVAU	−0.0137	−0.0653**	−0.0141
	(0.0158)	(0.0258)	(0.0114)
Adj R^2	0.9918	0.9695	
m1 (Z-statistic)			−1.66*
m2 (Z-statistic)			0.89
Hansen test (*p*-value)			0.18
N	330	330	330

The dependent variable is the TFCEE. *, **, and *** are the 10%, 5%, and 1% statistical significance levels of the estimated coefficients, respectively.

TABLE 5 Mediation effect verification results.

Variables	*GINNO*	*GINV*	*GUTI*	*ENER*
	(1)	(2)	(3)	(4)
Lagged dep. Var.	0.9427***	0.9790***	0.9889***	0.8687***
	(0.0321)	(0.0172)	(0.0839)	(0.0711)
ICT	2.8247***	1.7897***	0.7415*	−0.0778**
	(0.6099)	(0.4265)	(0.4127)	(0.0316)
Controls	Yes	Yes	Yes	Yes
m1 (Z-statistic)	−2.39**	−2.26**	−1.83*	−2.98***
m2 (Z-statistic)	−0.42	−0.69	0.03	0.64
Hansen test	0.85	0.94	0.80	0.29
N	330	330	330	330

The dependent variables in columns (1) to (4) are overall green innovation, green inventions, green utility models, and energy structure, respectively. *, **, and *** are the 10%, 5%, and 1% statistical significance levels of the estimated coefficients, respectively. We use the same set of control variables as in Equation (2). However, for this study's brevity, these coefficients are not presented but are available upon request.

energy development (43), promoting global *energy internet* construction (42). This helps reduce the use of traditional high-carbon energy sources, fosters the growth of clean energy sources and optimizes the energy structure. Increasing the proportion of clean and renewable energy helps cut carbon emissions, improving the TFCEE.

5.3 Dynamic threshold model results

In this section, we test whether the threshold effect exists in the ICT-TFCEE nexus. The threshold variables include green innovation (*GINNO*) and energy structure (*ENER*). In the first step, we conduct 1,000 repetitions of bootstrap self-sampling. Table 6 displays the self-sampling test results of the threshold value and a corresponding confidence interval. The Wald statistics and *p*-values all pass the significance test, informing that our model is suitable for further analysis.

Having estimated the threshold values for *GINNO* and *ENER* variables in Table 6, we run 2SGMM dynamic threshold panel regressions corresponding to Equation (4). The estimated results appear in Table 7, where $q_{it} \leq C$ ($q_{it} > C$) indicates that the threshold variable is below or equal to (above) the threshold value. Column (1) shows the results with green innovation (*GINNO*) as the threshold variable. We can observe that when green innovation exceeds the threshold value, the estimated coefficient on *ICT* changes from 0.1064 to 0.1737 and remains statistically significant. For instance, at $q_{it} \leq C$ ($q_{it} > C$), for every 10 per cent increase in *ICT*, we would expect the TFCEE to increase on average by 0.29 (0.47) per cent, holding all else constant. This result can be associated with the evidence that at the early stage of green innovation development, enterprises' research costs are high, and green patent application in production is still being explored. Because of that, the potential for TFCEE improvement through ICT development is somewhat limited. However, once the green innovation development exceeds a certain threshold, key technical challenges to improve the TFCEE no longer hold (38). This, in turn, decreases carbon emissions reduction costs and provides new impetus for ICT development to promote the TFCEE.

Column (2) of Table 7 displays estimated results with the energy structure (*ENER*) as the threshold term. Since *ENER* is represented by the share of coal in total energy consumption, a decrease in *ENER* implies optimization of the energy structure. We can observe that as *ENER* changes from above to below its threshold value, the coefficient on the *ICT* increases from 0.0932 to 0.1434 and remains statistically significant. The fossil fuel-based energy structure is associated with substantial carbon emissions, which impedes the TFCEE improvement. For instance, some underdeveloped regions in northwest China are highly dependent on fossil fuels, which will weaken their capacity to improve the TFCEE (56). As the cost of renewable energy decreases and the proportion of fossil fuels falls below a certain threshold, a cleaner energy structure can strengthen the relationship between ICT and TFCEE (44).

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TABLE 6 Test of the threshold effect.

Threshold variables	Dynamic threshold model	Threshold value	Wald statistics	*p*-Value	BS	95% confidence interval
GINNO	2SGMM	0.8480	607.8981	0.000	1,000	(0.0910, 6.0144)
ENER	2SGMM	0.4769	542.3234	0.000	1,000	(0.1242, 0.6421)

TABLE 7 Dynamic threshold panel regression results.

Variables	*GINNO*	*ENER*
	(1)	(2)
Lagged dep. Var.	0.8351***	0.8864***
	(0.0449)	(0.0143)
$ICT(q_{it} \leq C)$	0.1064*	0.1434***
	(0.0577)	(0.0168)
$ICT(q_{it} > C)$	0.1737***	0.0932**
	(0.0552)	(0.0370)
Controls	Yes	Yes
m1 (Z-statistic)	−1.67*	−1.65*
m2 (Z-statistic)	0.82	0.84
Hansen test	0.70	0.99
N	330	330

The dependent variable is the TFCEE. *, **, and *** are the 10%, 5%, and 1% statistical significance levels of the estimated coefficients, respectively. We use the same set of control variables as in Equation (2). However, for this study's brevity, these coefficients are not presented but are available upon request.

TABLE 8 Health co-benefits examination.

Variables	*INP*	*MOR*	*MMOR*
	(1)	(2)	(3)
Lagged dep. Var.	0.8956***	0.7685***	0.8617***
	(0.0866)	(0.1053)	(0.1880)
TFCEE	−0.0108*	−2.4048**	−0.2343**
	(0.0058)	(1.0470)	(0.1111)
Controls	YES	YES	YES
m1 (Z-statistic)	−2.26**	−2.66***	−1.80*
m2 (Z-statistic)	1.32	0.53	−1.56
Hansen test	0.34	0.65	0.76
N	330	330	330

The dependent variables in columns (1) to (3) are inpatients, mortality, and maternal mortality rate, respectively. *, **, and *** are the 10%, 5%, and 1% statistical significance levels of the estimated coefficients, respectively.

5.4 The health co-benefits of the TFCEE improvement

Excessive inhalation of carbon dioxide harms the respiratory system and reduces higher-level cognitive abilities (7), directly leading to adverse health effects. CO_2 can also indirectly have negative effects on health. For example, carbon dioxide decreases the content of essential nutrients for humans in crops (57); global warming exacerbates air pollution, increases the frequency of extreme weather events, and damages ecosystems (6). Increasing the TFCEE leads to lower carbon emissions for the same output, potentially decreasing adverse health effects on Chinese residents. However, whether the improvement in TFCEE directly influences public health in China has not been empirically tested.

Columns (1–3) of Table 8 display the output from 2SGMM regression models testing for the impact of TFCEE on the three indicators of public health: the ratio of inpatients to total population (*INP*), the mortality rate per 1,000 persons (*MOR*), and maternal mortality rate per 1,000 births (*MMOR*).[4] Higher values of these indicators indicate lower levels of public health and vice versa. We can observe that the coefficients of the *TFCEE* variable in all columns are significantly negative, indicating that TFCEE improves health levels. Accordingly, our analysis offers nascent robust empirical evidence supporting the health co-benefits of ICT driving TFCEE improvement.

5.5 Robustness test

To confirm the reliability of the estimated results presented in Table 4 and the associated research findings, we test their robustness concerning the following four aspects. First, we recalculate the TFCEE using the slack-based measure model (58). Second, we replace the core explanatory variable (*ICT*). Specifically, we adopt the principal component analysis (PCA) to recalculate the new ICT development index (*ICT_PCA*). Third, this study re-estimates the benchmark model using the difference GMM estimator. Finally, we rerun the benchmark model after shortening the sample period by 1 year, from 2008–2019 to 2009–2019, to account for the potential impact of the 2008 great financial crisis.

Results corresponding to the four robustness procedures are shown in Table 9. The coefficients on the *TFCEE* remain statistically significant, carry positive signs, and range from 0.6740 to 0.9512 in columns (1) and (2), respectively. Furthermore, the estimated coefficients on the ICT development variable in all four columns remain statistically significant and positive. Overall, Table 9 confirms that the results and research conclusions from Section 5.1 are robust and further corroborate hypothesis 1.

4 All three variables are at the provincial level and obtained from the China Health Statistical Yearbook.

TABLE 9 Robustness tests.

Variables	Alternative dependent variable	Alternative explanatory variable	Difference GMM	Shorter period of analysis
	(1)	(2)	(3)	(4)
LTFCEE	0.6740***	0.9512***	0.7936***	0.9329***
	(0.0483)	(0.0127)	(0.0257)	(0.0286)
ICT	0.2797***		0.0513*	0.0780***
	(0.0887)		(0.0255)	(0.0235)
ICT_PCA		0.0063***		
		(0.0012)		
Controls	Yes	Yes	Yes	Yes
m1 (Z-statistic)	−2.43**	−1.66*	−1.84*	−1.66*
m2 (Z-statistic)	−0.20	0.89	0.96	0.84
Hansen test	0.42	0.18	0.87	0.24
N	330	330	300	300

The dependent variable is the TFCEE. *, **, and *** are the 10%, 5%, and 1% statistical significance levels of the estimated coefficients, respectively.

6 Conclusions and policy implications

Considering the ICT's rapid advancements and the urgency of meeting goals for carbon peaking and net zero, the study takes data from 30 Chinese provinces during the 2008–2019 period. We use the 2SGMM dynamic models to empirically test the impact of ICT development on the TFCEE and the mediation, threshold, and moderating effects, as well as the health co-benefits. This study delivers several significant findings. First, ICT development significantly increases the TFCEE. Second, ICT can indirectly improve TFCEE through green innovation and energy structure optimization. Moreover, when green innovation (energy structure) switches from below to above (above to below) its threshold value, the promotional effect of ICT development on the TFCEE increases substantially in magnitude. Third, TFCEE improvement has significant public health-related co-benefits by significantly reducing the inpatient and mortality ratios.

Three policy implications can be derived from our findings. First, from the perspective of TFCEE improvement, the results suggest policies promoting the cross-industry application of ICT. Primarily, policymakers should focus on the digital and intelligent transformation of energy- and environment-related fields to realize the normalization of ICT applications, decoupling economic growth from carbon emissions and creating new impetus for the promotion of TFCEE. Second, concerning the mediating effects of ICT development on the TFCEE, Chinese decision-makers should foster favorable conditions for realizing the positive ICT effect on green innovation. For instance, they could consider upgrading the intellectual property protection system for green innovation. Moreover, the development of the energy internet should be regarded as an essential direction for energy structure optimization. It is also vital to promote intelligent upgrading of the energy system. Third, from the public health co-benefits perspective, the significant role of TFCEE in decreasing the inpatient and mortality ratios should be emphasized to enhance the motivation of relevant stakeholders in the field of public health toward improving the TFCEE.

Our examination of the ICT-TFCEE nexus is at the provincial level due to the availability of ICT development data. With continuous data enrichment, future research could be conducted at different spatial units, e.g., prefectural and enterprise levels. Moreover, once more data is available, it would be interesting to see whether the recent exogeneous macroeconomic shock of the COVID-19 pandemic and related policies (e.g., lockdowns) affect the documented results and findings. Finally, we advocate further research on the long-run convergence-divergence path in public health across the cities and provinces with different levels of ICT and the TFCEE by applying the distribution dynamics approach (59–61).

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JL: Conceptualization, Data curation, Software, Visualization, Methodology, Writing — original draft, Writing — review & editing. MW: Conceptualization, Data curation, Supervision, Methodology, Writing — original draft, Writing — review & editing, Project administration. TC: Conceptualization, Supervision, Validation, Writing — review & editing, Project administration.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Towards integrated sustainability for China's rural revitalization: an analysis of income inequality and public health

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Introduction: Ensuring healthy lives and promoting well-being are paramount among the priorities outlined in the 17 Sustainable Development Goals (SDGs) established by the United Nations. In China, rural revitalization stands as a pivotal national strategy aimed at fostering prosperity and sustainable development in rural areas. Despite its comprehensive evaluation system, which encompasses industry, ecology, culture, organization, and livelihood, the current index system overlooks the critical dimension of public health in rural areas. The existing body of literature predominantly focuses on the correlation between income and health, leaving a gap in understanding the relationship between income inequality and health from the perspective of villagers. This study addresses this gap by utilizing data from 3,771 villager samples and 302 village samples obtained from the 2019 China Rural Revitalization Survey (CRRS) to explore the correlation between income inequality and public health in China's rural areas.

Methods: We employ the Ordered Logistic Regression (Ologit) model in the baseline regression and heterogeneity analysis. Additionally, a mediating effect analysis, using the Sobel test, examines the role of villagers' health awareness as a mediating variable in the correlation between income inequality and villagers' health.

Results: The empirical findings of this study unveil a statistically significant adverse influence of income inequality on public health in China's rural areas. Furthermore, the research identifies that participation in regular exercise and the attainment of higher education levels serve as effective measures to alleviate the detrimental impact of income inequality on the health of rural residents. Additionally, income inequality is observed to shape villagers' health awareness, thereby influencing their overall health status.

Conclusion: The study's outcomes have significant implications for policymakers and governmental authorities, providing valuable insights into some pathways for enhancing public health in rural China. Ultimately, these insights contribute to the broader objective of achieving integrated sustainability in rural China.

KEYWORDS

China's rural revitalization strategy, public health, rural development, income inequality, ordered logistic regression model

1 Introduction

The United Nations (UN) introduced the Sustainable Development Goals (SDGs) in 2015, outlining 17 goals, 169 targets, and 232 indicators to assess global progress in sustainable development. Among these, the third major goal (SDG 3) focuses on "Good Health and Well-being," aiming to ensure healthy lives and promote well-being for all ages. SDG 3 has established a detailed set of scientific measures for individual and public health, bringing global attention to the importance of investing more in health-related issues. However, as developmental disparities continue to rise, achieving SDG 3 becomes more challenging (1). To enhance progress and achievements, the global SDGs agenda also highlights the significance of rural development. This emphasis is a crucial part of national strategies aimed at promoting a new initiative for rural revitalization (2, 3).

In China, rural residents account for 34.8% of the national total population, numbering 491.04 million (4). The Chinese Government introduced the rural revitalization strategy in 2017, driven by the need to address the growing material and cultural requirements of the rural population, particularly focusing on challenges associated with rural development (5). Aligned with the strategic plan for a sustainable economy (2018–2022), China has successfully achieved a stable grain output exceeding 0.65 trillion kg per year, with rural residents' real *per capita* disposable income witnessing a substantial increase of 28.9 percent. The income disparity between urban and rural populations has decreased from 2.71 to 2.5, indicating noteworthy progress in economic sustainability. The comprehensive assessment system for rural revitalization includes five core goal dimensions: local economy, cultural enrichment, social governance, ecological sustainability, and overall well-being (6). Unfortunately, the rural revitalization strategy has not placed adequate emphasis on the critical aspect of public health. Given the substantial rural population in China, promoting the country's rural revitalization strategy offers a practical reference for achieving global SDGs. Integrating the objective of enhancing public health into the overarching goal system of the current rural development process would enable a more comprehensive and integrated approach to achieving sustainability.

Health stands as a foundational human need, forming the cornerstone of individual well-being and family stability. The collective public health of a nation is instrumental in ensuring social stability and harmony. The significance of health has become increasingly apparent, particularly in the aftermath of the COVID-19 pandemic, which has imposed a growing financial burden on nations worldwide and disrupted global economies and health advancements (7). Given the substantial rural population in China, rural areas continue to grapple with challenges in public health, exerting a detrimental influence on the well-being and social satisfaction of rural residents (8). Consequently, this study is instituted with the aim of providing scientific insights to facilitate integrated sustainability, harmonizing economic development and public health. The research seeks to investigate potential impact factors on public health and the underlying mechanisms within the framework of China's rural revitalization strategy.

The correlation between income and health has been extensively explored by scholars, supported by ample empirical evidence that highlights the significant impact of individual income on personal health. Notably, higher income levels are consistently linked to improved health outcomes (9). The influence of income extends beyond physical health, also manifesting in individuals' life satisfaction and subjective well-being. This observation is underpinned by a nationwide analysis revealing a robust correlation between national income *per capita* and average life satisfaction (10). Countries with higher income levels generally exhibit a higher life satisfaction index compared to their lower-income counterparts. These studies on income and health span diverse samples, encompassing both developed and developing nations, establishing a well-documented relationship between these two variables (11–13). Given the well-established positive association between income and health, earlier scholars began to recognize the potential impact of income inequality on health, considering it as a pathway of influence (9, 14). Building upon collected baseline data encompassing county individual income, income inequality, self-rated health, and other variables, studies have indicated that individual income has a more pronounced effect on various health pathways, while income inequality appears to exert a modest influence on self-rated health but not on mortality (15). Recent research suggests that the impact of income on health is influenced by the interplay of both absolute income and relative income. Through decomposing their respective impacts and comparing their relative importance, the study found that relative income has a significant negative effect on health outcomes (16). This conclusion aligns with another study utilizing cross-sectional data from 7,070 participants in the Shandong Family Health Service Survey of Older People. Employing the binary logistic model and semi-parametric model, this research estimated the effect of absolute income and income relative deprivation (income inequality) on older people's self-rated health. The results indicate that income relative deprivation is negatively associated with self-rated health in both urban and rural older populations (17).

In summary, the current research concerning income and health exhibits several insufficiencies. Firstly, while existing research has established and proven the linkage between income and health, there is a notable gap in deeper studies on income inequality and health. Many of the current studies lack clear distinctions in their selected samples, and even few have explored this relationship from the perspective of rural residents. To address this gap, our study aims to fill the gap in nuanced studies about income inequality and health, focusing on a group of Chinese villagers. Furthermore, China's rural revitalization strategy has garnered increased attention in recent major government policies, positioning it as a central element in the construction of a modern, comprehensively developed country. However, the absence of a specific indicator to measure public health progress within this strategy has resulted in less public scrutiny on China's rural public health. Concurrently, there is a scarcity of research focusing on the public health status in rural China. In an effort to address this research gap, our study employs the China Rural Revitalization Survey (CRRS) database from the Institute of Rural Development of the Chinese Academy of Social Sciences and aims to analyze how income inequality among Chinese villagers influences rural public health. This database is specifically designed to address rural revitalization-related issues and provides a more comprehensive review of China's rural development including indices of income and health at both individual and village levels. Thus, compared to other general micro databases, the CRRS database provides more specific data for our current topic. Besides, our study employs various empirical methods to offer credible and scientific research findings

with strong robustness and consistency. Utilizing data on the health status of sampled villagers and income inequality, this current study employs empirical methods such as OLS regression and Ordered Logit regression to evaluate the potential influence of income inequality on public health within the framework of China's rural revitalization strategy. To ensure the robustness of our findings, the study conducts a Robustness test and Mediating effects analysis using the Oprobit model and Sobel test, respectively. These additional analyses aim to enhance the validity and reliability of research outcomes.

2 Materials and methods

2.1 Data sources and data processing

The data for this study were drawn from the China Rural Revitalization Survey, conducted by the Institute of Rural Development at the Chinese Academy of Social Sciences. Notably, the CRRS stands out for its recent and comprehensive dataset, offering insights into the economic and social dynamics of Chinese villages post the implementation of a rural revitalization strategy. Encompassing a broad survey sample across 10 provinces, including Guangdong, Zhejiang, Shandong, Anhui, Henan, Guizhou, Sichuan, Shanxi, Ningxia, and Heilongjiang, the study spans the eastern, central, western, and northeastern regions of China. Employing an equidistant random sampling method based on gross domestic product (GDP) *per capita*, the survey meticulously collected data at individual, household, and village levels. This included individual characteristics, family income, and village conditions. A total of 3,833 individual questionnaires and 308 village questionnaires were gathered. For analytical purposes, the study utilized the average income of the village to calculate the index of income inequality, assess villagers' health conditions, and collect other relevant data to gage public health. Additionally, certain individual and village characteristics were incorporated as control variables. Following the exclusion of missing and anomalous data, our dataset comprises 3,771 villager samples and 302 village samples, forming the basis for the subsequent analysis.

2.2 Model specification

In order to investigate the relationship between income inequality and public health in China's rural area, our empirical model is illustrated as follows:

$$Health_i = \alpha_0 + \alpha_1 RD_i + \beta_1 X_{1i} + \beta_2 X_{2j} + \varepsilon_i \qquad (1)$$

where the dependent variable of $Health_i$ denotes the health status of villager i; the key independent variable of RD_i is the index of income inequality of villager i; X_{1i} represents other personal characteristics that affect one's health status, such as age, education, and exercise habits. In addition, considering some factors of villages may also influence local public health, such as locations and overall economic condition, we include control variables at the village level, which are denoted by X_{2j}; α and β are the influence coefficients of the corresponding variables; ε_i is the error term.

Since the dependent variable in this study is an ordered variable, which is not statistically continuous, the method of Ordered Logistic Regression (Ologit) was adopted to estimate Eq. (1). The Ologit model is based on the cumulative distribution of the Logit model and assumes that the dependent variable is assigned ordinal values from 1 to J. The cumulative Logit for dependent variables $\leq j$ and $> j$ can be expressed in Eq. (2).

$$l_j(x_j) = \log\left[\frac{\Pr(y_i \leq j \mid x_i)}{\Pr(y_i > j \mid x_i)}\right] = a_j + \beta I + \varepsilon_i \qquad (2)$$

where I includes all the independent variables and control variables and β is its coefficient. J represents the set of categories for grade ranking, $j \in J = \{1,2,3\}$; α_j represents the intercept term for Ologit estimation. Besides, the odds ratio of the Ologit model is calculated by the relative incidence ratio of x and y, indicating that when the independent variable increases by one unit, the dependent variable's incidence ratio of the lower group is $e^{-\beta_i}$ times the incidence ratio of the adjacent higher group (18).

2.3 Variable measurement

2.3.1 Dependent variable

The dependent variable of $Health_i$ indicating villager's health status is collected from the question in the villager's questionnaire of CRRS: "How is your health status compared to your peers?," and optional responses include "Very Bad," "Bad," "Average," "Good," and "Very Good." We assigned a value of 1 to the variable of $Health_i$ if the answer is either "Very bad" or "Bad," a value of 2 if the answer is "Average," and a value of 3 if the answer is "Good" or "Very Good." Among the full samples, there are 522 villagers in poor health status (13.84%), 1,125 villagers in average health status (29.83%), and 2,124 villagers in good health status (56.32%) (Table 1).

2.3.2 Key independent variable

The key independent variable is the income inequality of villagers across China. The relative deprivation theory suggests that individuals are deprived when they compare themselves to people in their reference group and find themselves at a disadvantage. After grouping individuals based on their income levels, the lower the income of the individual, the greater the relative deprivation. Thus, relative deprivation is a concept at the individual level, whereas it is able to reveal the overall social distribution of incomes and income inequality. The Kakwani index has been widely applied in empirical studies to measure relative deprivation (RD) (17,19,20). In this study, the Kakwani index based on the villager's total income in 2019 was adopted to represent the income inequality of villagers. Its calculation is as follows: Set X as a group, and the number of villagers in the group is n. By sorting the villager's income in ascending order, we can acquire a total income distribution $X = (x_1, x_2, \cdots, x_n), x_1 \leq x_2 \leq \cdots \leq x_n$ in Eq. (3).

$$RD(x_j, x_i) = \begin{cases} x_j - x_i \ if\ (x_j > x_i) \\ 0 \ \ if\ (x_j \leq x_i) \end{cases} \qquad (3)$$

TABLE 1 Descriptive statistics of variables.

Variable category	Variable	Variable description	Mean	SD
Dependent variable	*Health*	Health Status: Poor = 1; Average = 2; Good = 3	2.425	0.722
Key independent variable	*RD*	Relative Deprivation Index	0.508	0.269
Individual-level control variable	*Exercise*	Doing Exercise: No = 0; Yes = 1	0.580	0.494
	Age	The age of villager	54.919	11.876
	Gender	Female = 0 ; Male = 1	0.934	0.248
	Height	Logarithmic Height	5.107	0.048
	Weight	Logarithmic Weight	4.183	0.198
	Edu	Uneducated = 1; Elementary School = 2; Secondary School = 3; High School = 4; Technical Secondary School = 5; Vocational and Technical school = 6; Junior College = 7; Undergraduate = 8; Postgraduate = 9	2.760	1.082
	Information	Information Adequacy: Not at All = 1; Not enough = 2; Almost enough = 3; Enough = 4; Sufficient = 5	3.831	1.039
Village-level control variable	*Distance*	Distance to Town Government (km)	5.505	5.548
	Poverty	Identified as Village in Poverty: No = 0; Yes = 1	0.278	0.448

The $RD(x_j, x_i)$ of villager i implies the relative deprivation of x_j to x_i. Summing $RD(x_j, x_i)$ over villager j and dividing by the villager's income, we can acquire the relative deprivation of villager i in Eq. (4).

$$RD(x_i) = \frac{1}{n\mu_x}\sum_{j=1}^{n} RD(x_j - x_i) = \frac{1}{n\mu_x}\left(\sum x_j > x_i, x_j \in X^{x_j} - \sum x_j > x_i, x_j \in X^{x_i}\right) \quad (4)$$

Therefore, $RD(x_i)$ is a decreasing function of the villager's income, and a larger $RD(x_i)$ indicates a higher level of village's income inequality. $RD(x_i)$ has a range of values from 0 to 1. In addition, we also calculate $VillageRD_j$ based on the average income of village j in 2019, which is used to replace RD_i in the robustness test.

According to Zhang, the degree of income inequality can be classified into four levels based on the Kakwani index, namely Low $(Kakwani < 0.5)$, Medium $(0.5 \le Kakwani < 0.668)$, High $(0.668 \le Kakwani < 0.75)$ and Very high $(Kakwani \ge 0.75)$ (21). As shown in Table 1, the average value of *RD* is 0.508, indicating that income inequality of villagers across China is at the medium level. We further calculated the average *RD* of the 10 sample provinces. Results show that Zhejiang Province has the lowest income inequality level of 0.315, while Shandong Province has the highest of 0.610. Other provinces have similar levels of income inequality, with *RD* of around 0.5.

2.3.3 Control variables

There are two sets of control variables. Individual-level control variables include some personal characteristics, i.e., *Age*,*Gender*, *Weight*, *Height*, and other personal details influencing health, i.e., education status (*Edu*), exercise habit (*Exercise*), and sufficient online information (*Informaiton*). Specifically, the variable of *Exercise* corresponds to the CRRS question of "Have you done more than 30 min of exercises in the last week?." The optional responses are "No" and "Yes" with assigned values of 0 and 1. The variable of *Information* refers to villagers' ability to acquire online information, which corresponds to the question of "Do you think you have obtained sufficient information through the Internet for your daily life and work?" The optional responses are "Not at all," "Not enough," "Almost enough, "Enough," and "Sufficient," and they are assigned a value from 1 to 5, respectively.

Village-level control variables included village's location and overall economic condition. Location is measured by its distance to town government (*Distance*). Overall economic condition is indicated by whether it is identified as village in poverty by the government (*Poverty*). The detailed description of variables and their statistics information are presented in Table 1.

3 Results

3.1 Baseline results

According to our empirical model, the relationship between income inequality and health is detailed in Table 2. Columns (1) and (2) present the estimated results using OLS regression. Notably, the coefficients of *RD* are consistently and significantly negative, even after incorporating a series of control variables. This underscores a substantial and negative correlation between income inequality and the health status of villagers.

We conducted the Ologit regression and found that the coefficient of *RD* is still negative at a significant level. The results show that with one unit decrease in income inequality, the odds of good health status versus the other two health status (average & poor) are 62.9% higher, provided that other variables remain constant. This verifies that reducing income inequality can effectively improve the public health in the rural area. Regarding the estimated results of control variables,

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TABLE 2 Baseline results.

Variable	(1)	(2)	(3)	(4)
	OLS		Ologit	
			Coefficient	Odds ratio
RD	−0.329*** (0.043)	−0.192*** (0.046)	−0.464*** (0.129)	0.629*** (0.081)
Exercise	0.126*** (0.024)	0.107*** (0.024)	0.313*** (0.065)	1.368*** (0.089)
Age		−0.003*** (0.001)	−0.008*** (0.003)	0.992*** (0.003)
Gender		0.0003 (0.048)	−0.007 (0.132)	0.993 (0.131)
Height		0.423 (0.273)	1.259* (0.750)	3.522* (2.641)
Weight		0.117* (0.065)	0.313* (0.186)	1.367* (0.254)
Edu		0.030*** (0.011)	0.068** (0.032)	1.071** (0.034)
Information		0.054*** (0.012)	0.151*** (0.033)	1.163*** (0.039)
Distance		−0.003 (0.002)	−0.008 (0.006)	0.992 (0.006)
Poverty		−0.040 (0.026)	−0.096 (0.073)	0.908 (0.066)
Cons	2.519*** (0.029)	−0.285 (1.297)		
Number of obs	3,771	3,771	3,771	3,771

Standard errors are in brackets; *, **, *** indicate significant at the significance level of 10, 5, and 1%, respectively.

Exercise, *Weight*, *Height*, *Edu* and *Information* exhibit significant positive influences on villagers' health, while *Age* negatively affects their health. These outcomes align with logical expectations, affirming the rationale of our empirical model. However, the village-level control variables, specifically the village's location and poverty condition, do not demonstrate significant influences on the health status of villagers.

3.2 Robustness test

In order to verify the robustness of the baseline model, we applied two methods, namely changing the regression model and replacing the independent variable (22). The results of robustness tests are shown in Table 3.

Initially, we replaced the Ologit model with the Ordered Probit Regression (Oprobit) model. The Oprobit model, while having similar applicability to the Ologit model, employs a different estimation method. If the results obtained from the Ologit model are robust, they should align consistently with the findings of the Oprobit model. As depicted in Column (1), the significantly negative effects of income inequality on villagers' health persist, validating the robustness of our results.

TABLE 3 Results of robustness test.

Variable	Replacing model	Replacing independent variable	
	(1)	(2)	(3)
	Oprobit model	Ologit model	Oprobit model
RD	−0.304*** (0.077)		
VillageRD		−0.455** (0.205)	−0.322*** (0.123)
Exercise	0.182*** (0.039)	0.316*** (0.065)	0.183*** (0.039)
Individual Characteristics	Controlled	Controlled	Controlled
Village Characteristics	Controlled	Controlled	Controlled
Number of obs	3,771	3,771	3,771

Standard errors are in brackets; *, **, *** indicate significant at the significance level of 10, 5, and 1%, respectively.

Furthermore, we modified the former key independent variable, *RD*, to *VillageRD*. *VillageRD* is calculated based on the average income of the village in 2019, representing the income inequality among villages. Utilizing either the Ologit or the Oprobit model, the negative and significant correlation between income inequality and health is consistently maintained (Columns (2) and (3)).

3.3 Heterogeneity analysis

According to the baseline regression, *Exercise* and *Edu* are two important factors affecting villagers' health. Thus, we used subsamples, namely villager groups identified by doing exercises or not and education level, to further explore the possible different effects of income inequality on public health in rural areas. In terms of doing exercises, we divided the full sample into two groups by the value of *Exercise*. In terms of the education level, the classification criterion is whether the villager obtains further education after the 9-year compulsory education (elementary and secondary school), and the two groups are named "Low education level" ($Edu \leq 3$) and "High education level" ($Edu > 3$). The results of heterogeneity analysis applying Ologit regression are shown in Table 4.

The results in Columns (1) and (3) indicate that there are apparent differences in the significance of *RD*. Among villagers doing exercises when income inequality is decreased by one unit, the odds of good health status versus the other two health status (average & poor) are 54.1% higher. The odds is smaller for the full sample in the baseline regression, indicating that doing exercise can eliminate the negative effects of income inequality on public health in the rural area. Hence, promoting the adoption of regular exercise among villagers emerges as an effective strategy to enhance people's health, notwithstanding the challenges in preventing income inequality and its associated negative effects on public health. Notably, for villagers who do not engage in exercise, their health shows no significant correlation with income inequality, as they typically experience a decline in health status.

TABLE 4 Results of heterogeneity analysis.

Variable	Doing Exercises		Not Doing Exercises		Low Education Level		High Education Level	
	Ologit							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Coefficient	Odds ratio	Coefficient	Odds ratio	Coefficient	Odds ratio	Coefficient	Odds ratio
RD	−0.614*** (0.171)	0.541*** (0.093)	−0.265 (0.197)	0.767 (0.151)	−0.542*** (0.140)	0.582*** (0.082)	−0.144 (0.331)	0.866 (0.287)
Exercise	–	–	–	–	0.320*** (0.070)	1.377*** (0.096)	0.340* (0.180)	1.404* (0.253)
Edu	0.084** (0.042)	1.088** (0.046)	0.044 (0.050)	1.045 (0.052)	–	–		–
Individual Characteristics	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Village Characteristics	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Number of obs	2,189	2,189	1,582	1,582	3,205	3,205	566	566

(1) The group of Low education level includes those uneducated and only receiving compulsory education (elementary and secondary school); the group pf High education level includes those having further educations (high School, technical secondary school, vocational and technical school, junior college, undergraduate and postgraduate). (2) Standard errors are in brackets. *, **, *** indicate significant at the significance level of 10, 5, and 1%, respectively.

In our study, we found that the negative impact of income inequality on villagers' health is significant only among those with a "Low education level." Improving income equality can notably enhance the health of individuals with only compulsory education or less. On the other hand, for those with higher education, income inequality does not seem to affect their health negatively. This might be because well-educated villagers know more about how to take care of their health, especially through participating in social activities. This finding is similar to what another study suggested – that older people with higher education tend to feel healthier, have fewer depressive symptoms, face fewer daily activity limitations, and engage more in social activities (23). Therefore, it is a valuable practice by the government to promote education, especially in rural areas, which could contribute to better public health and overall living standards (24).

3.4 Mediating effect of health awareness

The previous regression and analysis confirmed the substantial and negative impact of income inequality on public health in rural areas. Now, we aim to delve into the crucial role of people's health awareness in the connection between income inequality and villagers' health. Dietary habits serve as a vital indicator of people's health awareness and can profoundly affect both physical and psycho-social health, influencing overall life quality. Unhealthy dietary habits and lifestyles are widely acknowledged as significant risk factors for life-threatening diseases (25). Nonetheless, the precise mechanisms linking lifestyles and health outcomes remain unclear (26). Therefore, this study proposes to adopt a mediating effect analysis to examine the relationship between dietary habits, income inequality, and health levels of selected sample villagers. A mediating effect analysis based on the Sobel test is used. The Sobel test method has been found to have a strong detecting ability in the study of mediating effects (27, 28). The CRRS database comprehensively investigated villagers' health awareness including that reflected in villagers' dietary habits. For instance, there is a question asking respondents "Does your family purchase organic, green, or pollution-free vegetables?" and "Does your family purchase organic, green, or pollution-free pork?." We used these two questions as the proxy variables of health awareness, namely *Vegetable* and *Pork*. The optional responses are "No" and "Yes" which are assigned values of 0 and 1, respectively. Table 5 shows the results of the mediating effect analysis using *Vegetable* and *Pork* as the mediating variables. The *p* values of both mediating variables are below 0.05, indicating the existence of mediating effects. The Sobel test results suggest that both mediating effects are partial effects: the mediating effect of *Vegetable* is about 5.12% of the total effect, and the mediating effect of *Pork* is about 5.47%. Overall, both of the mediating effects of health awareness account for around 5% of the total effects of income inequality on villagers' health.

4 Conclusion and policy suggestions

4.1 Conclusion

This study seeks to establish an empirical model for examining the impact of income inequality on public health in rural areas of China. Guided by the relative deprivation theory, which suggests that income inequality can result from social comparisons, we calculated the Kakwani index using micro-data from 3,771 individual villagers and 302 village-level samples obtained from the 2019 China Rural Reform and Development Survey (CRRS) database. Utilizing regression techniques, including Ordinary Least Squares (OLS), Ordered Logit (Ologit), and Ordered Probit (Oprobit) models, we conducted our analysis. Our findings reveal a significant negative correlation between income inequality among villagers and their health status. Specifically, villagers with lower income inequality tend to exhibit better health,

TABLE 5 Analysis of mediating effects.

Variables	Health awareness effect (vegetable)			Health awareness effect (pork)		
	(1)	(2)	(3)	(4)	(5)	(6)
	Health	Vegetable	Health	Health	Pork	Health
RD	−0.192*** (0.046)	−0.144*** (0.027)	−0.182*** (0.046)	−0.192*** (0.046)	−0.114*** (0.025)	−0.181*** (0.046)
Vegetable			0.068** (0.028)			
Pork						0.092*** (0.030)
Control Variable	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
$P>\|Z\|$	0.025			0.011		
Mediating Effect	5.12%			5.47%		
Cons	−0.287 (1.283)	−0.785 (0.754)	−0.233 (1.282)	−0.287 (1.283)	0.702 (0.694)	−0.351 (1.282)

Standard errors are in brackets; *, **, *** indicate significant at the significance level of 10, 5, and 1%, respectively.

emphasizing the potential health benefits of reducing income disparities. In our heterogeneity analysis, we considered villagers' exercise habits and education levels. We found that villagers engaging in regular exercise tend to maintain better health, mitigating the adverse effects of disadvantaged income status. Additionally, education emerged as another avenue to mitigate the negative impact of income inequality on public health. Well-educated villagers typically possess greater knowledge and awareness of health management, buffering the negative effects of income inequality. Through a mediation analysis, we explored the underlying mechanisms through which income inequality influences health. Our analysis revealed that income inequality exerts a discernible influence on villagers' health awareness, subsequently shaping their overall health status.

This study contributes to addressing a research gap in the intersection of income inequality and public health within the context of China's rural revitalization strategy. The research findings, illustrating a negative correlation between income inequality and public health as perceived by China's villagers, provide valuable scientific insights applicable to the implementation of the UN's SDGs. Furthermore, this study stands as a foundational reference for future inquiries into the current state of public health and its determining factors in rural China. Nevertheless, there are avenues for potential improvement. Firstly, the utilization of the CRRS database is constrained by having only one published data edition, limiting the study to cross-sectional data. Plans are in place to track future releases of the CRRS, enabling the extension of research results accordingly. Secondly, the current CRRS questionnaire items on public health are observed to be general and lacking scientific indices for measuring villagers' objective health conditions. Future research endeavors aim to explore the possibility of integrating other valuable databases to address this gap.

4.2 Policy suggestions

Attaining integrated sustainability within China's rural revitalization strategy necessitates a comprehensive grasp of the rural population's needs. This study explores the potential influence of economic advancement through rural revitalization on the broader national health agenda, highlighting health challenges in rural areas. The findings provide valuable insights for policymakers and governments striving to improve public health in China's rural regions, ultimately fostering integrated sustainability in the country's rural revitalization efforts. Building upon these findings, we put forth two sets of suggestions:

In terms of national policies, although the Chinese government achieved the significant milestone of eradicating absolute poverty by 2020, enhancing residents' absolute individual income and living standards, particularly for the rural populace, remains a pivotal task. Policymakers might consider prioritizing the addressing of wealth distribution in society, recognizing it as a fundamental prerequisite for achieving sustainable economic development. Beyond economic considerations, China's forthcoming rural revitalization strategy should institute comprehensive metrics in public health, focusing on crafting indicators pertinent to the evolving needs of the vast rural population. These indicators would serve as prerequisites for monitoring the progress of the rural revitalization strategy and facilitating necessary policy adjustments.

In terms of practical attempts, a primary focus is directing increased investment towards enhancing public health infrastructures, including healthcare services and other health facilities. Equally paramount is the widespread dissemination of health-related information. Promoting healthy lifestyle choices, such as regular exercise and a balanced diet, holds considerable potential to elevate individuals' health awareness and, consequently, improve health outcomes. Furthermore, enhancing educational resources in rural areas emerges as a strategic avenue for advancing public health. The correlation between higher incomes and heightened health awareness is intricately linked to the level of education received. Therefore, an earnest effort to elevate educational standards in rural areas not only empowers minds but also serves as a catalyst for broader improvements in health awareness and overall well-being.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found at: http://rdi.cass.cn/ggl/202210/t20221024_5551642.shtml.

Author contributions

JL: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing. KG: Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Writing – original draft, Writing – review & editing. CC: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Putting communities at the forefront of community-led monitoring in Zimbabwe

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Introduction

The purpose of this opinion manuscript is to outline the role of community-led organizations in the fight against HIV including the monitoring of HIV-related health services in Zimbabwe. This is in line with the theme of the 2023 World AIDS Day of recognizing and celebrating the achievements of communities. Additionally, the World AIDS Day theme advocates for more resources to enable community-led organizations to unleash their full potential and leadership, including more effective community-led monitoring of the provision of HIV-health services to contribute to the end of AIDS by 2030.

In 2014, The Joint United Nations Programme on HIV/AIDS (UNAIDS) launched the 95-95-95 targets. The aim was to diagnose 95% of all HIV-positive individuals, provide antiretroviral therapy (ART) for 95% of those diagnosed, and achieve viral suppression for 95% of those treated by 2030. Having achieved the 95-95-95 UNAIDS targets with time to spare, Zimbabwe is on the trajectory to ending HIV/AIDS and, in turn, coming closer to achieving its health-related Sustainable Development Goals (1). Zimbabwe's success is attributable to factors including, strong political will, and employment of robust and innovative community-level HIV testing, treatment, and care service provision for both the general population and key populations. For example, for key populations, the country has used granular data and HIV risk profiling to ensure that interventions reach those at great risk of HIV acquisition. The country's approach highlights the necessity of localized targeted interventions that address sociodemographic constraints and geographic heterogeneity in HIV service provision.

In our view, HIV community-led monitoring (CLM), an accountability mechanism for the HIV response at different levels, led and implemented by local community-led organizations (CLOs) of people living with HIV (PLHIV), networks of key populations, other affected groups or other community entities, will be a crucial strategy to promote sustainability (2). In Zimbabwe, Community lead Monitoring has proved to be an effective mechanism for organized and systematic advocacy for the health and rights of key populations (3). Engaging peers in service delivery is an effective strategy to reduce stigma among key populations. Obtaining feedback from recipients of care can inform healthcare workers on how to improve the quality of service delivery and address issues such as stigma, that cause low uptake of services and poor health outcomes.

Current gaps in CLM in Zimbabwe

Despite the country having registered some progress in the implementation of CLM, the following gaps are still apparent and require attention to enhance the quality and utility of CLM-generated data;

Limited capacity of CLOs: Many CLOs in Zimbabwe lack the resources to implement CLM effectively as well as some of the necessary technical skills, particularly in areas including data management, and reporting.

Sustainability challenges: CLM is often funded by external donors, which raises concerns about its sustainability once donor funding dries up. One of the contributing factors to this gap is a general lack of advocacy efforts by the CLOs, that target the private sector players to be actively involved in supporting health interventions that affect communities that support their businesses. There is a need to develop innovative financing mechanisms to ensure the long-term sustainability of CLM in Zimbabwe.

Limited engagement with government: Government engagement in CLM is still relatively limited in Zimbabwe, despite being the key stakeholder in the HIV response. The limited involvement of the government in the implementation of CLM can result in the lack of policies and structures to support the programme, a problem that can lead to its premature collapse. There is a need to strengthen engagement between CLOs and the government to ensure that CLM findings are used to inform policy and programming.

Data quality challenges: The quality of data collected through CLM in Zimbabwe still leaves a lot to be desired, with aspects of data quality including completeness, timeliness and consistency among others, affected. This is due to factors, including, the lack of training on data collection and analysis tools, and the lack of standard methodologies among different CLOs. There is a need to develop standardized CLM tools and methodologies to improve the quality of data collected.

Recommendations for strengthening CLM in Zimbabwe

To strengthen CLM in Zimbabwe and ensure that it becomes more effective, the following recommendations are put forward;

1. For some of the key gaps outlined in the section above to be addressed, there is a need to provide training for community organizations to strengthen their activities supporting PLHIV. Policymakers in Zimbabwe must support these organizations with funding and training opportunities to ensure that their work achieves the desired impact. Underfunding of community-led initiatives will result in their activities achieving limited impact.
2. The government of Zimbabwe must continuously consider how to make community initiatives more sustainable by increasing the allocation of domestic resources raised by the National AIDS Council from the National AIDS Levy Trust Fund (NALTF). The NALTF was established by the Zimbabwe legislature in 1999, the AIDS Levy entails a 3% income tax for individuals and a 3% tax on profits of employers and trusts (which excluded the mining industry until 2015). It is managed by the parastatal NAC through a decentralized structure of AIDS Action Committees. The NALTF amongst others contributes 15% of the financial resources for the procurement of the national ARV requirements.
3. Strengthen monitoring of treatment literacy: Effective community-level HIV treatment literacy is essential to support Zimbabwe's robust HIV response. CLM must strengthen its monitoring of treatment literacy, especially when the general population regards HIV/AIDS under control. Treatment literacy means that people, individually and in communities, understand what HIV drugs are, why they are needed, and what they can and cannot do. As the HIV-positive cohort in Zimbabwe ages and non-communicable diseases (NCDs) become more prevalent, treatment literacy must address this dimension.
4. CLM needs to provide greater granularity so that the needs of different types of health facilities, urban vs. rural, state-owned vs. NGO or religious-owned health facilities, and other strata, are accurately articulated during routine rounds of CLM monitoring. This will allow for the rapid identification and address of specific shortcomings in service provision.
5. Community-based monitoring (CBM) refers to service users assessing the effectiveness, quality, accessibility, and impact of health programs and services they receive. Conversely, CLM is a specific type of CBM that is led and implemented by CLOs of PLHIV, networks of key populations, other affected groups, or other community entities. CLM is important because it puts communities at the forefront of HIV health service delivery monitoring. CLOs have a unique understanding of the needs and challenges faced by their communities, and they are well-positioned to identify and address gaps in service provision. Funders of HIV programs should ensure that resources continue to flow to CLOs, as they play a vital role in CLM. CLOs may not have the administrative strength and depth of international organizations and large national NGOs. However, this should not be held against them, as they are closest to the individuals who receive HIV-related health services at facilities dotted around the country. Any gaps in program quality and service delivery models that do not meet the needs and expectations of PLHIV threaten individual outcomes and public health goals. CLM is an essential tool for identifying and addressing these gaps.
6. Differentiated service delivery (DSD) is a client-centred approach that simplifies and adapts HIV services across the cascade to reflect the preferences, expectations, and needs of people living with and vulnerable to HIV while reducing unnecessary burdens on the health system (4). DSD provides an opportunity for the HIV and Universal Health Coverage agendas and is increasingly evolving to a more client-centred vision of chronic care services, which includes reducing the number of facility visits for stable HIV clients (5). CLM implementation in Zimbabwe has tended to focus on health facilities, leaving out those individuals on DSD who, on average, visit the facility every 6 months to get their refills. Service delivery concerns of individuals on DSD are less likely

to be captured by CLM as these individuals rarely visit health facilities and are, therefore, less likely to participate in CLM data collection surveys.

CLM needs to identify innovative approaches so that those stable clients on DSD approaches can also join in CLM data collection surveys. Some possible approaches include:

- Using mobile phone surveys: Mobile phone surveys can be a convenient and effective way to collect data from individuals on DSD, especially those who live in rural areas or have difficulty travelling to health facilities.
- Partnering with community-based organizations (CBOs): CBOs can be vital in identifying and engaging individuals on DSD in CLM data collection surveys. CBOs have a strong presence in communities and can help to build trust with individuals on DSD.
- Using peer educators: Peer educators can educate individuals on DSD about the importance of CLM and assist them in participating in CLM data collection surveys.

It is important to note that any approach used to collect data from individuals on DSD should respect their time and needs. It is also essential to ensure that the data collected is confidential and secure.

7. CLM activities have also been introduced not only for HIV but also for TB and Malaria programs. There is a need for discussions about reducing redundancy between these CLM programs and ensuring that value for money is achieved. One way to minimize redundancy is coordinating CLM activities across different disease programs. This could be done by developing standard CLM tools and methodologies and sharing data and lessons learned. Another way to reduce redundancy is to focus on CLM activities that significantly impact health outcomes. For example, CLM could be used to monitor the quality of care provided for key populations, such as sex workers, and people who use drugs. Finally, it is essential to ensure that CLM is implemented cost-effectively. This could be done using innovative data collection methods like mobile phone surveys and partnering with CBOs.
8. For CLM to have the desired impact and leverage and for it to be able to result in the rapid and effective resolution of HIV service delivery and quality bottlenecks at the health facility level, networks of PLHIV need to increase their engagement with other key players at the community level, such as traditional leaders. Traditional leaders have a different type of agency and better access to the levers of government to cause positive change in health service delivery, which groupings of PLHIV may not have. Traditional leaders must be well-informed about HIV health service delivery challenges in their communities to contribute to advocacy activities. Additionally, traditional leaders can apply resources they receive from the central government to address health service delivery bottlenecks, such as abolishing user fees at the local level or crowdfunding to maintain or install health facility-level infrastructure such as boreholes. In Zimbabwe, traditional leaders make up approximately a quarter of the membership in the Senate and can therefore be important advocates for health service delivery matters for PLHIV. They can assist PLHIV networks in advocating to the central government to address local health service provision bottlenecks.

We also propose some specific approaches for how CLM networks and traditional leaders can work together to improve HIV service delivery:

- Conduct joint assessments of HIV service delivery: CLM networks and traditional leaders can work together to conduct joint assessments of HIV service delivery in their communities. This will help to identify common challenges and areas for improvement.
- Develop and implement joint advocacy plans: CLM networks and traditional leaders can work together to develop and implement joint advocacy plans to address the challenges identified in the joint assessments. These advocacy plans could target local government officials, policymakers, and other stakeholders.
- Mobilize communities to support HIV service delivery: Traditional leaders can use their influence to mobilize communities to support HIV service delivery. This could involve encouraging community members to participate in CLM activities, to volunteer their time and skills at health facilities, and to donate resources to support HIV programs.

Conclusion

Zimbabwe has achieved the 95-95-95 UNAIDS targets, a significant milestone in the fight against HIV/AIDS. However, it is essential to remain vigilant and invest in strategies to ensure that the gains made are not lost. Too often, decision-makers treat communities as problems to be managed, rather than as leaders to be recognized and supported. The HIV response is hurt when community leadership—the greatest power for progress—is unacknowledged, undersupported, underresourced, underremunerated, and in some places even under attack. Additionally, it has been a long-standing principle of the HIV response for people living with or affected by HIV to have a place at the decision-making table. CLM is a critical strategy for promoting sustainability in the HIV response. It puts PLHIV at the forefront of monitoring and advocacy efforts. This helps to ensure that the needs of PLHIV are heard and that services meet their needs. PLHIV-led organizations are responsible for implementing CLM activities in their communities. In addition to PLHIV-led organizations, other community players, such as traditional leaders, also play a role in CLM implementation, with Traditional leaders offering a unique understanding of their communities and helping to mobilize support for its activities. As Zimbabwe strives to achieve sustainability and eliminate HIV/AIDS before 2030, it is essential to re-double efforts to ensure that CLM is well-resourced. PLHIV-led organizations and other community players must be supported to implement effective CLM activities.

To ensure the sustainability of Zimbabwe's HIV response, there is a need for community initiatives led by key organizations such as ZNNP+ to be funded using domestic financial resources (taxes and levies) collected by the NALTF. By making more sustainable funding available to community initiatives, the country will be more likely to maintain the 95-95-95 target achievement and ultimately work toward ending the HIV/AIDS epidemic as a public health threat by 2030, Finally, in line with World AIDS Day 2023 theme, communities' leadership roles need to be made core in all HIV plans and programmes. They need to be fully and reliably funded. Barriers to communities' leadership roles need to be removed (6).

Author contributions

TM: Writing – original draft. BM: Writing – review & editing. TD: Writing – review & editing. EM: Writing – review & editing. AM: Writing – review & editing. IC: Writing – review & editing. MM: Writing – review & editing. GM: Conceptualization, Writing – original draft.

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Evaluation of physical and mental health conditions related to employees' absenteeism

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Background: Employees' health conditions are issues for not only employees themselves but also companies and society to keep medical costs low and productivity high.

Data and methods: In this analysis, 15,574 observations from 2,319 employees at four operational sites of a large corporation were used. The dataset contained physical and mental health conditions obtained from annual mandatory medical checkups, the Brief Job Stress Questionnaire (BJSQ), and work record information. Health and other factors related to long-term absenteeism (over three days in a quarter) were analyzed. Data were collected between February 2021 and January 2022, and we converted into quarterly observations. A logit (logistic regression) model was used in the analysis.

Results: Age and gender were identified as important basic characteristics. The estimates for these variables were positive and negative and significant at the 1% level. Among the variables obtained from the medical checkups, the estimates for diastolic blood pressure, HbA1c, anamnesis, heart disease history, smoking, increased weight, and frequency of alcohol consumption were positive and significant at the 1% level, further those for taking antihypertensive medications and kidney disease history were positive and significant at the 5% level. In contrast, the estimates for systolic blood pressure and amount of alcohol consumption were negative and significant at the 1% level. The estimate for taking antihyperglycemic medications and health guidelines were negative and significant at the 5% level. Among the variables obtained from the BJSQ, the estimates for amount of work felt, fatigue and support from family and friends were positive and significant at the 1%, and the estimate for irritation was positive and significant at the 5% level. The estimates for controlling job and physical complaints were negative and significant at the 1% level, and those for usage of employee's ability to work and suitability of the work were negative and significant at the 5% level. As all four operational sites were located in the northeastern region of Japan (cold and snowy in winter), the seasonal effects were significant at the 1% level. The effect of year was also significant and significant differences were observed among the sites at the 1% level.

Conclusion: Some physical and mental health conditions were strongly associated with long-term absenteeism. By improving these conditions, corporations could reduce the number of employee absence days. As absenteeism was costly for corporations due to replacement employees and their training costs to maintain operations, employers must be concerned

about rising healthcare (direct and indirect) costs and implement investments to improve employees' health conditions.

Limitations: This study's results were based on only one corporation and the dataset was observatory. The employees were primarily operators working inside the building and most of them are healthy. Therefore, the sample selection biases might exist, and the results cannot be generalized to other types of jobs, working conditions, or companies. As medical checkups and the BJSQ are mandatory for most companies in Japan, the framework of this study can be applied to other companies. Although we used the BJSQ results, better mental measures might exist. Similar analyses for different corporations are necessary.

KEYWORDS

absenteeism, absence days, physical and mental health, medical checkups, job stress

1 Introduction

The International Labour Organization (ILO) (1) estimated that losses due to health problems would account for approximately 3.94% of annual global GDP. The World Health Organization (WHO) (2) reported that the economic loss caused by work-related health problems [any illness caused or made worse by workplace factors (3)] would be 4%–6% of GDP in most countries. Maintaining and improving employee health are serious issues for employers. WHO (2) also mentioned that "workplace health initiatives can help reduce sick leave absenteeism by 27% and health-care costs for companies by 26%". Several studies have been conducted on the productivity, characteristics, and health conditions of employees (4–17). Various authors have also evaluated monetary costs and returns on health investments (18–21). Loeppke et al. (22) stated that health-related productivity costs were over four times higher than medical costs. In their analysis, they developed a database by integrating the medical and pharmacy claims data with the productivity and health information obtained from the 15,380 Health and Performance Questionnaire (HPQ) respondents of four companies. Then, they added information collected on employer business measures to the database.

Health-related productivity losses have been attributed to absenteeism (repeatedly being absent from work due to health problems) (23) and presenteeism (being present at work but with reduced productivity due to health conditions) (24). Presenteeism is a complicated problem (25) and its proper measurement is difficult. Worker absence is a good proxy for employees' health conditions (26). Since most of the corporation's employees clock in and out of work, and additional trained employees are required to maintain corporate operations, absenteeism is the cornerstone metric guiding corporate policy for healthcare investment (27). Nawata (28) evaluated the health factors affecting absenteeism using data obtained from 1,136 employees at one operational site of a large corporation. However, this study has the limitations: (i) the number of observations was not large and the observation period was just three months, and (ii) only limited factors of physical health conditions obtained from medical checkups were used, ignoring the factors representing mental health conditions. Mental health is important for employee well-being, productivity, and absenteeism (29–42). Goetzel et al. (43) emphasized that employers must be concerned about rising mental healthcare costs. Bryan et al. (44, p.1519) found "that a change in mental health has an effect on absenteeism more than three times greater than a change in physical health".

Since 2015, annual stress checks have become mandatory for companies with 50 or more workers in Japan under the Amendments of Industrial Safety and Health Act (45). The Japanese government also launched the Stress Check Program to screen workers with high psychological stress in the workplace (46). These amendments aim to prevent workers' mental disorders and improve working conditions that might cause job stress. Medical checkups and stress checks are performed as part of the regular operations of companies, and all costs are paid by the companies. That is, not only all direct costs but also necessary times for medical checkups and stress checks are treated as paid working hours. Hence, employers must be aware of these results to improve employee health. Tsutsumi and Kawakami (46) mentioned that the Japanese Stress Check Program might be effective in improving workers' mental health. The Brief Job Stress Questionnaire (BJSQ) (47) is usually used for stress checks, in which each worker answers 57 job stress questions. Watanabe et al. (48) also reported that the BJSQ helped to measure psychosocial factors at work. Therefore, we used the BJSQ results to represent the employees' mental health conditions. The BJSQ comprises four parts: job concerns, health conditions, people around the worker, and satisfaction. The 57 questions are then summarized into 19 items scored from 1 to 5; a higher score represents better conditions, that is, 5 is the best and 1 is the worst (49).

In this study, both physical and mental health conditions related to absenteeism were analyzed using 15,574 observations obtained from 2,319 employees over the period of February 2021 to December 2022. To the best of the author's knowledge, this study is the first attempt analyzing the relationship using a large individual dataset.

2 Data and models

2.1 Data

The dataset contained information on medical checkups, BJSQ answers, and work records obtained from employees at four

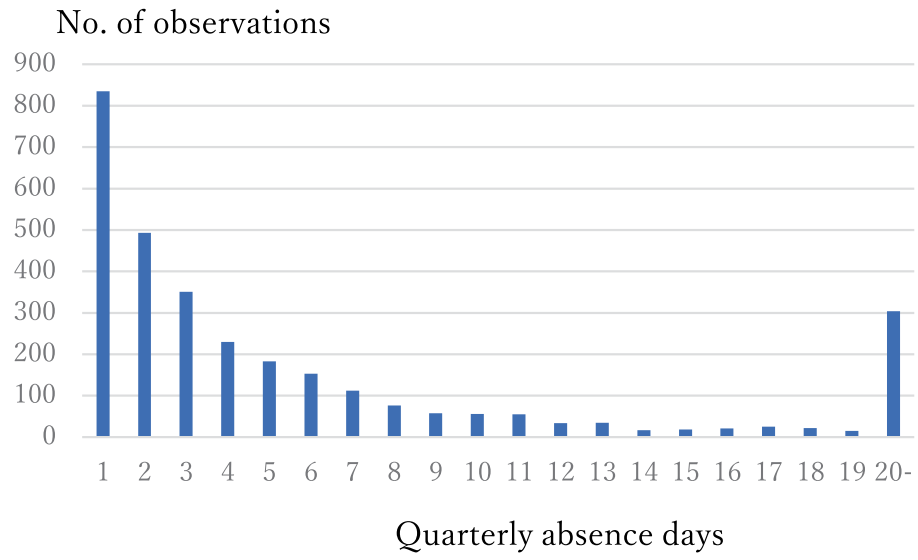

FIGURE 1
Distribution of quarterly absence days.

operational sites of a large corporation. Most employees were operators helping end consumers of client companies through telephones or the Internet at indoor operational sites. The sample period was from February 2021 to December 2022. Work records included information on work schedules, actual work hours, and employee absences. As seasonal factors (especially cold and snow in winter) matter in the locations of the sites, the sample period was divided into eight quarters: the first quarter (Q1) of 2021 to the fourth quarter (Q4) of 2022, and quarterly absence days were considered. Absence days were obtained from non-working days due to disability (sick or injured) and personal reasons. Paid, maternity and parental, nursing care, bereavement, auspicious, and special leaves absence days admitted by the corporation's regulations were excluded.

The distribution of absence days has a heavy right tail (Figure 1). We defined long-term absenteeism as the absence of an employee for over three days in a quarter (more than one day per month), following Nawata (28). As Q1 of 2021 only contained two months of working records, and the reasons for absences were not available for one month in Q4 of 2021 at one site, we defined long-term absenteeism if an employee was absent for over two days in those cases. Some employees resigned and some were hired during the sample period. As we consider quarterly data, these errors would be smaller than the annual data case. Working records were combined with annual medical check-ups in the same year. If an employee underwent two or more medical check-ups per year, the latter result was used. A total of 2,765 employees underwent medical checkups at least once during the study period. Among them, 2,699 employees had absence day data for at least one quarter of the year they underwent medical checkups, and we obtained 18,549 (person-quarter) observations. Figure 1 shows the distribution of quarterly absence days. The total number of absence days was 24, 619. A total of 15,456 or 83.3% of observations had no absence days. However, 1,459 or 7.9% of observations classified as long-term absenteeism accounted for 21,880 or 88.9% of total absence days. Hence, reducing long-term absenteeism is important for employers. A total of 16,660 observations from 2,409 employees provided BJSQ answers in the same year. After excluding observations with missing data, 15,574 observations obtained from 2,319 employees were used in the final model.

2.2 Models

We set three indices determined by employee, year, and quarter given by (i,t,q) and converted the data into quarterly (one dimensional) observations. We define $L\_Absence_{itq}$ =1 if the i-th employee has long-term absenteeism at the q-th quarter of year t and 0 otherwise. The continuous integer index (hereafter, observation number) $\ell = g(i,t,q)$, $\ell = 1,2,\ldots,n$, was assigned for each (i,t,q). Note that the assignment is one to one and (i,t,q) is uniquely determined when ℓ is given. Let q_1 the final quarter that the (i-1)-th employee worked and q_2 be the first quarter that i-th employees worked at year t, $\ell_1 = g(i-1,t,q_1)$ and $\ell_2 = g(i,t,q_2)$. If these employees worked throughout the year, $q_1 = 4$ and $q_2 = 1$. The observation number is assigned so that $\ell_1 + 1 = \ell_2$ and $\ell_2 + 1 = g(i,t,q+1)$ if the i-th employee had worked in both q and $q+1$ quarters in year t. Let n_1 be the number of observations in year t. Then, the observation number starts from $n_1 + 1$ in the next year. We obtained 18,549 (person-quarter) observations.

Of these observations, 7.9% were $L\_Absence_\ell$ =1. The basic model used in the analysis is the logistic regression (logit) model with the fixed time effect given by

$$P[L\_Absence_\ell = 1] = \Lambda(x_\ell'\beta + \gamma_{tq}),\ \ell = 1,\ 2,\ldots,\ n, \quad (1)$$

where Λ is the distribution function of the logistic distribution given by $\Lambda(\omega) = (\exp(\omega))/(1+\exp.(\omega))$; x_ℓ is a vector of covariates representing the employee's characteristic and health condition; β is a vector of unknown parameters; γ_{tq} is the fixed time effect, and n is the number of all observations. Since the medical checkup and BJSQ

TABLE 1 Assignment example of observation number ℓ in year t and values of x_ℓ when employees worked throughout year t.

Employee number	i-1	i				$i+1$
Quarter q	... 4	1	2	3	4	1 ...
Observation number ℓ	$\dots \ell_0$	ℓ_0+1	ℓ_0+2	ℓ_0+3	$\ell_1=\ell_0+4$	$\ell_1+1\dots$
x_ℓ	$\dots x_{i-1,t}$	x_{it}	x_{it}	x_{it}	x_{it}	$x_{i+1,t}\cdots$

results are available only once a year, we assume that x_ℓ does not change in year t so that $x_\ell \equiv x_{tiq} = x_{ti}$ for any possible $1 \le q \le 4$ where x_{ti} represents the medical checkup and BJSQ results of the i-th employee in year t. Table 1 shows the assignment example of the observation number ℓ and $x_\ell$when employees worked thought the year. Here after, we omit the subscript ℓ to avoid unnecessary complications.

2.3 Selection of covariates

As shown by Nawata (50), the selection of covariates is important. If we do not add the appropriate covariates, we obtain misleading results. However, if we add covariates that are irrelevant to absenteeism, we may lose the efficiency of the estimation due to multicollinearity among covariates and a reduction in the number of observations by missing values. The number of factors obtained from the medical checkups and the BJSQ was 41 and 19, respectively. Quarter, site location and year dummies were the other potential covariates. Therefore, it was necessary to control for the number of covariates.

The basic characteristics of employees are as follows:

Female (dummy variable) is 1 if female and 0 if male, and *Age* (age of an employee).

Since these factors were fundamental, not affected by the health conditions and highly significant in all models, we selected health factors based on the models with these factors.

We employed the procedure used in Nawata (28) to select the proper medical checkup and BJSQ covariates. The dataset was observatory and causality problems might exist, and we analyzed the variables possibly related to absenteeism. The procedure is based on likelihood ratio statistics and the Akaike information criterion (AIC), one of the most widely used criteria in model selection. It is important to use likelihood ratio statistics because t-test statistics may provide misleading results in binary choices and similar models (51, 52). Let $x_1, x_2, \dots, x_k$ be (potential) covariates. The medical checkup covariates were selected by the following stepwise procedure that increases the covariates one by one:

i) Estimate the model given by

$$P[L\_Absence = 1] = \Lambda(\beta_0 + \beta_1 Age + \beta_2 Female), \quad (2)$$

$$P[L\_Absence = 1] = \Lambda(\beta_0 + \beta_1 Age + \beta_2 Female + \beta_3 x_j), \quad j = 1,2,\dots,k.$$

Let the log likelihoods of the first and second equations and their difference be $\log L_0$, $\log L_{1j}$ and $LR_{1j} = \log L_{1j} - \log L_0$ for $i = 1,2,\dots,k$ in Eq. (2) using without missing values. $2 \cdot LR_{1j}$ is the likelihood test statistic of $H_0 : \beta_3 = 0$ and asymptotically follows $\chi^2(1)$ under the null hypothesis. Choose x_j that maximizes LR_{1j}.

ii) Without a loss of generality, we can assume that the first variable x_1 maximizes LR_{1j}.

Let

$$P[L\_Absence = 1] = \Lambda(\beta_0 + \beta_1 Female + \beta_2 Age + \beta_3 x_1), \quad (3)$$

$$P[L\_Absence = 1] = \Lambda(\beta_0 + \beta_1 Female + \beta_2 Age + \beta_3 x_1 + \beta_4 x_j),$$

$j = 2,3,\dots,k$, and calculate the second stage log likelihoods an the difference, $\log L_{1j}$, $\log L_{2j}$ and $LR_{2j} = \log L_{2j} - \log L_{1j}$ for j = 2,3,..., k in Eq. (3) using observations without missing values. Let x_2 be a variable that maximizes LR_{2j}.

iii) Repeat steps $m+1$ times by increasing covariates one by one until $LR_{m+1,j} < 1$ for all $j > m$ It corresponds to minimizing the AIC. The selected model becomes Eq. (4) given by

$$P[L\_Absence = 1] = \Lambda\begin{pmatrix}\beta_0 + \beta_1 Female + \beta_2 Age + \beta_3 x_1 \\ +\beta_4 x_2 + \dots + \beta_{m+2} x_m\end{pmatrix}. \quad (4)$$

This procedure allowed to select the following variables from the medical checkups. The deals of the section procedure are available upon request to the author.

SBP (systolic blood pressure) mmHg,

DBP (diastolic blood pressure) mmHg,

GOT (glutamic-oxaloacetic transaminase) units per liter (U/L),

GPT (glutamic-pyruvic transaminase) U/L,

Triglyceride (serum triglyceride level) mg/dL,

HDL (high-density lipoprotein cholesterol) mg/dL,

*Hb*A1c (hemoglobin A1c) %,

Anamnesis (dummy variable) is 1 if having anamnesis of any disease and 0 otherwise,

M_BP (dummy variable) is 1 if taking antihypertensive medications to control blood pressure and 0 otherwise,

M_Glucose (dummy variable) is 1 if taking antihyperglycemic medications to control glucose and 0 otherwise,

CBD (dummy variable) is 1 if there is a history of cerebrovascular disease and 0 otherwise,

Heart_D (dummy variable) is 1 if there is a history of heart disease and 0 otherwise,

Kidney_D (dummy variable) is 1 if there is a history of kidney disease and 0 otherwise,

Anemia (dummy variable) is 1 if having anemia and 0 otherwise,

Smoke (dummy variable) is 1 if smoking and 0 otherwise,

Weight_20 (dummy variable) is 1 if weight increased by 10 kg or more from age 20, and 0 otherwise,

Exercise (dummy variable) is 1 if exercising for 30 min or more twice or more in a week for more than a year, and 0 otherwise,

Chew_Food (can chew food items; integer 0–2) is 0 if everything, 1 if something, and 2 if difficult to chew,

Eat_Fast (eating speed; integer 0–2) is 0 if eating slower than other people, 1 if eating normally, and 2 if eating faster than others,

Alcohol_Freq (frequency of alcohol intake; integer 0–2) is 0 if never, 1 if sometimes, and 2 if every day,

Alcohol_Amount (amount of alcohol intake; integer 0–4) is 0 if none, 1 if drinking less than 180 mL of Japanese sake wine (with an alcohol percentage of approximately 15%) or equivalent alcohol per day when drinking, 2 if drinking 180–360 mL, 3 if drinking 360–540 mL, and 4 if drinking 540 mL or more),

Sleep (dummy variable) is 1 if sleeping well and 0 otherwise,

H_Guidance (dummy variable) is 1 if will take health guidances and 0 otherwise.

The following variables were selected from the BJSQ (stress check) answers using the same procedure of the medical checkup case. These variables take integers 1–5; a larger value is better (stress is less), 1 is the worst, and 5 is the best. Tsutsumi et al. (53) considered the cut-off points to identify the high-stress employees. Since the cut-off points were obtained from the BJSQ answers and we assumed that they associated with absenteeism continuously, we directly used the values of these items in the analysis.

M_Burden (mental burden concerning to quantity of work),

S_P_Burden (subjective physical burden),

Control_Work (control level of work),

Ability_Usage (utilization of knowledge and skills at work),

W_Suitability (suitability of the work for an employee),

Reward (rewarding work),

Irritation (irritation),

Fatigue (fatigue),

Depression (depression),

P_Complaint (physical complaints),

C_Support (support from co-workers),

F_Support (support from family and friends), and.

Satisfaction (work and family life satisfaction).

Since the year and seasonal factors were important, we considered that the time effect consisted of year and quarter effects and given by $\gamma_{tq} = \zeta_t + \eta_q$. The following dummy variables were used to represent the effects of the year, season, and site:

Y22 (year dummy) is 1 if year 2022 and 0 if 2021,

Q1, Q3, and *Q4* (quarter dummies representing the first, third, and fourth quarters, respectively. The base is the second quarter, where the probability of long-term absence is the lowest), and.

Site2, Site3, Site4 (site dummies representing the second, third, and fourth sites. The base is the first site with the largest number of employees is largest).

Forty-five covariates were used in the analysis and $x'\beta+\gamma_{tp}$ in Eq. (1) becomes Eq. (5) given by

$$x'\beta = \beta_0 + \beta_1 Female + \cdots + \beta_{25}\ M\_Burden + \cdots + \beta_{38} Y22 + \cdots + \beta_{45} Site4. \quad (5)$$

The study design is summarized in Figure 2, and the variables not used in the analysis are listed in Appendix A. A summary of the covariates is provided in Table 2. The list of abbreviations used in the study is given in Table A1 in Appendix B. The total number of observations used in the estimation of Eq. (3) is 15,574, of which 1,148 have *L_Absence* = 1 and 14,426 have *L_Absence* = 0.

3 Results of estimation

Table 3 presents the estimation results. In the analysis, we used EViews 12. The gross percentage of long-term absenteeism (*L_Absence* = 1) was 7.4%, McFadden's R^2 was 0.0921, and the likelihood ratio statistic of the equation was 775.05. Among the basic characteristics, the estimate for *Female* was positive, and its t-value was quite large and highly significant. The odds ratio (OR) for females compared to males was 2.26 with a 95% confidence interval (CI) ranging from 1.86 to 2.74. The estimate for *Age* was negative and significant at the 1% level. The OR comparing employees aged 30–40 years was 0.69, with a 95% CI of 0.69–0.75. Figure 3 shows the ORs and 95% CIs for *Female* and *Age*.

Among variables obtained from medical checkups, the estimates for *DBP* (OR:1.23; CI: 1.09–1.38), *HbA1c* (1.11; 1.03–1.19), *Anamnesis* (1.36; 1.18–1.57), *Heart_D* (2.88; 2.09–3.98), *Smoke* (1.67; 1.45–1.92), *Weight_20* (1.44; 1.24–1.67), and *Alcohol_Freq* (1.50; 1.30–1.73) were positive and significant at the 1% level. The ORs and 95% CIs were given in parentheses. The ORs were calculated from one standard deviation increments of the variables for continuous variables and one point increments for discrete variables such as dummy variables. The estimates for *M_BP* (1.37; 1.06–1.76) and *Kidney_D* (2.53; 1.05–6.11) were positive and significant at the 5% level. In contrast, the estimates for *SBP* (0.74; 0.66–0.84) and *Alcohol_Amount* (0.71; 0.64–0.79) were negative and significant at the 1% level. The estimates for *M_Glucose* (0.56; 0.35–0.90) and *H_Guidance* (0.85, 0.73–0.99) were positive and significant at the 5% level. Figures 4, 5 show the ORs and 95% CIs for significant variables of positive and negative estimates obtained from medical checkups, respectively.

Concerning variables obtained from the BJSQ, the estimates for *M_Burden* (1.40; 1.30–1.52) and *F_Support* (1.13; 1.07–1.20) were positive and significant at 1%, and that for *Irritation* (1.10; 1.02–1.18) was positive and significant at the 5% level. The estimates for *Control_Work* (0.81; 0.74–0.87) and *P_Complaint* (0.81; 0.75–0.87) were negative and significant at the 1% level, while those for *Ability_Usage* (0.901; 0.828–0.981) and *W_Suitability* (0.900; 0.825–0.981) were negative and significant at the 5% level. Figure 6 shows the ORs and 95% CIs for these variables.

Year and all quarter dummies were positive and significant at the 1% level. The ORs and 95% CIs were (1.36; 1.13–1.54), (1.41;1.17–1.71), (1.14; 1.37–1.65), and (1.83,1.53–2.19) for *Y22, Q1, Q3,* and *Q4*, respectively. For the site dummies, the estimate for *Site2* (1.61, 1.61–2.03) was positive and significant at the 1% level. Figure 7 shows the ORs and 95% CIs for these variables.

Concerning multicollinearity among covariates, the variance inflation factors (VIFs) were not large except for *SBP* (3.29), *DBP* (3.24), *GOT* (5.68) and *GPT* (6.22). The VIFs for these variables are in parentheses. Except for these variables, the largest VIF was 2.78 and not large; thus the multicollinearity problem is not particularly serious.

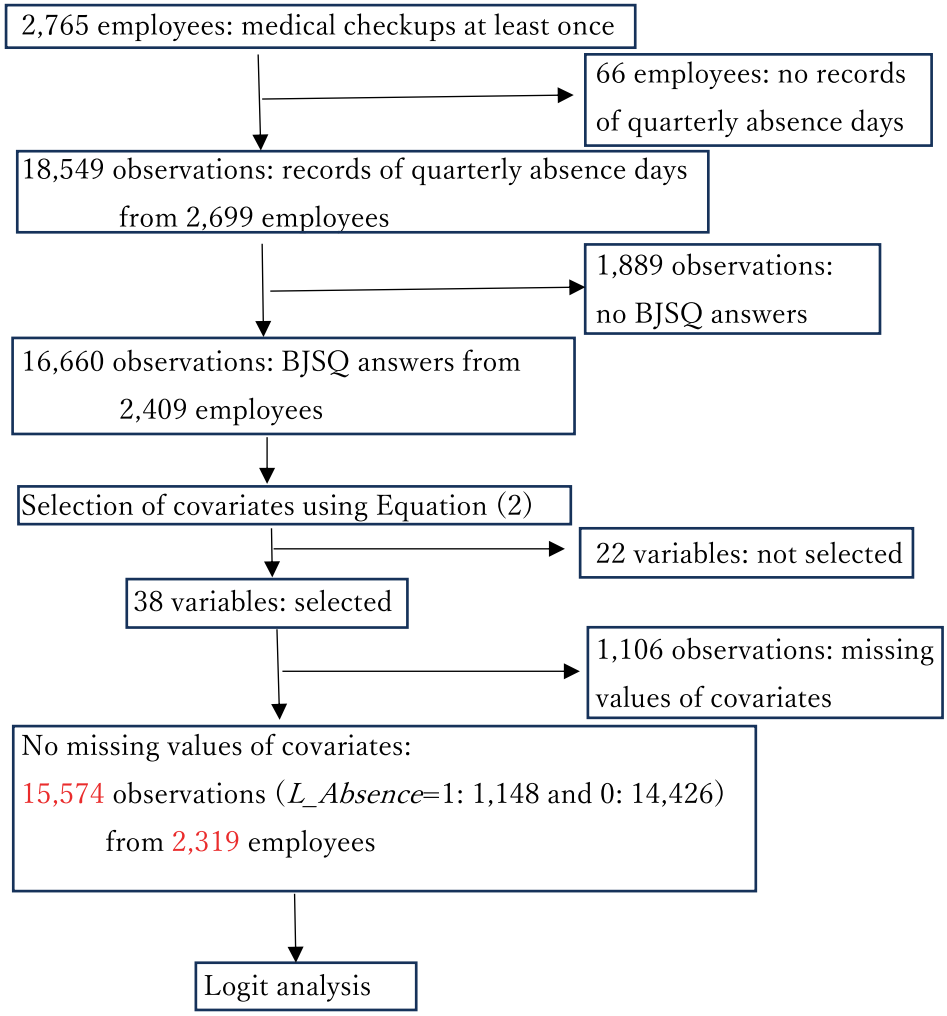

FIGURE 2
Flow chart of the study.

The correction coefficient of BP variables is relatively high (0.814). As the standard deviations (SDs) of *SBP* and *DBP* are different, we standardize them and define *S_SBP=SBP/s1* and *S_DBP=DBP/s2*, where *s1* (=19.70) and *s2* (=13.41) are the SDs of *SBP* and *DBP*. We consider the level and difference of BP as $BP\_L = (S\_SBP + S\_DBP)/2$ and $BP\_D = S\_SBP\text{-}S\_DBP$. These correspond to the first and second principal components of the standardized BP levels. The method makes the estimators for concerning variables most efficient (54) in the two variable cases. We then estimated the logit model again and obtained the results shown in Table 4.

Note that these changes are simple linear transformations, and the estimation results of the other variables and the model fitness remain the same as those of Table 3. The estimate for *BP_L* was negative and not significant at the 1% level; however, the estimate for *BP_D* was negative and highly significant (*p*-value is 0.0000).

The correlation coefficient between *GPT* and *GOT* is 0.901. When we considered the level and difference between these variables, the *p*-value were 0.139 and 0.287 for the level and difference variables, respectively, and the results were not significant.

4 Discussion

4.1 Basic characteristics

Age is a significant factor affecting long-term absenteeism. However, the paid leave days given to employees depend on the number of working years at the company, and the days become longer as the working years increase [Article 39 of the Labor Standards Act (55)]. Evidently, the working experience of younger employees tends to be shorter than that of older employees. Unfortunately, working years were not available for the dataset. Therefore, additional studies concerning to age and working years are required.

Gender is an important factor. The OR for females compared to males is 2.26 [In this case, because the probability of long-term absenteeism is relatively low, the OR approximates the probability ratio (56)]. This means that the long-term absenteeism probability of females is approximately twice that of males. The corporation depends heavily on female employees. Almost three-fourths of employees are female, and their absence directly affects corporate performance. Labor and health policies aimed at female employees are necessary.

TABLE 2 Summary of covariates.

Variables obtained from medical checkups			Variables obtained from BJSQ and quarter, site, year dummies		
Variable	Mean	SD	Variable	Mean	SD
Female	0.74		*M_Burden*	2.77	0.91
Age	39.34	10.51	*S_P_Burden*	3.51	0.71
SBP	124.32	19.70	*Control_Work*	2.89	0.93
DBP	74.63	13.41	*Ability_Usage*	2.69	0.75
GOT	23.28	13.90	*W_Suitability*	2.66	1.00
GPT	26.30	28.53	*Reward*	2.69	1.03
Triglyceride	101.47	78.47	*Irritation*	3.09	1.08
HDL	60.53	14.70	*Fatigue*	2.71	1.02
HbA1c	5.48	0.62	*Depression*	2.96	1.16
Anamnesis	0.569	0.50	*P_Compaint*	2.84	1.11
M_BP	0.085		*C_Support*	2.75	0.98
M_Glucose	0.031		*F_Support:*	3.14	1.36
CBD	0.007		*Satisfaction*	2.88	0.84
Heart_D	0.021		*Y22*	49.3%	
Kidney_D	0.002		*percent of observations by quarter*	Q1:24.1%, Q2:25.1%, Q3:25.4%, Q4:25.4%	
Anemia	0.250		*percent of observations by site*	Site1:51.6%, Site2:6.9%, Site3: 30.3%, Site4: 11.2%	
Smoke	0.241				
Weight_20	0.382				
Exercise	0.114				
Chew_Food	0:84.65%, 1:15.27%,2:0.08%				
Eat_fast	0:12.8%, 1:58.6%, 1:28.5%				
Alcohol_Freq	0:17.1%, 1:60.4%, 2:22.5%				
Alcohol_Amount	0:45.6%, 1:26.2%, 2:19.9%, 3:6.3%m 4:2.0%				
Sleep	0.569				
H_Guidance	0.253				

SD: standard deviation.

4.2 Variables obtained from the medical checkups

Concerning blood pressure (BP), the relationships of *SBP* and *DBP* to absenteeism are opposite. The estimate for *SBP* is negative and that for *DBP* is positive. This means that higher SBP may reduce long-term absenteeism, whereas higher DBP may increase it. The results of Table 4 suggest that the (standardized) difference between SBP and DBP does matter, but the BP level may be less important. There have been many studies on the relationship between BP and diseases (especially cardiovascular diseases) (50). Therefore, it might be necessary to reevaluate the relationship between BP and disease from this viewpoint.

HbA1c is positively related to absenteeism. *Anamnesis* and histories of heart disease and kidney disease may increase the probability of long-term absenteeism. Compared to those without them, the ORs are 1.36, 2.88 and 2.53 for those with anamnesis, heart disease, and kidney disease, respectively. Therefore, special healthcare by the corporation should be necessary for such employees.

Smoking habits and large weight increases can also affect absenteeism. The ORs are 1.67 and 1.44 compared to those without them. These results are consistent with those of previous studies (20, 57–59). Health guidelines may reduce absenteeism as expected. These factors are modifiable through, and it may be worthwhile for the corporation to help improve these factors. The results for alcohol consumption are mixed. If an employee drinks more frequently, it may increase absenteeism; however, if an employee drinks more alcohol at once, the probability of absenteeism may decline. We cannot determine the reasons for this finding, and further studies regarding alcohol consumption are necessary. Antihypertensive medications would increase absenteeism, but antihyperglycemic medications would decrease.

4.3 Variables obtained from the BJSQ

The BJSQ primarily represents employees' mental elements. Among them, the burden concerning the quantity of work (*M_Burden*) is positive and highly significant (t-value = 8.45, p-value = 0.000). It is not a good sign, and it is reasonable to consider that employees might be overworking because they cannot take off days due to too much work. In the worst case, overwork results in

TABLE 3 Results of estimation.

Variable	Coefficient	SE	Variable	Coeffcient	SE
Constant	−2.3945	0.5017	*M_Burden*	0.3398	0.0402**
Female	0.8132	0.0991**	*S_P_Burden*	0.0386	0.0481
Age	−0.0367	0.0040**	*Control_Work*	−0.2152	0.0404**
SBP	−0.0150	0.0031**	*Ability_Usage*	−0.1039	0.0434*
DBP	0.0154	0.0044**	*W_Suitability*	−0.1056	0.0440*
GOT	−0.00392	0.00541	*Reward*	0.0788	0.0426
GPT	0.00367	0.00273	*Irritation*	0.0922	0.0359*
Triglyceride	0.0005	0.0004	*Fatigue*	−0.1605	0.0468**
HDL	−0.0049	0.0028	*Depression*	−0.0193	0.0430
HbA1c	0.1633	0.0592**	*P_Compaint*	−0.2130	0.0390**
Anamnesis	0.3078	0.0732**	*C_Support*	0.0702	0.0366
M_BP	0.3130	0.1292*	*F_Support*	0.1242	0.0276**
M_Glucose	−0.5824	0.2455*	*Satisfaction*	−0.0894	0.0497
CBD	−0.9947	0.5973	*Y22*	0.3046	0.0645**
Heart_D	1.0592	0.1649**	*Q1*	0.3458	0.0964**
Kidney_D	0.9272	0.4504*	*Q3*	0.3147	0.0956**
Anemia	0.0666	0.0739	*Q4*	0.6024	0.0916**
Smoke	0.5107	0.0725**	*Site2*	0.4763	0.1190**
Weight_20	0.3663	0.0757**	*Site3*	0.1312	0.0770
Exercise	−0.0721	0.1150	*Site4*	0.1526	0.1038
Chew_Food	0.0581	0.0868			
Eat_fast	−0.0640	0.0518	No. of observations		
Alcohol_Freq	0.4083	0.0725**	0: 144266, 1: 1148, total 15,574		
Alcohol_Amount	−0.3393	0.0558**	Log likelihood −3720.59		
Sleep	−0.1155	0.0705	McFadden R^2 0.092122		
H_Guidance	−0.1627	0.0764*	Likelihood ratio statistic 755.05		

SE: standard error, **: significant at the 1% level; *: significant at the 5% level.

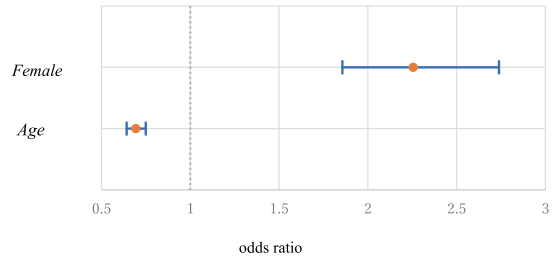

FIGURE 3
Odds ratios and 95% confidence intervals of *Female* and *Age* (Age 30 vs. Age 40).

employee suicide (60). Employers and managers at operational sites should pay attention to avoiding employee overwork.

W_Control, Ability_Usage, W_Suitability are significant at the 1% or 5% levels. These variables represent motivation, suitability, and willingness to work. Because the meanings of these variables are similar, we consider the case in which the values of all variables increase by one. $\hat{\beta}_{29}, \hat{\beta}_{30}$ and $\hat{\beta}_{31}$ are the estimators of these variables. Since $V\left(\sum \hat{\beta}_i\right) = \sum V\left(\hat{\beta}_i\right) + 2\sum_{i<j} \mathrm{cov}\left(\hat{\beta}_i, \hat{\beta}_j\right)$ and $\mathrm{cov}\left(\hat{\beta}_i, \hat{\beta}_j\right)$ $= -0.00021, -0.00034$ and -0.00021 for $(i=29, j=30)$, $(i=29, j=31)$ and $(i=30, j=31)$, $V\left(\hat{\beta}_{29} + \hat{\beta}_{31} + \hat{\beta}_{32}\right)$ =0.00394. Therefore, the OR is 0.65 with 95% CI of 0.58–0.74 (the OR and CI are calculated by comparing $\sum x_i$ and $\sum\left(x_i + 1\right)$). This finding suggests that employers and managers can reduce long-term absenteeism by one-third through suitable work arrangements that would motivate employees.

Irritation is significant at the 5% level. However, the sign is positive. Further studies are necessary to address employee irritation. *Fatigue* and physical complaints (*P_Complaint*) are significant at the 1% level. Compared to the one-point improvement case, the ORs become 0.85 and 0.81, suggesting that long-term absenteeism could be reduced by about 15% and 20% through one-point improvement in these factors. The estimate for support from family and friends (*F_Support*) is positive and significant at the 1% level. It is reasonable to assume that family and friends advise employees to take off days more often when conditions are poor. Surprisingly, the estimate for work and family life satisfaction is not significant at even the 5% level.

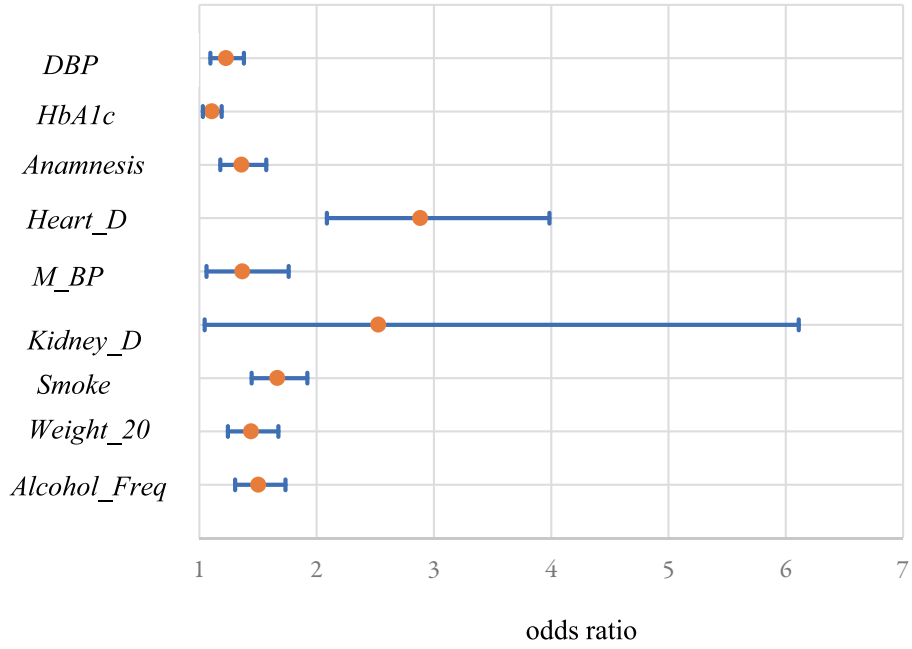

FIGURE 4
Odds ratios and 95% confidence intervals of significant variables of positive estimates obtained from medical checkups.

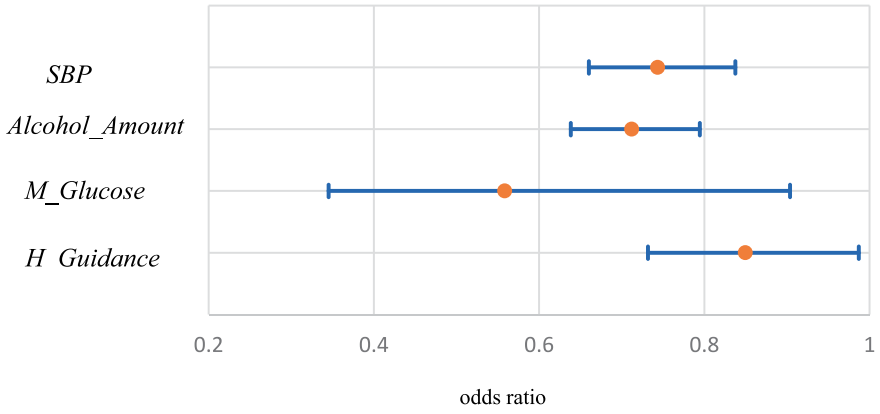

FIGURE 5
Odds ratios and 95% confidence intervals of significant variables of negative estimates obtained from medical checkups.

Unlike the results of Bryan et al. (44), these results may imply that physical factors are more important than mental factors. Li and Wang (61) evaluated the work-family initiatives including reduced work hours, flexible schedule and telework. They found that the mental health benefits of flexible schedule and telework initiatives were larger than reduced hours initiatives. It may be worthwhile for the government and employers to promote flexible work time systems to reduce employees' physical burdens and complaints.

4.4 Year, quarter, and site dummies

The estimate of the dummy variable for 2022 (*Y22*) is highly significant, suggesting a large difference in 2021 and 2022. The average daily number of new coronavirus patients (COVID-19) patients in Japan was 4,010 in February–December 2021, and 75,175 in January–December 2022 (62). This huge difference might have affected absenteeism; however, further investigation is necessary to evaluate the relationship of COVID-19 to absenteeism.

All estimates for quarter dummies are significant. The seasonal factors are important, especially in the fourth quarter (*Q4*, October–December). The operational sites are located in the northeastern region of Japan. The first snowfall occurs in mid-November; moreover, the daytime becomes shorter, and the weather becomes colder daily in the fourth quarter, which might affect the behaviors of employees. The estimate for *Site2* is positive and significant. The percentages of observations answered the BJSQ are 93.5, 43.6, 94.2, and 93.4% at Sites

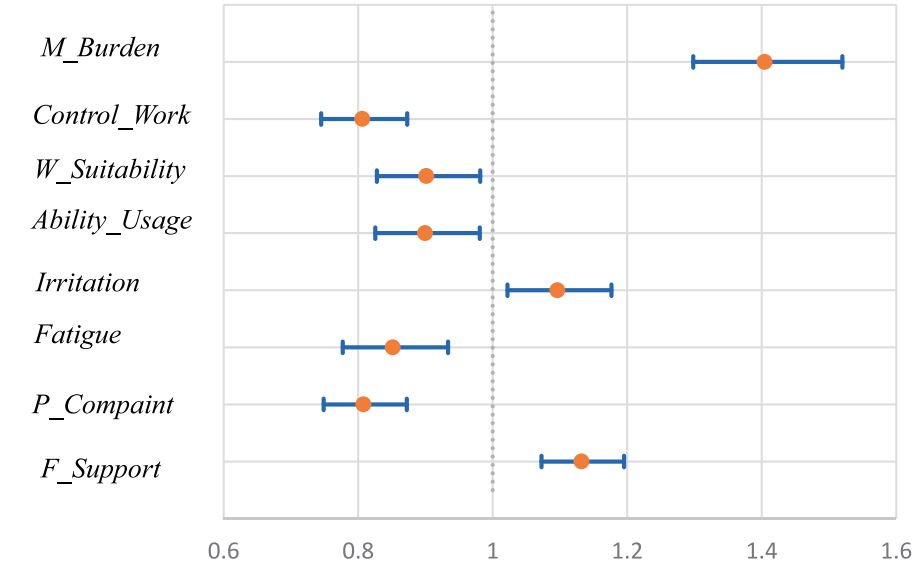

FIGURE 6
Odds ratios and 95% confidence intervals of significant variables obtained from the BJSQ.

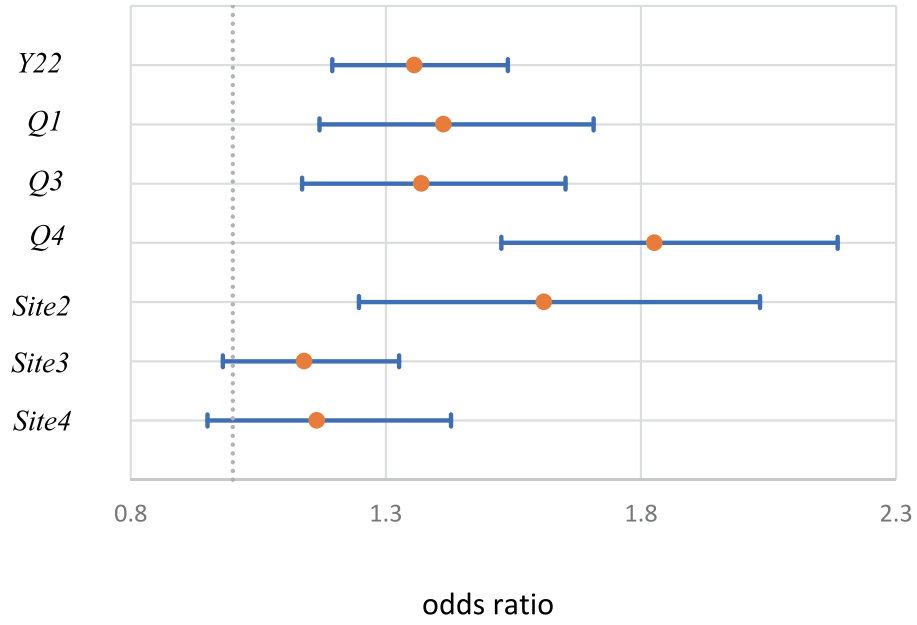

FIGURE 7
Odds ratios and 95% confidence intervals of year, seasonal, and site dummies.

1, 2, 3, and 4. The value of Site 2 is the smallest, which might affect employees' labor and health management.

5 Conclusion

This study analyzed the physical and mental health factors of employees that may be related to absenteeism. The dataset included the results of annual medical checkups, BJSQ, and work records at four operational sites in a large corporation. The sample period was from February 2021 to January 2022. Because there were too many potential covariates, health-related covariates were selected using the stepwise procedure. Subsequently, 15,574 observations from 2,319 employees were used in a logistic regression (logit) model.

The long-term absenteeism probability for females was much higher than that for males. The corporation depends heavily on female employees. Labor and health policies aimed at female employees are necessary for the corporation. The opposite relations

TABLE 4 Estimation results of *BP_L* and *BP_D*.

Variable	Coefficient	Standard error	*p*-value
BP_L	−0.0903	0.0406	0.0261
BP_D	−0.2510	0.0563	0.0000

were observed for SBP and DBP. These results suggest that the (standardized) difference between SBP and DBP was more important than the BP level. HbA1c, anamnesis and histories of heart disease and kidney disease were positively related to the probability of long-term absenteeism. Smoking habits and large weight increments were positively associated with absenteeism. Health guidelines might reduce the absenteeism. It may be worthwhile for the corporation to help improve them. The results for alcohol consumption were mixed. Antihypertensive medications would increase absenteeism but antihyperglycemic medications would decrease.

Among the BJSQ vaeiables, the quantity of work was positive and highly significant, and employers and managers should pay attention to avoiding overworking employees. Improving workers' motivation through suitable work arrangements could reduce long-term absenteeism by one-third. Fatigue and physical complaints were also important, and long-term absenteeism cloud be reduced by improving physical conditions. The estimate of support from family and friends was positive and significant. However, the estimate of work and family life satisfaction was not significant even at the 5% level.

The estimate of the dummy variable for 2022 was highly significant. Therefore, COVID-19 might have affected absenteeism. Seasonal factors were important, particularly in the fourth quarter. The estimate for *Site2* was positive and significant, and it may be necessary to revise the labor and health management policies at the site. Among the major countries, the Japan is the only country performing annual mandatory health checkups and job stress checks for most employees regardless of their health conditions (63). It is extremely costly to do such a survey in other countries. The results of the paper would help when the similar types of studies or policy analyses are done in other countries.

The results of this study are based on operational sites of one corporation and the dataset was observatory. The employees were mainly operators working inside the buildings, and most of them are healthy people. Therefore, the sample selection biases might exist, and results may differ for different working conditions, job types, or companies. Hence, the results of this study cannot be generalized. However, annual medical checkups and the BJSQ for employees are mandatory for most companies, and the framework of this study is applicable to most companies in Japan. The influence of presenteeism is not evaluated. The implementations to improve the employees' health conditions are also important. These are the limitations of the study and should be investigated in future studies.

Data availability statement

The data were provided to the author under the official agreement of Hitotsubashi University and the corporation. The data for this study are not publicly available to protect personal information. A new agreement with the corporation is necessary for future research. Researchers may contact the corresponding author with the dials of agreement.

Ethics statement

The studies involving humans were approved by Institutional Review Board of Hitotsubashi University (2022C003). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

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

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2023.1326334/full#supplementary-material

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The relationship between health insurance and economic performance: an empirical study based on meta-analysis

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Health insurance stands as a pivotal facet of social wellbeing, with profound implications for the overarching landscape of economic development. The existing research, however, lacks consensus on the relationship between health insurance and economic performance and provides no evidence about the magnitude of the correlation. This lack of information seriously impedes the high-quality development of the healthcare system. Therefore, to scientifically elucidate the relationship between the two, this study involved a meta-analysis, analyzing 479 effect values derived from 34 independent research samples. The results reveal a strongly positive correlation between health insurance and economic performance [r = 0.429, 95% CI = (0.381, 0.475)]. Findings show that health insurance in developed countries more effectively fosters economic performance than in developing countries. Moreover, public health insurance exerts a stronger promoting effect on economic performance than commercial health insurance. The relationship between health insurance and economic performance is moderated by data type, research method, country of sample origin, literature type, journal impact factor, publication year, type of health insurance, and the research populations. Based on meta-analysis, this study not only scientifically responds to the controversy of the relationship between health insurance and economic performance, and the magnitude of a correlation, but also further reveals the inner conduction mechanism between the two. Our research findings are meaningful for policymakers to choose an appropriate healthcare strategy according to their unique attributes, propelling sustainable economic development.

KEYWORDS

health insurance, economic performance, meta-analysis, the magnitude of a correlation, moderating effects

1 Introduction

As a primary component of the health strategy, health insurance not only ensures accessibility to medical services but also contributes to improving life expectancy, and social welfare (1). It serves as a long-term safeguard mechanism, dispersing health risks and preventing a return to poverty due to illness, playing a crucial role in economic development. Implementing and enhancing health insurance strengthens the economic foundation and improves economic performance (2). For instance, the government stimulates domestic demand and enhances residents' consumption by improving medical coverage and increasing healthcare spending, replacing precautionary savings (3–5). Prior research has also shown that health insurance enhances productivity and makes human capital more valuable, leading to a positive contribution to economic growth (2, 6, 7).

With the swift evolution of the healthcare system, the relationship between health insurance and economic performance has become a hot research topic in the field of public health. In particular, it significantly impacts the sustained progress of a nation or region's healthcare system, the wellbeing of its inhabitants, and the overall economy. Therefore, exploring the relationship between the two is of significant practical importance for establishing and improving focused healthcare systems. This study focuses on the following questions: First, does health insurance promote economic performance? Second, what is the magnitude of the correlation between health insurance and economic performance? Third, why do existing empirical research conclusions differ?

While scholars have explored the impact of health insurance on economic performance from various perspectives, there is no consensus on the relationship between the two. In varied research contexts and datasets, studies have shown that the relationship between the two may be positive, negative, or uncorrelated (2, 8–10). A consensus is emerging, however, that investing in health insurance is a strategy for cultivating human capital. Some scholars contend that health insurance fosters human capital by improving educational outcomes through the development of cognitive abilities (11). Furthermore, it directly stimulates economic performance by increasing individual income through higher labor productivity, marginal productivity, working hours, and the duration of production activities (12–14). Researchers have found that health insurance significantly reduces medical expenditure risks, lowering poverty and boosting income, preventing health-related poverty for low-income groups, and enhancing residents' consumption capacity (8, 15–18). However, not all studies support the view that healthcare positively influences economic performance. Some scholars have argued that excessive healthcare spending may adversely affect the economy by crowding out tangible capital investment (12). Healthcare consumption is also driven not only by necessity but also by the desire to maintain health. This may result in excessive investment in human capital, as the demand for quality services during economic growth remains unmet, and the role of health insurance in reducing residents' catastrophic medical expenses is not fully realized (9, 10, 12, 19–22) This could imply a heightened crowding-out effect on physical capital investment. Some scholars also believe that healthcare may hinder economic growth, given that population aging often correlates with increased healthcare spending (20).

In summary, numerous empirical studies have analyzed the relationship between health insurance and economic performance, yielding valuable and reference-worthy research conclusions. However, in terms of research content and perspective, existing studies still exhibit the following shortcomings. Firstly, while the majority of literature results suggest a positive impact of healthcare insurance on economic performance, scholars in diverse research contexts have also highlighted potential negative or unrelated relationships between the two. This contradictory relationship impedes the direct application of current research findings to the development of healthcare systems. Thus, further exploration is warranted to better understand the impact of healthcare insurance on economic performance. Secondly, previous studies only focus on the impact of health insurance on economic performance, neglecting the magnitude of the correlation between the two. Given increasing national demands for healthcare quality and wellbeing, exploring the extent of the impact is crucial for formulating and implementing health service policy formulation and implementation. Thirdly, although scholars have conducted qualitative reviews and quantitative summaries of health insurance's economic performance, current research still has limitations. Subjective influences and representative biases often exist in the literature selection of qualitative studies, affecting the accuracy and objectivity of research results. In quantitative research, there were significant differences in the measurement and definition of some key variables, leading to a lack of scientific, comprehensive, and systematic studies. So, there is a pressing need for more precise and objective research methods to overcome current research bottlenecks.

To fill the above research gaps, this study aims to contribute several novel insights into the relationship between health insurance and economic performance by meta-analysis methodology. Compared with the existing literature, this study's marginal innovation lies in three aspects. First, this study provides a scientific response to contradictions in findings about the relationship between health insurance and economic performance. Through meta-analysis, we systematically summarized and further investigated existing empirical studies on the impact of health insurance on economic performance, accurately presenting the relationship between the two. This not only enhances the content and methodology of healthcare research but also provides robust empirical evidence to support high-quality development. Second, grounded in a scientific response to the relationship between health insurance and economic performance, this study aims to explore in depth the strength of the correlation. By integrating varied research samples and model factors. With a more objective and precise, understanding of the magnitude of the correlation, we provide valuable references for formulating rational health insurance strategies. Third, no attention has yet been paid to the causes of heterogeneity in the relationship between health insurance and economic performance. This study delves into the reasons for divergent research conclusions and identifies moderating variables leading to diverse research outcomes across four levels: samples, literature, measurement, and variables. Moreover, the study extensively examines scenarios in which medical insurance exhibits diverse effects on economic performance, offering references for formulating strategies and improving economic outcomes.

The research roadmap is as follows: firstly, a review of the existing relevant literature is conducted, developing hypotheses and an analytical framework. Secondly, the literature is rigorously screened and information is extracted, strictly adhering to the steps of meta-analysis, followed by effect size calculation and an exploration of heterogeneity. Thirdly, the results of the meta-analysis are conducted, including a publication bias test, overall effect and moderating effect analysis, and a robustness test. Finally, the results of this research are presented and discussed.

2 Research hypothesis and framework

2.1 The impact of health insurance on economic performance and its sub-dimensions

The distinct economic performance generated by health insurance has garnered significant attention from scholars. Scholars have primarily examined the mechanisms that underlying how health insurance impacts economic performance, from both a societal and individual perspective. At the societal level, the widespread accessibility of health insurance has profound implications for economic performance. Firstly, health insurance plays a pivotal role in shaping economic performance by mitigating inequality and enhancing labor productivity. According to Roemer's theory of equal opportunity, health disparities arising from environmental factors are deemed unjustifiable (23). Universal health insurance enables residents to share medical resources more equitably, alleviating health inequalities arising from different environmental conditions. With health insurance, people can access medical services more promptly, reducing productivity losses due to illness, contributing to the overall productivity of society, and promoting economic development (15). Health insurance also facilitates the accumulation of human and material capital within families, effectively driving investments in health and promoting the overall improvement of workforce quality (24). Secondly, health insurance can maintain economic stability. By mitigating the financial impact of medical expenses on household budgets, it curtails the financial risks of illness. This, in turn, helps in sustaining the financial stability of households and mitigating economic fluctuations triggered by medical costs. Furthermore, health insurance contributes to improving the overall health status of society, curbing the spread of diseases. When health levels are higher, disruptions in the labor force are minimized and stability in the labor market is fostered. These combined factors actively propel sustainable economic development, establishing a more stable and dependable economic environment (25). Thirdly, health insurance alleviates fiscal pressure. By making early treatment and chronic disease management affordable for people, health insurance alleviates long-term medical expenses, providing a buffer for public finances (26). Fourthly, health insurance contributes to maintaining social order, which in turn affects economic performance. It does this by reducing destabilizing factors arising from health issues, such as family breakdowns, and by reducing the social upheaval caused by large-scale disease outbreaks, which improves labor availability and quality (27).

At the individual level, health insurance empowers people to take care of their own and their families' wellbeing and alleviates the economic burden imposed by diseases, or long-term treatment. Consequently, people are more able and motivated in economic activities. Specifically, health insurance cuts residents' medical service costs through dynamically adjusting policies, including deductibles, caps, funding mechanisms, reimbursement rates, and payment methods. By sharing medical expenses, health insurance alleviates the economic burden on individuals facing sudden illnesses or long-term treatments (15, 18, 28). Hence, individuals are more capable of maintaining their own and their family's health without the overwhelming pressure of medical expenses. Besides, individuals participating in healthcare insurance are more prone to receiving medical service timely, diminishing the risk of chronic diseases, thus enhancing their quality of life and facilitating engagement in social and economic activities. Moreover, in line with the life cycle theory, individuals adopt unique asset allocation strategies at various life stages, with these shifts closely connected to their health conditions and physical functions (29). With better health and less uncertainty about medical expenses, individuals can focus on career development or entrepreneurial activities. Health insurance also provides risk protection, diminishing the need for individuals to save for medical costs and boosting individual consumption capacity (30, 31).

In summary, health insurance improves health and wellbeing from both the societal and individual perspectives, promoting economic performance. On the one hand, health insurance effectively safeguards the quality of human capital, enhances productivity, and stimulates economic growth. On the other hand, healthcare insurance reduces the risks of illness, alleviates the economic burden when ill-health does arise. Furthermore, health insurance directly influences resident' consumption tendencies, reducing precautionary savings and boosting domestic demand, thereby increasing the level of consumption. Therefore, this study proposes the following hypothesis:

H1: A positive correlation exists between health insurance and economic performance.

Some studies indicate that the development of the insurance industry promotes economic growth (32–34). The promotion effect is primarily achieved through two pathways: risk transfer, reducing uncertainty and fostering consumption and research; and financial intermediation, with insurance companies investing premiums in financial markets, stimulating investment (35). Health insurance also creates progress in the health industry, boosts social welfare by increasing health expenditure, and enhances the national health level (27, 36). The beneficial role of health insurance in providing financial support for consumption is increasingly evident, leading to synchronized growth in insurance consumption and economic development (33). Health insurance, beyond typical economic impacts, collaborates with medical institutions and health management entities, providing residents with health consultation, chronic disease management, and related services. This not only improves national health and reduces illness risks and insurance payouts but also contributes to a sizable "big health industry", fostering economic growth. Health insurance has driven the development of sectors such as pharmaceuticals, medical services, education, and older adult care, creating economies of scale and promoting economic growth. Therefore, this study proposes the following hypothesis:

H1a: Health insurance helps to promote economic growth.

Medical economic burden pertains to financial losses incurred through healthcare spending. Researchers use medical expenditure as a metric to measure the economic burden of healthcare spending. This encompasses outpatient fees, hospital charges, medication

costs, and related outlays on medical services, equipment, and healthcare expenses (21). Health insurance, integral to the healthcare system, aims to alleviate residents' economic burden, ensuring the nation's right to health and life. With the broader reach of medical insurance coverage, the health insurance fund can economically compensate by sharing medical care costs, reducing the actual medical expenses for insured individuals, and alleviating their healthcare economic burden. In addition, health insurance, as a risk-sharing mechanism, spreads risk across a wider population through collected premiums. In cases of accidents or illness, it mitigates economic losses for individuals and families by offering medical services and corresponding compensation. Furthermore, health insurance negotiates reasonable medical expenses with healthcare institutions, curbing the rapid growth of healthcare costs and alleviating the economic burden. By providing medical support during illness, insurance also reduces the risk of unemployment and the loss of a wage or salary. Therefore, this study proposes the following hypothesis:

H1b: Health insurance helps to reduce the medical economic burden.

From a health economics perspective, human efforts to combat disease risks involve preventive measures and the establishment of a health insurance system. This system, as part of the health system, may support workers and boost consumer confidence. Health insurance, therefore promotes consumption through a transfer effect, leveraging the law of large numbers to reduce individual economic burdens and enhance medical service accessibility. Despite being post-event compensation, health insurance effectively increases relative income, potentially redirecting it to other consumption areas. Insurance system may also stimulate consumption through the reduced need for the precautionary savings, as it lessens the economic burden of diseases and enhances individual' ability to cope with future risks. The decreased uncertainty in future healthcare expenditures may lead people to reallocate budgets allocations, promoting current consumption. Therefore, this study proposes the following hypothesis:

H1c: Health insurance helps improve the consumption levels.

Drawing on the theoretical analysis and research hypotheses above, Figure 1 illustrates the foundational framework for this study.

2.2 Factors that moderate the relationship between health insurance and economic performance

2.2.1 Sources of difference from the sample

(1) Variations in the sampling countries. Health insurance systems in different countries are shaped by factors such as coverage scope, types of insurance, and the level of medical services. These variations contribute to diverging research outcomes regarding the relationship between health insurance and economic performance. In contrast to developing countries, developed countries typically have more robust healthcare insurance systems, abundant funds, and higher protection levels, potentially leading to a more noticeable impact on economic performance. For instance, with the United States taken as the sample source country, Raghupathi and Raghupathi concluded that there was a positive correlation between health insurance and economic performance (2). The improvement of residents' health conditions through health insurance indeed contributes to economic improvement. Beko et al. analyzed the influence of Slovenian health insurance on the national economy, revealing that it fosters national economic output and augments household income (37). Nevertheless, some studies have questioned the positive impact of health insurance on economic performance (38). Karan et al., using nationally representative data from India, found that health insurance did not significantly reduce hospitalization expenses but increased non-medical costs for households by around 5%, without alleviating the medical expenditure burden on impoverished families (39). In light of such varied research conclusions, it is imperative to discern the disparities attributable to the diverse source countries of the samples.

2.2.2 Sources of difference from the measurements

(1) The variations in measuring economic performance arise from different data types. Research data, primarily including panel and cross-sectional types, can impact research results. Cross-sectional data are challenged by non-dynamism issues, while panel data, featuring multiple cross-sections over time, better address this problem and offer a more comprehensive view of variable relationships. Consequently, the utilization of different data types in existing research produces divergent research findings. For example, through the analysis of cross-sectional data, Wagstaff et al. found that health insurance did not promote economic performance (40). After analyzing panel data, Zhou et al. concluded that health insurance alleviates the financial burden on patients and promotes economic performance (41). Hence, the difference in data types may have an impact on the research results regarding the relationship between health insurance and economic performance.

(2) Different research methods are employed. Existing studies of health insurance and economic performance have primarily used difference-in-differences and various regression models such as Logit regression, Ordinary Least Squares (OLS), etc. These distinct methods come with different assumptions and applicable scopes, potentially yielding divergent results. Yang employing the difference-in-differences method, observed that the income-increasing and poverty-reduction effects of health insurance are minimal, lacking a significant impact on economic performance (10). In contrast, Wang found that healthcare insurance did enhance economic performance in a study using panel regression and quantile regression analysis (5). It is crucial, therefore to identify and understand where variations in results can be attributed to differences in the research models used.

2.2.3 Sources of difference from the literature

(1) The difference in publication years. Literature published in different years is influenced by research trends, policy environments, and various factors, leading to diverse perspectives

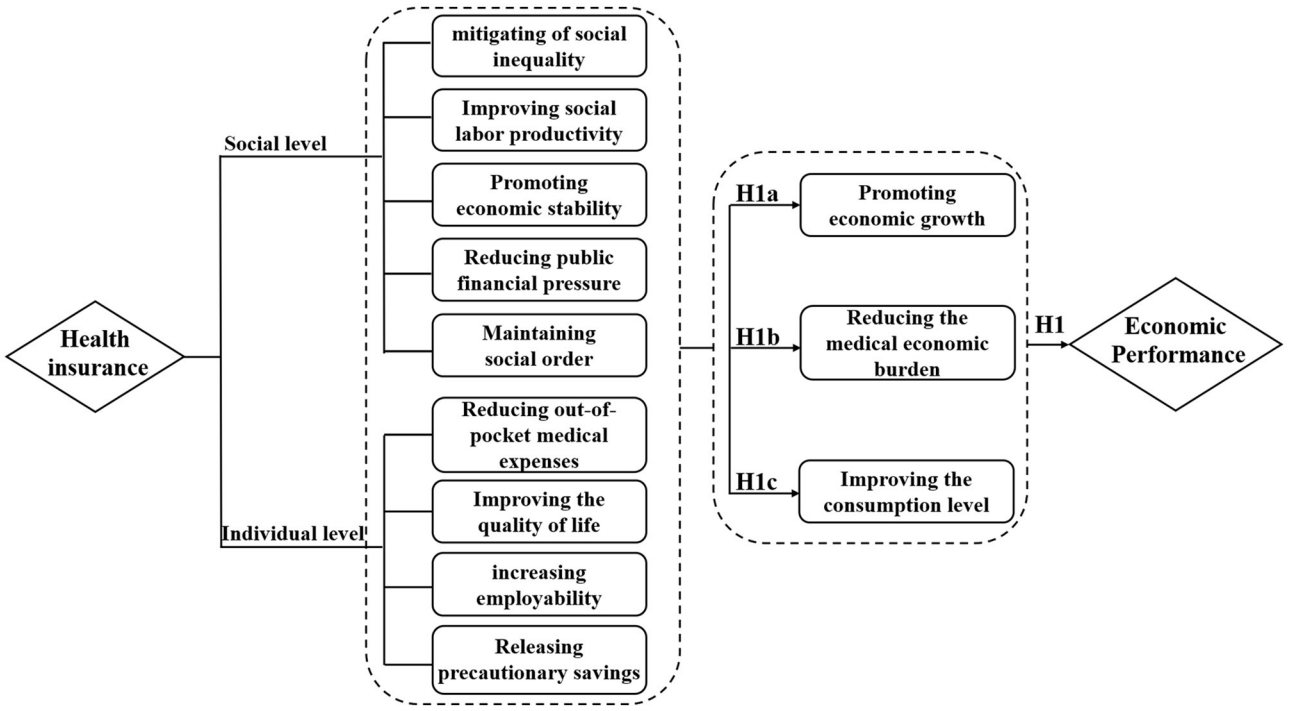

FIGURE 1
Meta-analysis diagram of the relationship between health insurance and economic performance.

on whether health insurance promotes economic performance. In recent periods, the relationship between health insurance and economic performance has become a focal point in research, garnering attention from academia and researchers. Consequently, researchers may emphasize the positive impact of health insurance to align with academic trends. Additionally, policymakers, committed to promoting health insurance and the economy, may influence researchers to demonstrate a positive relationship, supporting policy formulation. Thus, disparities in publication years may impact the perceived link between health insurance and economic performance.

(2) Different types of literature. Various types of literature are influenced by the review process, which may result in different publication orientations for studies on the relationship between health insurance and economic performance. The literature selected for this study includes theses and journal papers. Compared to theses, journal papers undergo peer review and are more likely to publish statistically significant research. Studies yielding statistically insignificant results or challenging the prevailing literature are frequently confronted with difficulties in publication. Nevertheless, research yielding insignificant results may provide a more precise gauge of the authentic correlation between the two.

(3) The impact factors vary among different journals. Differences in journal impact factors may lead to different research orientations. Generally, compared to journals with lower impact factors, those with higher impact factors have greater academic influence and tend to prefer publishing studies with statistically significant results. In addition, with the increasing attention to the relationship between health insurance and economic performance in recent years, high-impact factor journals, to maintain the continuity of their academic influence, also emphasize the innovativeness of research conclusions. Therefore, the varying impact factors of journals may be one of the reasons for differences in the relationship between the two.

2.2.4 Sources of difference from the variables

(1) The types of health insurance vary. The research samples consist of two types of health insurance: commercial health insurance and public health insurance. As an essential component of the multi-level health insurance system, commercial health insurance has rapidly developed with strong policy support. Compared to public health insurance plans, market-oriented commercial health insurance regulates the relationship between supply and demand based on voluntary participation and profit. It has significant advantages in specialized operation, management efficiency, and innovation. Commercial health insurance, characterized by "high funding and high payouts," plays a crucial role in promoting consumer upgrading. For instance, the study of Zhao et al. indicates that commercial health insurance contributes to the construction of a multi-level healthcare system and enhances economic performance (8). Lei and Lin found that public health insurance did not reduce patients' out-of-pocket expenses (22). Given this, the different types of health insurance may lead to differences in the results of the relationship between the two.

(2) The study populations are different. Existing literature has chosen study populations from both middle-aged and older adult resident groups, as well as the entire resident

population. Considering the differences in medical needs and consumption patterns, the choice of different study populations may influence the relationship between health insurance and economic performance. In the case of the middle-aged and older adult population, increasing age correlates with declining physiological functions, heightened illness risk, and subsequently increased medical expenses, placing greater economic pressure. Middle-aged and older adult individuals are more focused on preventive medical services, while the overall resident population tends to prioritize the treatment of acute illnesses. For example, Wang et al. investigated the impact of health insurance on economic performance using the middle-aged and older adult population in China as the study subjects, revealing that health insurance alleviates residents' economic burden and enhances consumption capacity (42). Liu and Zhao taking the entire resident population as the study subjects, found that health insurance did not reduce the economic burden (43).

To explore the impact of these factors on the relationship between health insurance and economic performance, this study proposes:

H2: Differences at the level of sample, measurement, literature, and variable can moderate the relationship between health insurance and economic performance.

3 Research method

This study employs a meta-analysis to quantitatively identify the relationship between health insurance and economic performance, along with the significance of moderating variables. Meta-analysis is a systematic and rigorous quantitative method that scientifically reviews and reanalyzes multiple quantitative results for the same research question. By collecting sample data from studies with different backgrounds, this method comprehensively evaluates research results, dissects differences among studies, and ultimately draws more accurate and robust conclusions. Therefore, it efficiently addresses issues where research findings are contentious. Additionally, this method compensates for the limitations of descriptive literature reviews in conducting quantitative analyses of research results. It demonstrates higher clarity, comprehensiveness, rigor, and systematicity in the selection, acquisition, and evaluation of original literature.

3.1 Study design

Following the research objectives, research questions, and the data requirements of the meta-analysis method, this study formulated the following detailed data retrieval process. Firstly, strict literature inclusion criteria were applied, and data were gathered from various databases through searches and browsing. Secondly, relevant information and correlation coefficients were extracted from the literature and encoded, covering study description and effect value statistics. The study primarily categorizes factors influencing the health insurance and economic performance relationship. Finally, STATA was used for bias analysis, overall testing, and moderation effect testing on the data to derive research conclusions. The research design is outlined in Figure 2.

3.2 Criteria for selecting studies

This study performed a quantitative meta-analysis following the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (44). PRISMA contributes to heightened transparency, diminishes potential biases, and avoids the redundant application of reviews, consequently enhancing both the reporting quality and methodological robustness of the meta-analysis. Functioning as a consensus-based reporting framework, PRISMA mandates that meta-analysis: (1) accumulate relevant studies, (2) categorize study characteristics, (3) compute effect sizes for each study, and (4) scrutinize features for potential moderating effects.

The criteria for select studies were based on the research question, objectives, and PRISMA requirements for methods. Specific criteria are as follows: (1) The literature has to focus on the impact of health insurance on economic performance; (2) It must be quantitative studies, excluding case analysis, theoretical and review literature; (3) The literature data need to be sufficient in terms of sample size, correlation coefficients, standard error and other convertible indicators (t-values, p-values, z-values, and so on); (4) Study samples should be independent, with only the latest publications retained in the case of repeated studies using the same data. Literature published in the form of theses, journal papers, and conference papers will be treated as a single study. If a literature piece involves multiple different study samples, relevant coefficients for each sample will be independently coded.

3.3 Literature retrieval and screening

To ensure data representativeness and completeness, this paper follows the literature selection process outlined by Havranek et al. and strictly adheres to the following steps for literature retrieval and screening (45). Firstly, the prominent databases, including PubMed, Web of Science, Scopus, CNKI, and PQDT were scrutinized. Secondly, the keywords "Health Insurance," "Health care," "Medicare," "Healthcare," "Medical care insurance," and "Medical insurance" were combined with "Economic performance," "Economic development," "Economic growth," "Economic efficiency," "Economic benefit," "Financial burden," "Economic burden," "Financial Strain," and "empirical analysis." Literature containing these keywords in the title or abstract was retrieved. To avoid omissions, we conducted a supplementary manual search while reviewing the literature. With a literature retrieval deadline set for October 6, 2023, a total of 5,284 literature records were collected using this process. Based on this, we further determined the literature inclusion criteria through a preliminary review of the titles, abstracts, or full texts. (1) Evaluating the research design of the literature to determine its focus on health insurance's impact on economic performance. Irrelevant studies were excluded. (2) The literature must be quantitative studies,

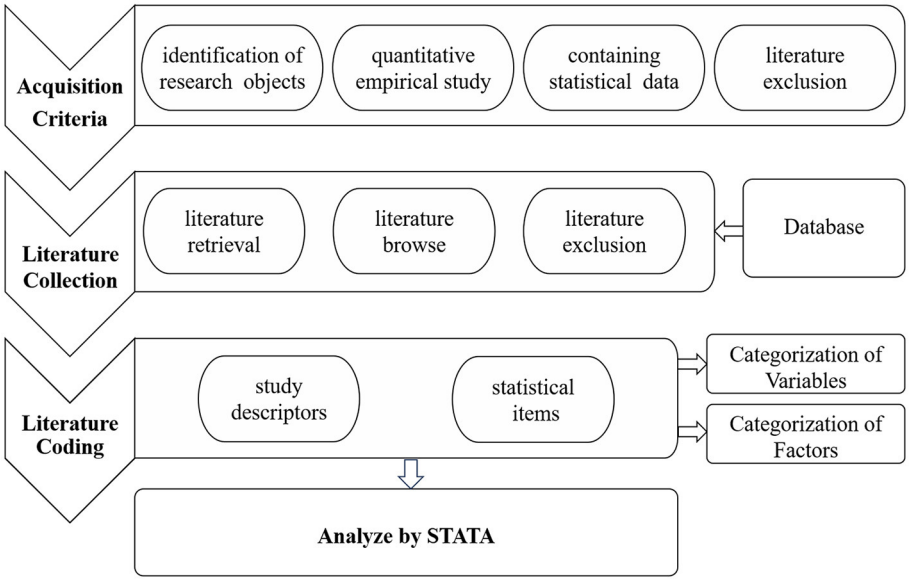

FIGURE 2
Research design of meta-analysis on the relationship between health insurance and economic performance.

excluding theoretical, review, case analysis, and other non-empirical studies. (3) We assess the adequacy of data by reading the full text. Literature with incomplete data was excluded. (4) Careful verification of the multiple-stage or repeated publication situations of the same sample was conducted, treating them as independent studies. Finally, 34 articles were included as analytical samples. The literature selection process for this study is shown in Figure 3.

3.4 Data coding rules and effect size calculation

Once the analysis sample was determined, the next step involved extracting relevant information and data from the literature. The raw data needed to be encoded and transformed to calculate key indicators for meta-analysis. To minimize coding errors, two trained coders independently encoded the 34 selected articles. The coders coded descriptive items and effect size statistics independently. Descriptive items primarily included content related to study design and literature publication, categorized into four levels: sample, measurement, literature, and variable. Sample-level descriptive items involved coding countries of origin. Measurement-level descriptive items include coding research methods and data types. Literature-level descriptive items encompassed coding information such as literature type, the impact factor, and publication year. Variable-level descriptive items coded the type of health insurance and research populations.

After converting and coding relevant information in the literature, key indicators for meta-analysis, specifically effect sizes, could be calculated. Effect size serves as a measure of the strength of the relationship between the independent variable and the dependent variable, indicating practical significance. In this study, the effect size generally corresponded to the correlation coefficient between variables, as the included literature used correlation coefficients or regression techniques for analysis. Therefore, an effect size based on the correlation coefficient (r-based) was used to represent the relationship between health insurance and economic performance. According to the formula provided by Rosenthal (46), the estimation parameters (t-values) of the original studies are converted into correlation coefficients (r) using the formula: $r = \sqrt{[t^2/(t^2 + df)]}$. Here, df is the degree of freedom related to the t-value, which can be calculated based on the sample size and variable values in the original study.

To account for variations in sample size among the original studies, the correlation coefficient (r) was further transformed into the standard effect size of Fisher's Z. The standard error of Z (SEz) was then calculated to correct for the bias resulting from differences in sample size. The specific calculation method for standard error is as follows: (1) $Z_r = 0.5\ln[(1+r)/(1-r)]$; (2) Calculate the variance of Z, $Vz = 1/(n-3)$; (3) Calculate $SE_z = \sqrt{V_Z}$.

The above calculation process was performed using Stata17 software. The unit of analysis for effect sizes was independent samples. If multiple independent samples exist in the original study, they were coded multiple times. The final consistency coefficient for coding was 94% (>90%), affirming the high reliability of this coding method and supporting the credibility of the results (47). Ultimately, we extracted 479 effect sizes from the 34 empirical studies.

4 Results of meta-analysis

4.1 Publication bias analysis

It is necessary to assess publication bias to ensure the accuracy and reliability of the results before conducting the meta-analysis. The current methods for testing publication bias mainly include the funnel plot method, fail-safe number method, Egger's test, Begg's

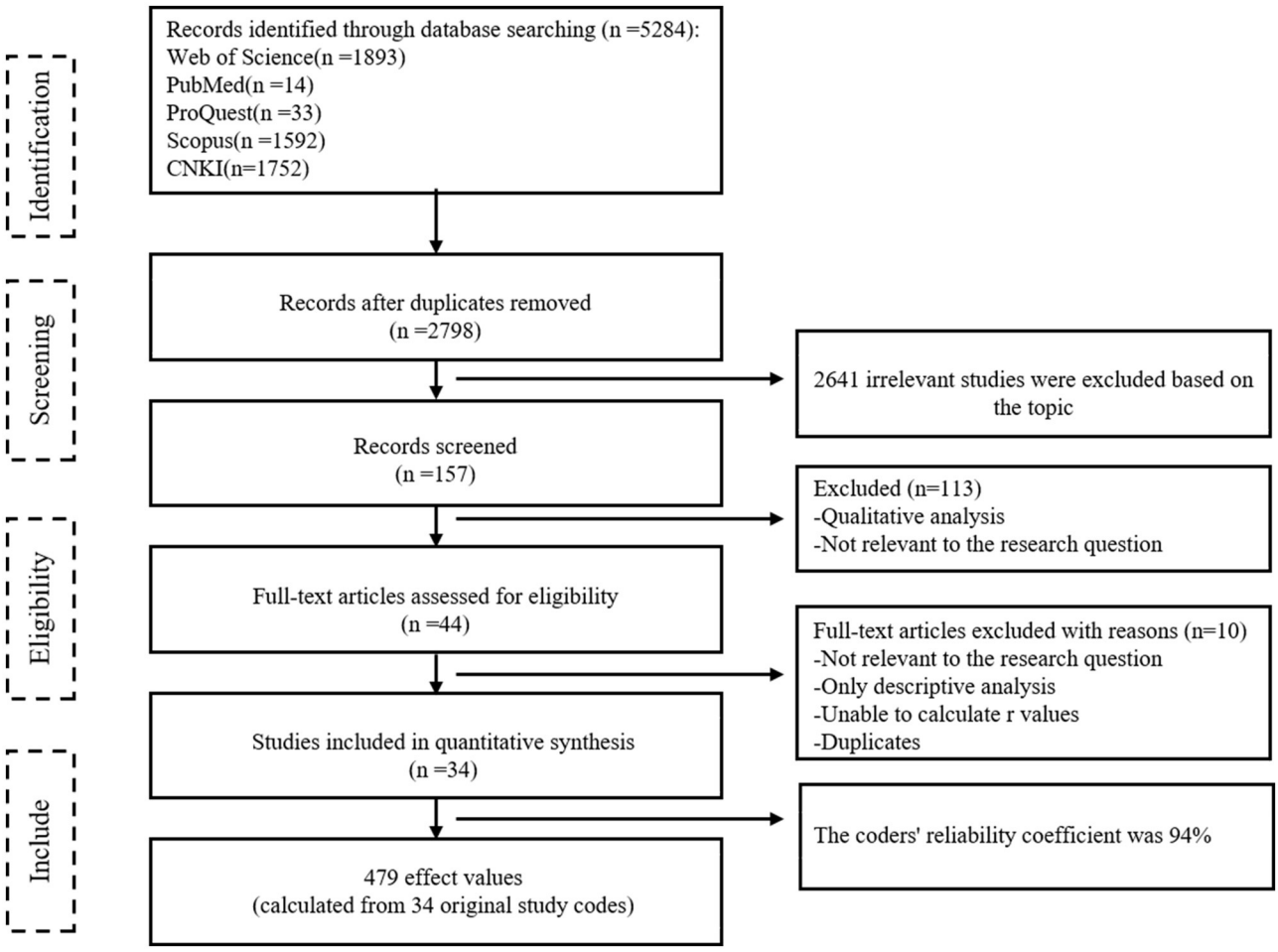

FIGURE 3
The PRISMA flow diagram of reviewing the literature.

method, and Trim method. This study employed the first two methods to assess publication bias.

As shown in Figure 4, the funnel plot of the sample literature included in the meta-analysis is presented. The distribution of effect sizes is mainly concentrated at the top of the funnel plot, spreading on both sides of the overall effect size, forming an inverted funnel shape. However, there is a small number of effect sizes that are not evenly distributed. Therefore, relying solely on visual inspection to determine the existence of publication bias is not precise enough and additional methods are needed for a comprehensive judgment.

The fail-safe number method is a quantitative method for testing publication bias. As shown in Table 1, the fail-safe value in this study is 321,170, significantly higher than the "5 k + 10" criterion (2,405). Furthermore, the fail-safe values for other sub-dimensions also passed the test, indicating unbiased and robust results.

4.2 Overall test

This study conducts an overall test on the effect sizes and the standard errors, including a heterogeneity test and the model results evaluation. Effect sizes were combined to comprehensively assess the reliability of the hypothesis about the relationship between health insurance and economic performance. Q-statistics, significance level, and I^2 are used to evaluate the heterogeneity (48). When $Q >$ df (Q), $p < 0.05$, and $I^2 > 50\%$, the results of various studies are considered heterogeneous. In these cases, a random-effects model should be chosen to combine effect values; for others, a fixed-effects model is selected.

Table 2 shows the results of the overall test of health insurance and economic performance. According to the heterogeneity test results, $Q = 3{,}229.21 > 478$, $P < 0.05$, and $I^2 = 85.20\%$, indicating high heterogeneity among the 478 effect sizes in the meta-analysis. True differences in the effect sizes and random errors accounted for 85.20 and 14.80% of the observed variation, respectively. Therefore, a random-effects model needed to be selected. The variance value is 0.322, suggesting that 32% of the variation can be utilized to calculate weights.

The model testing results showed the correlation coefficient between health insurance and economic performance was 0.429, with a 95% confidence interval of (0.381, 0.475). Gignac and Szodorai proposed guidelines to interpret the magnitude of a correlation (49). In magnitude, values of $1 < r < 0.2$, $0.2 < r$

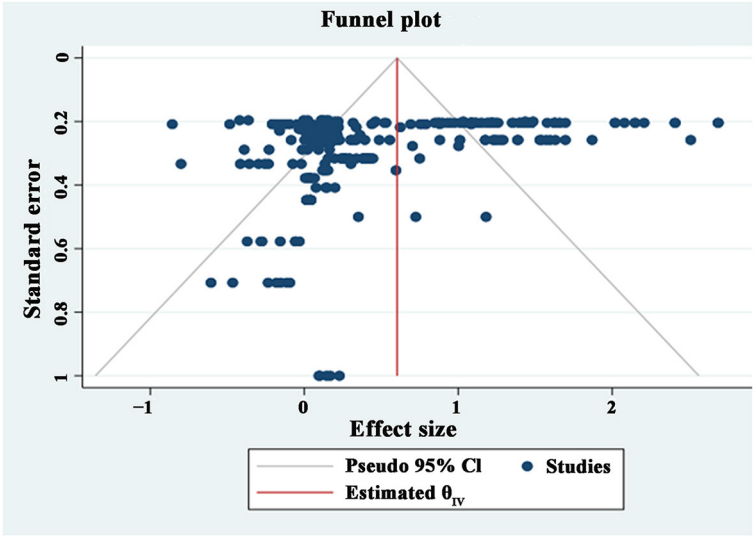

FIGURE 4
Funnel plot.

TABLE 1 Test of publication bias.

Category	Sample size	Fail-safe number	
	K	Threshold	$N_{fs0.05}$
All	479	2,405	321,170
Economic growth	128	650	126,497
Reducing medical economic burden	213	1,075	13,954
Improving the consumption level	138	700	8,611

< 0.3, and $r > 0.3$ are considered small, medium, and large, respectively. The correlation coefficient between health insurance and economic performance in this study exceeded 0.3, confirming a robust positive correlation and supporting Hypothesis 1. The correlation coefficient for economic growth, reducing medical economic burden, and improving the consumption level were 0.485, 0.159, and 0.258, respectively. All coefficients are significant at the 95% confidence interval ($p < 0.05$). This suggests that health insurance has a positive impact on economic growth, reducing medical economic burden, and improving the consumption level. Hypotheses H1a, H1b, and H1c are all validated. The relationship between health insurance and economic performance was highly positive, while the relationship between health insurance with reducing medical economic burden and improving the consumption level was moderately positive.

Meta-analysis allows for a scientific and precise assessment of the relationship between health insurance and economic performance. In addition, the first research question in this study can be answered: Does health insurance promote economic performance? However, it is noteworthy that the distribution of effect size for the relationship between the two varies significantly among research reports. There may be some moderating factors influencing the intensity of effect size, necessitating further tests to identify potential inconsistencies reason.

4.3 Moderation effect test

The overall effect test of the meta-analysis indicates high heterogeneity between health insurance and economic performance, suggesting that the relationship between the two is influenced by potential moderating variables. To test this effect, we coded and conducted subgroup analyses on the collected data. Table 3 presents the subgroup analysis results. Specifically: (1) There was a significant difference in the relationship between health insurance and economic performance when using samples from developed countries or developing countries ($p < 0.05$). Moreover, the promotion effect of health insurance on economic performance is stronger in developed countries ($r = 0.669$) compared to developing countries ($r = 0.297$). (2) There was a significant difference in the research results on the relationship between the two when using panel data and cross-sectional data ($p < 0.05$). Subgroup analysis shows that the relationship between health insurance and economic performance was significantly higher in panel data ($r = 0.498$) than in cross-sectional data ($r = 0.188$). Furthermore, the research method had a significant moderating effect on the relationship between the two ($p < 0.05$). Compared to non-regression methods ($r = 0.334$), regression methods ($r = 0.462$) showed a stronger positive correlation. (3) From the literature perspective, publication year, literature type, and the impact factor can all moderate the relationship between health insurance and economic performance ($p < 0.05$). Subgroup analysis indicated that health insurance's promotion effect on economic performance was stronger for publications after 2010 ($r = 0.431$) than before 2010 ($r = 0.358$). Compared to theses ($r = 0.202$), journal papers ($r = 0.502$) showed a

TABLE 2 Meta-analysis results of the health insurance and economic performance.

Variable	Heterogeneity test				Effects model					The magnitude of a correlation
	Df	*P*	I^2(%)	*Q*	*z*	Variance	Point estimation	Lower limit	Upper limit	
All	478	0.000	85.20	3,229.21	15.74	0.322	0.429	0.381	0.475	Large
Economic growth	127	0.000	88.43	1,097.86	17.17	0.353	0.746	0.693	0.791	Large
Reducing medical economic burden	212	0.000	74.97	846.94	6.73	0.205	0.242	0.173	0.308	Medium
Improving the consumption level	137	0.000	39.21	225.37	15.73	1.650	0.295	0.260	0.329	Medium

TABLE 3 Meta-analysis results of the moderating effects.

	Variables	Category	*K*	95%CI			Heterogeneity test		
				Estimated value	Lower limit	Upper limit	*Q*	Df	*P*
Sample	Country	Developed country	133	0.669	0.595	0.731	1,575.38	132	0.000
		Developing country	339	0.297	0.250	0.343	1,081.90	338	
Measurement	Data type	Panel	352	0.498	0.445	0.547	2,643.90	351	0.000
		Cross-sectional	127	0.188	0.107	0.266	378.57	126	
	Research method	Regression method	348	0.462	0.407	0.514	2,596.01	347	0.000
		Other methods	117	0.334	0.233	0.427	576.87	116	
Literature	Publication year	≤2010	13	0.358	0.037	0.613	86.25	12	0.000
		>2010	466	0.431	0.383	0.477	3,142.70	465	
	Literature type	Thesis	144	0.202	0.141	0.261	157.25	143	0.000
		Journal	335	0.502	0.449	0.551	2,955.13	334	
	Impact factor	≤5	108	0.391	0.296	0.478	580.48	107	0.000
		>5	147	0.659	0.588	0.720	1,770.02	146	
Variable	Health insurance type	Commercial health insurance	99	0.297	0.240	0.353	182.76	98	0.000
		Public health insurance	380	0.466	0.410	0.519	2,946.82	379	
	Research populations	Middle-aged and older adult	100	0.092	0.013	0.170	186.43	99	0.000
		Overall	368	0.489	0.438	0.537	2,685.48	368	

stronger positive correlation. Additionally, a higher impact factor of the journal correlated with a more positive relationship between health insurance and economic performance. (4) From the variable perspective, the type of health insurance and the research populations can significantly moderated the relationship between the two ($p < 0.05$). Public health insurance ($r = 0.466$) has a stronger promotion effect on economic performance than commercial health insurance ($r = 0.297$). The relationship between health insurance and economic performance was significantly higher in studies with the overall research population ($r = 0.489$) than in studies with the middle-aged and older adult as the research population ($r = 0.092$).

In summary, the country of sample origin, data type, research method, publication year, literature type, journal impact factor, type of health insurance, and research populations all presented significant moderating effects regarding the relationship between health insurance and economic performance ($p < 0.05$). Therefore, hypothesis H2 was supported.

4.4 Robustness test

Drawing on the research of Tilley et al. (50), this paper applied the meta-regression analysis method to test the robustness of the moderation effect results mentioned above. As indicated in Table 4, the regression coefficients at the sample level, measurement level, literature level, and variable level were all positive, and the results are highly significant ($p < 0.05$). Hypothesis H2 was validated. These findings align with the subgroup analysis, confirming the robustness of the meta-analysis results.

TABLE 4 Robustness test.

	Moderating variables	*N*	*B*	SE	*T*	*P*	σ	I^2
Sample	Country	133/339	0.810	0.048	17.06	0.000	0.310	0.807
Measurement	Data type	352/127	0.550	0.032	17.26	0.000	0.286	0.828
	Research method	348/117	0.501	0.034	14.77	0.000	0.315	0.840
Literature	Publication year	13/466	0.376	0.169	2.23	0.026	0.310	0.839
	Literature type	144/335	0.152	0.058	2.60	0.010	0.290	0.833
	Impact factor	108/147	0.413	0.066	6.31	0.000	0.400	0.892
Variable	Health insurance type	99/380	0.271	0.062	4.39	0.000	0.301	0.833
	Research populations	100/368	0.453	0.073	6.25	0.000	0.281	0.822

5 Discussion

5.1 Relationship between health insurance and economic performance

There have been diverse perspectives and research outcomes around the relationship between health insurance and economic performance, but no research has clarified these variations. This study applied meta-analysis to evaluate the overall relationship between the two, revealing a strongly positive correlation. It indicates that health insurance positively influences economic performance, supporting the first perspective and clarifying the debate about the direction of relationship and magnitude. This study contradicts the view of a non-existent or negative correlation between health insurance and economic performance, underlining the statistically significant relationship that shouldn't be ignored or overstated in practice.

Specifically, health insurance positively influences economic growth, alleviates economic burdens, and enhances consumption capabilities in the process of promoting economic performance. A crucial aspect of the relationship between health insurance and economic performance is the factor of workers' productivity (51). Poor individual health may lead to the loss of labor and productivity. The health insurance system, by improving residents' health, enhances labor capabilities, efficiency, and quality of life, effectively ensuring the quality of human capital and subsequently improving economic performance. With the development of health insurance, more funds are allocated to research and development of new medical technologies, equipment, and treatment methods. These innovations increase productivity in the healthcare industry, reduce medical costs, enhance the quality of medical services, and consequently drive the development of the healthcare sector, contributing to economic growth. Additionally, health insurance, through its risk transfer function, reduces uncertainty, encourages individual consumption, and promotes increased business investments, leading to economic growth. Moreover, through its economic compensation function, health insurance reduces out-of-pocket medical expenses for insured individuals, thereby alleviating their economic burden. Through widespread adoption and promotion of health insurance and the guidance it provides to individuals, people can make more rational use of healthcare resources, avoiding waste and excessive consumption. This not only helps in lowering healthcare costs but also enhances the efficiency of healthcare resource utilization, further mitigating the economic burden. Furthermore, health insurance stabilizes future expectations by alleviating concerns about medical expenses, reducing the need for precautionary savings. This allows redirected funds for higher-level consumption, enhancing people's quality of life and boosting related industries, contributing to economic growth. With reduced their expenditure on their healthcare, people have more disposable income for other consumption. This increased disposable income enhances people's consumption capabilities, driving the growth of goods and services sales, and further stimulating economic growth.

5.2 Moderation effect analysis

It is essential to note that the overall conclusions drawn from the meta-analysis only focus on the correlation between two variables and do not invalidate studies that lack support. The correlation degree of the relationship between health insurance and economic performance may also be affected by other variables. This study conducted subgroup analyses at the sample, measurement, literature, and variable levels, systematically investigating potential moderating factors influencing the relationship between the two. Specific investigation results revealed several points:

At the sample level, studies conducted in developed countries show a stronger positive effect of health insurance on economic performance compared to studies in developing countries. This was mainly related to human capital, as healthier individuals are more effective in both physical and mental labor. In developed countries where labor is scarce, the impact of health insurance on human capital efficiency is more apparent. Furthermore, developed countries generally have more robust health insurance systems with comprehensive management and regulatory mechanisms, ensuring service quality and efficiency. Residents can access higher-quality medical services, leading to higher labor efficiency. In contrast, developing countries may lack robust management and regulatory systems, resulting in lower healthcare standards. These factors make the positive impact of health insurance on economic performance more pronounced in developed countries.

At the measurement level, this study found that using panel data yielded a stronger positive effect of health insurance on economic performance than using cross-sectional data. Panel data analysis provides a dynamic analysis of the development of

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TABLE 5 Meta results of various variables.

Variables	Category	Subdimension	Hypothesis	Significance	The magnitude of a correlation
				Yes/no	
Core variables and the subdimensions	Overall		H1	Yes	Large
	/	Economic growth	H1a	Yes	Large
	/	Reducing medical economic burden	H1b	Yes	Medium
	/	Improving the consumption level	H1c	Yes	Medium
Moderating variables and the subdimensions	Country	Developed country	H2	Yes	Large
		Developing country			Medium
	Data type	Panel		Yes	Large
		Cross-sectional			Small
	Research method	Regression method		Yes	Large
		Other methods			Large
	Publication year	≤2010		Yes	Large
		>2010			Large
	Literature type	Thesis		Yes	Medium
		Journal			Large
	Impact factor	≤5		Yes	Large
		>5			Large
	Health insurance type	Commercial health insurance		Yes	Medium
		Public health insurance			Large
	Research populations	Middle-aged and older adult		Yes	Small
		Overall			Large

health insurance, offering more comprehensive data and more robust results. Cross-sectional analysis, which collects data at a specific point in time, may yield less accurate conclusions, even with representative samples, potentially leading to bias. Additionally, employing regression methods results in a stronger positive effect of health insurance on economic performance compared to other methods. This suggests that the research method influences the study's outcomes. Regression analysis can more accurately describe the complex relationship between the two by setting variables and establishing mathematical models. Moreover, the results of regression analysis can be verified through statistical methods to ensure reliability and accuracy. Non-regression analysis results may lack such verification mechanisms, reducing their relative reliability. Therefore, regression analysis can more accurately describe and handle the relationship between health insurance and economic performance. Thus, this study concluded that regression analysis was more effective than non-regression analysis in capturing the promoting effect of health insurance on economic performance.

At the literature level, the publication year, type of literature, and journal impact factors significantly moderated the relationship between health insurance and economic performance. In terms of the publication year, more recent publications exhibited a stronger positive effect of health insurance on economic performance. This implies continuous improvements in health insurance, providing essential support for economic development. Literature published in high-impact journals demonstrated a more pronounced positive effect of health insurance on economic performance than literature in low-impact journals. This highlights the emphasis of high-impact journals on paper quality and the statistical significance of results. Studies published in journals, compared to theses, exhibit a stronger positive effect of health insurance on economic performance. This distinction may stem from the peer review process, which tends to view a positive correlation between the two as having favorable policy implications.

At the variable level, this study identifies significant moderating effects of health insurance type and research populations on the relationship between health insurance and economic performance. Health insurance types include commercial health insurance and public health insurance. Public health insurance exhibits a more pronounced positive effect on economic performance compared to commercial health insurance. This could be attributed to public health insurance having a wider reach, substantially reducing the overall medical economic burden and accruing more human capital, thereby fostering economic growth. Regarding research populations, existing literature mainly focused on middle-aged and older adult populations and the overall populations. Literature concentrating on the middle-aged and older adult population might not fully capture the entire developmental trajectory of health insurance, thereby weakening its impact on

economic performance. Conversely, literature focusing on the overall population maximizes the comprehensive advantages of health insurance, showcasing the maximum impact on economic performance. Hence, in comparison to literature focusing on the middle-aged and older adult populations, literature concentrating on the overall populations concludes that health insurance has a more robust positive effect on economic performance. The research results are summarized in Table 5.

6 Conclusions

As disease patterns evolve and population aging intensifies, it is crucial to consider the issue of poverty caused by illness. Health insurance serves as a vital instrument for addressing the problem of illness-induced poverty, enhancing residents' health, bolstering the labor force, and boosting productivity. In the ongoing evolution and enhancement of the health insurance system, the pivotal question of whether health insurance safeguards residents' health while concurrently promoting economic performance has emerged as a critical focus for optimizing institutional efficacy. Moreover, evaluating the economic performance of health insurance is essential for enhancing the coordination of the medical security system and achieving sustainable development of the economy and society.

The results of this study indicated a significant positive correlation between health insurance and economic performance, supporting H1. Furthermore, this study clarifies that the correlation between the two is strongly positive. This suggests that health insurance has significant economic spillover effects. Policymakers should deepen the reform of the healthcare system, to strengthen poverty reduction and income increasing effects of health insurance. They should aim to establish a more equitable, mature, and sustainable healthcare system.

Additionally, this study employs moderation effect tests to delve deeper into the relationship between health insurance and economic performance. The source country of the sample, data type, research method, publication year, type of literature, impact factor, health insurance type, and research populations exhibit moderating effects on this relationship. It is found that public health insurance has a greater impact on economic performance than commercial health insurance. Consequently, it is advisable to judiciously balance the proportions of public and commercial health insurance, progressively elevating the overall standard to establish a high-quality universal healthcare system. Moreover, policymakers should intensify support for pivotal groups and sectors, refining the precision of health insurance. For example, efforts should be made to expand the coverage of health insurance for the older adult, ensure medical security for vulnerable groups, and actively respond to the challenges of an aging population.

This study explores the relationship between health insurance and economic performance, yielding comprehensive and objective conclusions. By clarifying this relationship, the foundation is laid for establishing an optimal health insurance framework that, enhances economic wellbeing. Moreover, diversifies health insurance studies but also provides ample empirical evidence for ongoing improvements in social human capital efficiency, fostering sustainable economic development. Simultaneously, the precise identification of the magnitude of the correlation between the two serves as a scientific cornerstone for informed decision-making, guiding the formulation of judicious and effective health insurance policies.

7 Limitations

This study systematically reviews existing literature through meta-analysis, examining the relationship between health insurance and economic performance. It validates and gauges the strength of this relationship, overcoming biases in prior individual studies to draw relatively comprehensive conclusions. However, this study still has some limitations. Firstly, it only considers empirical testing literature, neglecting qualitative sources like case studies in the meta-analysis. Secondly, the multifaceted nature of the relationship between health insurance and economic performance remains incompletely explored, with certain influencing factors unaddressed. For example, the inclusion of different types of literature can impact the relationship between health insurance and economic performance. In the future, efforts can be made to overcome methodological limitations by including more non-empirical literature for analysis, thereby obtaining more accurate research results. Moreover, the results of the meta-analysis depend on the quality of the encompassed studies. Should these studies exhibit methodological shortcomings, biases, or inadequate statistical power, the findings of the meta-analysis could be compromised. Future research can address our shortcomings in the following ways: (1) Exploring new methods to study the relationship between health insurance and economic performance, such as adopting systematic literature reviews and qualitative meta-analyses. Overcoming methodological limitations by including more non-quantitative literature for analysis can lead to more accurate research results. Using network analysis and CiteSpace-based bibliometric analysis to visualize and interpret the structure and dynamics of research on health insurance and economic performance. Additionally, citation analysis, a bibliometric method using extensive citation data, reveals connections and patterns in the literature, aiding a deeper understanding of current research trends. (2) The multifaceted nature of the relationship between health insurance and economic performance remains incompletely explored, with certain influencing factors unaddressed. Future research could delve into the impact of intermediary variables, such as innovation elements, on this relationship. (3) Given the critical connection between health insurance and economic performance, it is profitable to investigate their route in fostering sustainable economic development.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

CF: Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. CL: Data curation, Methodology, Writing – review

& editing. XS: Funding acquisition, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The influence of digital platform on the implementation of corporate social responsibility: from the perspective of environmental science development to explore its potential role in public health

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Introduction: This paper aims to explore the intersection of corporate social responsibility (CSR) and public health within the context of digital platforms. Specifically, the paper explores the impact of digital platforms on the sustainable development practices of enterprises, seeking to comprehend how these platforms influence the implementation of environmental protection policies, resource management, and social responsibility initiatives.

Methods: To assess the impact of digital platforms on corporate environmental behavior, we conducted a questionnaire survey targeting employees in private enterprises. This survey aimed to evaluate the relationship between the adoption of digital platforms and the implementation of environmental protection policies and practices.

Results: Analysis of the survey responses revealed a significant positive correlation between the use of digital platforms and the environmental protection behavior of enterprises ($r = 0.523; p < 0.001$), Moreover, the presence of innovative environmental protection technologies on these platforms was found to positively influence the enforcement of environmental policies, with a calculated impact ratio of ($a * b / c = 55.31\%$). An intermediary analysis highlighted that environmental innovation technology plays a mediating role in this process. Additionally, adjustment analysis showed that enterprises of various sizes and industries respond differently to digital platforms, indicating the need for tailored environmental policies

Discussion: These findings underscore the pivotal role of digital platforms in enhancing CSR efforts and public health by fostering improved environmental practices among corporations. The mediating effect of environmental innovation technologies suggests that digital platforms not only facilitate direct environmental actions but also enhance the efficiency and effectiveness of such initiatives through technological advances. The variability in response by different enterprises points to the importance of customizable strategies in policy formulation. By offering empirical evidence of digital platforms' potential to advance CSR and public health through environmental initiatives,

this paper contributes to the ongoing dialogue on sustainable development goals. It provides practical insights for enterprises and policy implications for governments striving to craft more effective environmental policies and strategies.

KEYWORDS

digital platform, corporate environmental protection behavior, corporate social responsibility, sustainable development, intermediary analysis

1 Introduction

Global environmental issues have gained prominence in today's society, raising a great deal of concern. Environmental challenges such as climate change, resource depletion and ecosystem destruction threaten the sustainable development of the earth and the survival of mankind (1, 2). In this context, enterprises not only need to find a balance between economic interests and environmental protection, but also need to hypothesize social responsibilities and contribute to sustainable development (3). As a tool for information dissemination, cooperation and interaction, and resource integration, digital platform is regarded as an emerging force that may have a far-reaching impact on corporate environmental protection behavior and social responsibility (4). In the past decades, corporate social responsibility (CSR) has become an important part of business practice. Enterprises no longer only pay attention to economic performance, but link their economic activities with social and environmental issues to ensure sustainable development (5–7). Meanwhile, the rise of digital platform has changed the interaction between enterprises and their stakeholders, providing enterprises with more opportunities to disseminate environmental information, cooperate to solve environmental problems, and supervise their environmental protection behavior (8). However, despite these potential opportunities, there are still many unknown factors about the actual impact of digital platforms on corporate environmental behavior and social responsibility (9).

In recent years, with the rapid development of digital technology, digital platform has become an important force to promote social change. Especially in corporate social responsibility and public health, the role of digital platform has become increasingly prominent. Early studies such as Wang et al. (10) have pointed out that digital transformation can promote enterprises to implement environmental protection policies and social responsibility plans more efficiently. However, there is still a lack of existing literature on how the digital platform affects the sustainable practice of enterprises under the guidance of the development of environmental science, especially the contribution to public health. At present, digital platform plays a vital role in the practice of CSR. Through digital means, enterprises can manage resources more effectively, improve energy efficiency, reduce carbon emissions and other environmental protection behaviors. Taking an energy company as an example, the company uses digital platform to implement intelligent energy management system, monitor energy usage, and optimize energy distribution, thus reducing energy waste and improving energy utilization efficiency. Through digital monitoring and data analysis, enterprises can know the energy consumption in real time, adjust production plans in time to reduce carbon emissions, and realize green production. These measures not only help enterprises to comply with environmental laws and regulations and fulfill their social responsibilities, but also bring them economic benefits and brand reputation. Looking forward to the future, the potential of digital platform lies in promoting enterprises to achieve sustainable development goals and promoting environmental protection behavior and social responsibility practice to a higher level. The continuous innovation and application of digital technology will provide more environmental protection solutions and tools for enterprises and support the realization of environmentally friendly production. However, the digital platform also faces some challenges, such as data privacy protection and information security risks, which need to be effectively controlled. Meanwhile, in the process of digital transformation, enterprises may face challenges in technology upgrading and talent training, and it is necessary to strengthen their understanding and application ability of digital technology. Considering the development perspective of environmental science, the relationship between digital platform and CSR is very important. Through the application of digital platform, enterprises can better practice environmental protection behavior, promote sustainable development, and integrate social responsibility into all aspects of business operations. The in-depth discussion of this relationship fills the gap in the existing research and provides new ideas and viewpoints for the related influence in the field of public health. By combining the concepts of digital platform, environmental science and CSR, future research will help to better explore the potential role of digital platform in CSR and public health, and promote the development of enterprises in a more sustainable and socially responsible direction. Therefore, this paper attempts to fill this knowledge gap and explore the subject through empirical research. Specifically, this paper uses the methods of descriptive statistical analysis, correlation analysis and hypothesis test analysis to evaluate the relationship between the use of digital platforms and corporate environmental behavior, investigates the impact of digital platforms on CSR policies and practices, explores the intermediary variables and moderating variables between digital platforms and corporate environmental behavior, and compares the differences in the impact of digital platforms on corporate environmental behavior and social responsibility between different industries and geographical regions. This paper deeply discusses the important role of digital platform in enterprise operation and the possible positive impact of corporate social responsibility on public health and environmental protection. With the acceleration of digital transformation, enterprises increasingly rely on digital platforms to optimize their operational efficiency and market competitiveness, which provides new opportunities and challenges for enterprises to fulfill their social and environmental responsibilities. By revealing how the digital platform can help enterprises to better implement CSR strategy, and then have a positive impact on environmental protection, this paper aims to

provide policy makers and business managers with empirical insights and suggestions to promote the realization of sustainable development goals.

In order to achieve the above research objectives, this paper adopts various research methods, including quantitative questionnaire survey, to collect relevant data of enterprises and digital platforms. Then, descriptive statistical analysis is used to summarize the basic characteristics of the data, correlation analysis is used to test the relationship between variables, and hypothesis testing analysis is used to verify the research hypothesis. In addition, intermediary analysis and adjustment analysis are used to deeply understand the influence mechanism of digital platform on corporate environmental behavior and social responsibility. This paper fills the knowledge gap of the influence of digital platform on corporate environmental behavior and social responsibility, and provides practical and policy enlightenment. By deeply understanding the relationship between digital platform and sustainable development of enterprises, it can provide strong support for enterprises and governments to formulate more effective environmental protection policies and strategies.

There are three innovations in this paper. First, from the perspective of environmental science development, the influence mechanism of digital platform on corporate environmental behavior and social responsibility is deeply explored. The second is to put forward the application strategy of digital platform in corporate environmental behavior and social responsibility to provide guidance for corporate practice. Thirdly, by means of questionnaire survey, descriptive statistical analysis, correlation analysis and hypothesis test analysis, the influence mechanism of digital platform on corporate environmental behavior and social responsibility is comprehensively studied.

2 Literature review

Scholars have carried out extensive research in the field of corporate environmental behavior and CSR. They paid attention to the motivation, influencing factors and effects of corporate environmental protection behavior, and discussed the influence of CSR on corporate performance and sustainable development from different dimensions. Afsar and Umrani (11) investigated the influence of perceived CSR on employees' environmental behavior. The results showed that perceived CSR had a significant and positive impact on environmental commitment. Raza et al. (12) investigated hotel employees' views on CSR activities and their influence on employees' voluntary environmental protection behavior based on the theory of social exchange and identity. The results showed that CSR had a direct impact on employees' voluntary environmental protection behavior. Latif et al. (13) analyzed the relationship between CSR and employees' environmental behavior from the perspective of sustainable development, and found that employees' perceived CSR actively promoted employees' environmental behavior. Deng et al. (14) studied the relationship between CSR initiatives in hospitals and employees' environmental behavior, and found that CSR directly and indirectly affected employees' environmental behavior through environment-specific transformational leadership. Guan et al. (15) proposed that CSR was mainly related to the environmental performance and economic performance of enterprises. Nowadays, people can improve the environmental performance and economic performance of enterprises by promoting employees' environmental behavior and altruistic values, and realize CSR. Giacalone et al. (16) believed that CSR involved the aim of having a positive impact on the community operated by the analyzed company. International organizations and government agencies had also issued a series of environmental science guidelines to encourage enterprises to adopt sustainable development practices, reduce carbon emissions and protect ecosystems. The Global Environment Outlook report provided a comprehensive assessment of the global environmental situation, and called on governments, enterprises and all sectors of society to take actions to reduce carbon emissions, protect ecosystems and promote sustainable development. The report included detailed analysis and suggestions on many environmental problems such as climate change, biodiversity loss and land degradation, and encourages enterprises to take environmental protection measures to promote the realization of global sustainable development goals. It shows that the environmental protection behavior of enterprises has a far-reaching impact on their economic performance and social reputation. Environmental protection behavior not only helps to reduce the environmental footprint of enterprises, but also improves the trust of consumers and investors in enterprises. However, the environmental protection behavior of enterprises is influenced by many factors, including laws and regulations, market pressure and social expectations. Therefore, it has become an important topic to study how to promote enterprises to participate in environmental protection activities more actively.

The emergence of digital platform provides a new perspective for studying corporate environmental behavior and CSR. Among them, technologies and algorithms play a key role in the digital platform, which can be used for data analysis, user behavior prediction and information dissemination. The participation of artificial intelligence (AI) can effectively interact with experts and non-experts in different social places to promote the wise judgment of opaque artificial intelligence systems and realize their democratic governance (17). Li (18) believed that big data analysis played an important role in green governance and CSR. Kong and Liu (19) thought that digital transformation has greatly promoted CSR, and it was helpful to improve pollution control ability and internal control efficiency in enterprises with low financing constraints and high regulatory pressure, thus improving CSR performance. Li (20) evaluated the financial investment environment of enterprises based on blockchain and cloud computing, and found that cloud computing technology and blockchain technology expanded the construction performance of financial investment data from 5.98 to 9.27. The computing performance was improved by 3.29. Based on two-stage structural equation modeling-artificial neural network (ANN) method, Najmi et al. (21) discussed the role of consumers in the recycling plan of scrapped mobile phones. Yan et al. (22) used two-stage structural equation modeling and ANN to analyze the impact of the adoption of financial technology on the sustainable development performance of banking institutions. The research results showed that green finance and green innovation fully mediate the relationship between the application of financial technology and the sustainable development performance of banking institutions (22). Diaz and Nguyen (23) predicted the minimum prediction error of CSR index through gray correlation analysis and gray correlation analysis, and found that BPN model had the smallest prediction error, which was better than recurrent neural network (RNN) and radial basis function neural network model. Ezzi et al. (24) analyzed the important role of blockchain technology in explaining CSR performance, and the results

showed that the implementation of blockchain technology had a significant and positive impact on CSR performance.

Wang et al. (25) constructed a recommendation and resource optimization model by using neural network algorithm from the perspective of cultural and creative industries to promote enterprise project decision-making and resource optimization. The research showed that the entrepreneurial project recommendation and resource optimization model can significantly improve the recognition accuracy, reduce the prediction error, and contribute to the sustainable development of social economy and the optimization of entrepreneurial resources. Combined with the research content of this paper, these research results can provide effective decision-making reference for enterprises and promote the realization of sustainable development goals. Wang et al. (26) used blockchain technology to build an intelligent contract, established a risk management system for online public opinion, and tracked public opinion through risk correlation tree technology, thus improving the accuracy of risk prediction and credibility detection. The research results showed that with the support of blockchain technology, the three experimental schemes designed can reasonably predict the risk and detect the credibility of NPO. This work was helpful to optimize the control measures of network environment and provide an important reference for improving the management level of network public opinion. Deng et al. (27) promoted the mechanism of public participation and enhanced the vitality of the economic market of resource-based cities by increasing policy intervention. This study had important reference value for promoting urban resource management and economic efficiency. Li et al. (28) paid attention to the influence of the pilot policy of low-carbon cities on urban entrepreneurial activities and its role in promoting green development. The results showed that the pilot policy of low-carbon cities generally inhibits entrepreneurial activities, but the level of green innovation can alleviate this inhibitory effect. In addition, the pilot policy of low-carbon cities inhibited the entrepreneurial activities of high-carbon industries, while encouraging the entrepreneurial activities of emerging industries, which led to the changes and upgrading of industrial structure. Li et al. (29) discussed the development path of clean energy and related issues of sustainable development of mining projects in the ecological environment driven by big data. Through this study, it was hoped to provide empirical support and decision-making reference for mining projects in the development of clean energy, promote the sustainable development of mining industry and realize a win-win situation of economic and ecological benefits. This was of great significance for protecting the ecological environment and realizing the sustainable utilization of resources. Li et al. (30) investigated the influence of regional digital finance development on corporate financing constraints. It was found that digital finance can significantly alleviate the financing constraints of enterprises, and the impact on small and medium-sized enterprises and private enterprises was more significant. Li et al. (31) discussed the impact of climate change on corporate environmental, social and governance performance. According to the empirical results, the environmental, social, and governance (ESG) performance of enterprises was significantly inhibited by climate change. It was also found that eliminating the mismatch between internal and external resources would help to alleviate the adverse impact of climate change on ESG performance.

The above literature review provides a comprehensive overview of the relevant research status and scholars' views on corporate environmental behavior, CSR and digital platform. The research shows that scholars have carried out extensive research in the fields of corporate environmental behavior and CSR, and paid attention to different aspects of these fields, including environmental commitment, environmental behavior of employees, and sustainable development performance. Their research reveals the profound influence of environmental protection behavior of enterprises on their economic performance and social reputation, and the direct influence of CSR on employees' voluntary environmental protection behavior. In addition, as a new technology and tool, digital platform has attracted the interest of research circles. Technologies and algorithms play a key role in the digital platform, which can be used for data analysis, user behavior prediction and information dissemination, thus affecting the environmental protection behavior and CSR of enterprises. Many studies have shown that AI, big data analysis, blockchain and other technologies have a positive impact on CSR performance and environmental protection behavior (32–35). However, these studies also have some limitations, such as differences in research methods, limitations in sample selection and heterogeneity between different fields. Therefore, this paper aims to explore the influence mechanism of digital platform on corporate environmental behavior and social responsibility, adopt various research methods, and pay attention to the differences between different industries and geographical regions. This will help to fill the knowledge gap in existing research and provide more specific guidance for enterprises and policy makers to promote the realization of sustainable development goals.

The design of this paper focuses on the interaction between digital platform and corporate social responsibility and its influence on environmental protection behavior, which reflects the complexity and scientific value of the study. Based on the theoretical framework and previous empirical research, this paper investigates how the digital platform affects the environmental protection behavior by promoting the practice of corporate social responsibility. This not only deepens the understanding of the role of digital platform in the field of corporate social responsibility, but also provides a new perspective on how to use digital technology to promote environmentally friendly behavior of enterprises, thus filling the gaps in the existing literature.

3 Research methodology

3.1 Cross-influence of CSR and development of environmental science

CSR and environmental science development are two interrelated fields, and their cross-influence is very important for understanding the mechanism behind corporate environmental protection behavior. This section deeply discusses the relationship between CSR and the development of environmental science, and establish the theoretical basis of the research. In this section, the guiding principles of environmental science development, including environmental protection and sustainable development policy documents issued by international organizations such as the United Nations Environment Programme and government agencies, are shown in Table 1.

In Table 1, the common goal of core policies and plans is to encourage enterprises to adopt sustainable development practices, reduce carbon emissions and protect ecosystems, thus promoting global sustainable development. Enterprises can fulfill their social and

TABLE 1 Guidance document for the development of environmental science.

Document name	Document content	Document publishing organization
2030 Agenda for Sustainable Development	Sustainable Development Goals (SDGs) in 17 aspects including economy, society and environment. It aims to solve global challenges, including poverty, climate change and ecosystem deterioration	United Nations sustainable development agenda
The Global Environment Outlook Attached with Global Environment Outlook Policy Options	Analysis of environmental problems and policy suggestions	United Nations Environment Programme (UNEP)
World Energy Outlook Renewable Energy Outlook	Sustainable energy development and carbon emission reduction	International Energy Agency (IEA)
Clean Energy Plan Water Resource Protection Plan	Protect the environment and promote sustainable development	United States Environmental Protection Agency

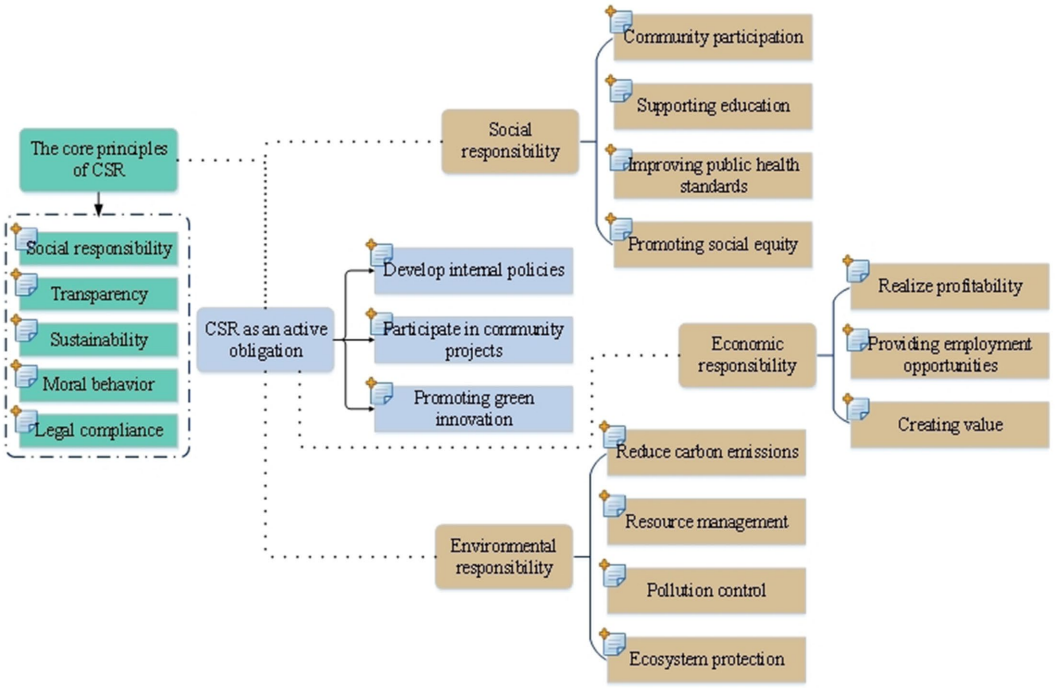

FIGURE 1
Cross-influence of CSR and the development of environmental science.

environmental responsibilities by actively participating in these initiatives and complying with relevant policies. Meanwhile, they can gain economic and reputation benefits in terms of sustainability. These policies and plans provide a framework and guidance for enterprises to play an active role in environmental protection behavior (36, 37).

CSR covers the social and environmental impacts of enterprises in their business activities, and emphasizes the active obligations of enterprises in fulfilling their social responsibilities (38). Figure 1 shows the cross influence of CSR and the development of environmental science.

In Figure 1, in the cross-influence between CSR and environmental science, the core principles and active obligations of CSR play a key role. The core principles of CSR, such as social responsibility, transparency and sustainability, guide enterprises to actively consider social and environmental factors in their business activities. Meanwhile, CSR, as an active obligation, requires enterprises not only to fulfill their legal obligations, but also to actively participate in solving social and environmental problems. These behaviors are the concrete application of CSR in the environmental field, which shows how enterprises actively fulfill their social and environmental responsibilities and promote the practice of sustainable development.

3.2 Potential mechanism of digital platform in enterprise environmental protection behavior

Digital platform refers to a platform based on digital technology and Internet, which connects different participants and provides various services and solutions through online interaction and data sharing (39). Figure 2 shows the technical architecture of digital platform.

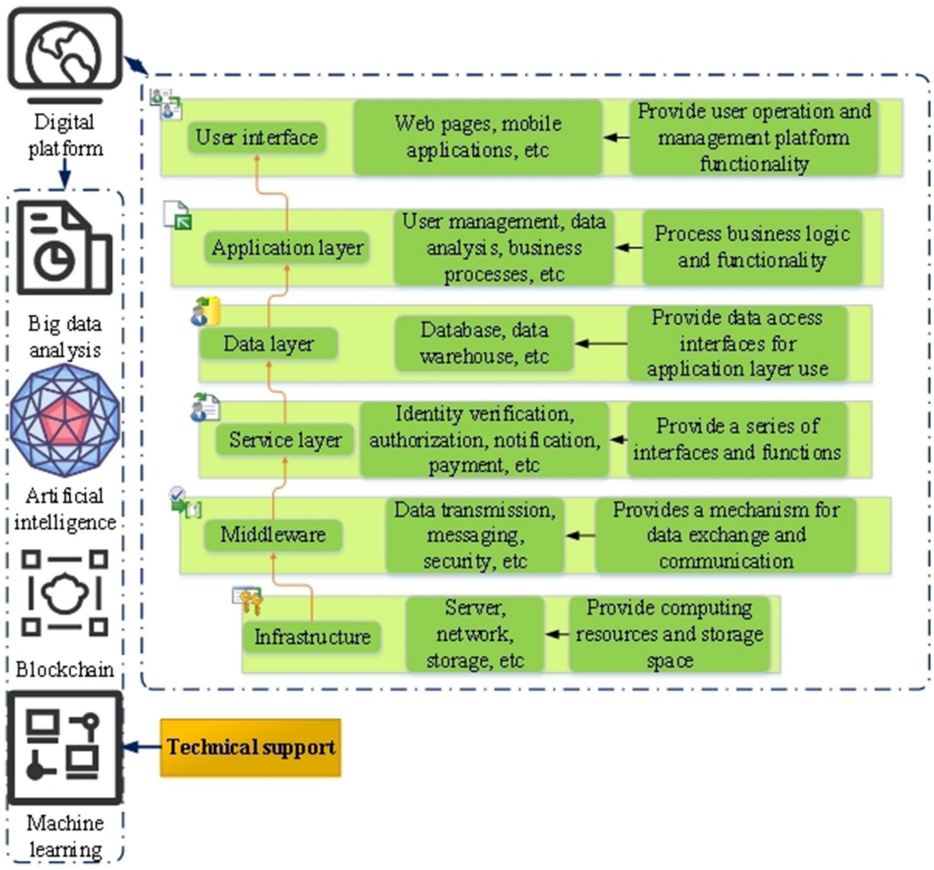

FIGURE 2
Digital platform technology architecture.

The technical architecture of Figure 2 digital platform includes infrastructure, middleware, service layer, data layer, application layer and user interface. The user interface is the part where users interact with the digital platform, which provides the functions of users to operate and manage the platform. The application layer is responsible for handling business logic and functions. The data layer is responsible for data storage, reading, updating and deleting, and provides data access interfaces for the application layer. The service layer is a part that provides various services, and provides a series of interfaces and functions for the application layer to call and use. Middleware is a part that connects various components and levels, provides a mechanism for data exchange and communication, and ensures the coordination and interaction between various parts. Infrastructure provides computing resources and storage space to ensure the stability and reliability of the digital platform (40, 41). Figure 3 shows the potential mechanism of digital platform in enterprise environmental protection behavior.

In Figure 3, digital platform plays an important role in corporate environmental behavior. Through data analysis, resource management, carbon management, environmental protection innovation and other mechanisms, the digital platform helps enterprises to better fulfill their social and environmental responsibilities, promote the practice of sustainable development, improve the environmental performance of enterprises, create economic value for enterprises, and promote the positive relationship between environmental protection and sustainability (42).

3.3 Research hypothesis

The research hypothesis is a speculative statement about the relationship among different variables. The research hypothesis of this paper focus on the influence of digital platform on corporate environmental behavior and social responsibility.

> *Hypothesis 1*: There is a positive correlation between the widespread application of digital platforms and corporate environmental protection behavior.
>
> *Hypothesis 2*: There is a positive correlation between the environmental protection innovation technology of digital platform and the implementation of environmental protection policies of enterprises.
>
> *Hypothesis 3*: There is a positive correlation between social responsibility tools of digital platform and CSR activities.

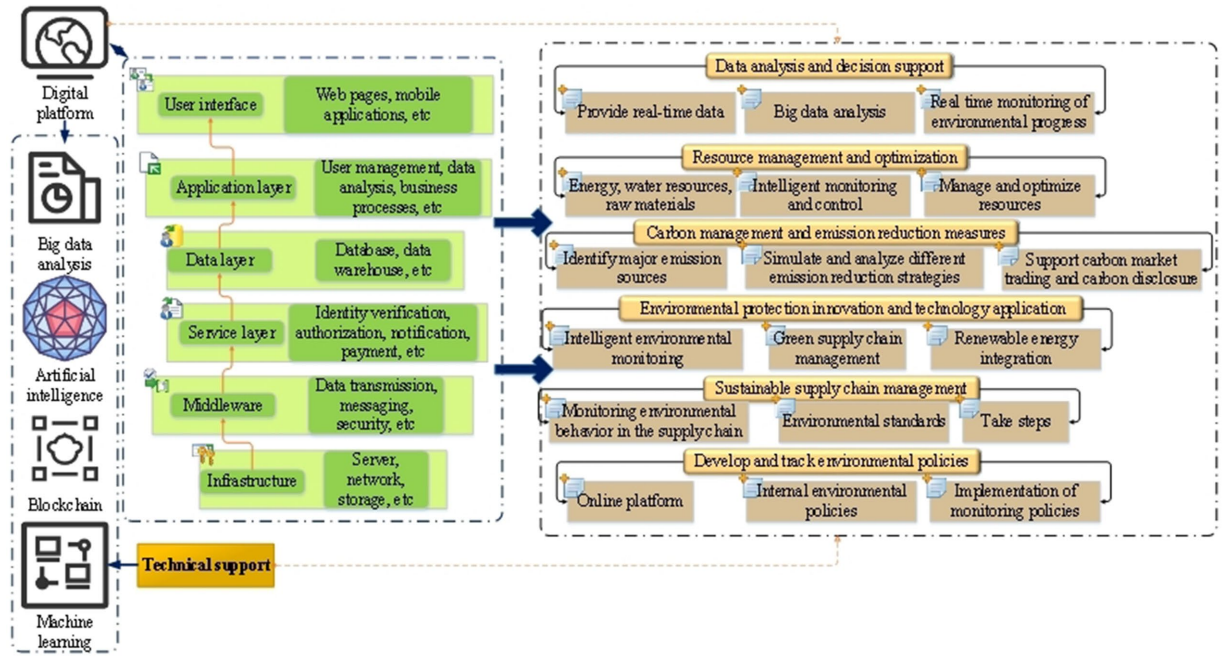

FIGURE 3
Potential mechanism of digital platform in enterprise environmental protection behavior.

> *Hypothesis 4*: There is a positive correlation between enterprise scale and industry type on digital platform and enterprise environmental behavior.

3.4 Method of data capture

In this study, the questionnaire design is to explore the influence of digital platform on corporate social responsibility practice by investigating employees in private enterprises. In order to ensure that the questionnaire can accurately reflect the actual digital actions and CSR activities of enterprises, a series of measures have been taken to enhance the reliability and validity of the questionnaire. Firstly, before designing the problem, the relationship between CSR and the development of environmental science is deeply studied, and the cross influence of CSR and environmental science is clarified. With reference to the policy documents on environmental protection and sustainable development issued by international organizations such as the United Nations Environment Programme, the theoretical basis of the research is constructed. This helps to ensure that the questionnaire design is closely related to the research objectives. Secondly, in the process of questionnaire design, 20 professionals with relevant backgrounds are invited to fill in the first edition of the questionnaire, and the expression and order of questions are adjusted according to their feedback to improve the clarity and logic of the questionnaire. This step is helpful to optimize the questionnaire design, ensure that the questions are accurate and clear, and capture the required information effectively. In addition, referring to the published related research, a measurement tool is constructed based on the indicators used in these studies to ensure the relevance and effectiveness of the questionnaire. In order to further improve the reliability and representativeness of the questionnaire, the online survey platform is used to distribute the questionnaire, and a reminder mechanism is set up to increase the response rate. Meanwhile, small rewards are provided for participants who completed the questionnaire to ensure the data quality. Cronbach's α coefficient and exploratory factor analysis are used to verify the internal consistency test of sample data to evaluate the consistency and reliability of the questionnaire results. In addition, Pearson correlation coefficient is used to evaluate the correlation among different variables to ensure the accuracy and reliability of data analysis. In the questionnaire design, the respondents of private enterprises are divided into three categories: managers, team members and ordinary employees to ensure that employees with different positions and responsibilities are covered to fully understand the digital actions and CSR activities of enterprises. Through the questionnaire collection and analysis of employees in different positions, people can better understand the views and practices of digital platforms and environmental protection behaviors at all levels within the enterprise, and thus draw more objective research conclusions. The comprehensive application of the above measures makes it possible to explore the influence of digital platform on corporate social responsibility practice more comprehensively and accurately, and ensure that the obtained data has high credibility and representativeness, thus providing a solid foundation for subsequent analysis and conclusions. The specific questionnaire design and collection contents are as follows:

The choice of questionnaire survey in this paper is mainly based on its ability to effectively collect a wide range of data, while ensuring anonymity and authenticity. Compared with other data collection methods, questionnaire survey can cover a wider audience and get direct feedback on their opinions and behaviors, which is very important for exploring the role of digital platform in corporate environmental protection behavior.

TABLE 2 Study the definition and selection basis of variables.

Variable name	Definition	Selection basis
Digital platform usage	The frequency and depth of enterprises' application of digital platforms in their daily operations	According to the existing literature, the wide application of digital platform is considered to be an important factor affecting the environmental behavior of enterprises
Corporate environmental protection behavior	Include measures to reduce carbon emissions, manage resources and adopt sustainable practices	Environmental protection behavior is a key aspect to measure the practice of corporate social responsibility, and it also directly reflects the response of enterprises to the development guide of environmental science
Application of social responsibility tools	CSR activities implemented by enterprises through digital platforms, such as charitable donations and community support	Social responsibility tool is a means for enterprises to fulfill their social responsibilities, which is helpful to promote the positive role of enterprises in the field of public health
Environmental innovation technology	New technologies applied by enterprises to improve the efficiency and effect of environmental protection	Environmental innovation technology is regarded as the key driving force to promote environmental protection behavior and sustainable development of enterprises

In this paper, the data of environmental behavior and environmental science development released by the United Nations Environment Programme are used as the control data set of questionnaire survey results. Questionnaire survey is the main means to obtain information about environmental behavior and social responsibility of participating enterprises. Siyal et al. (43) used questionnaires to analyze how inclusive leaders cultivate employees' innovative work behavior and creativity, and the results showed that inclusive leadership had a positive impact on innovative work behavior and creativity. In this paper, the respondents of private enterprises are divided into three categories: managers (M) who are related to environmental protection behavior and social responsibility activities of enterprises, team members (T) who are responsible for social responsibility, and ordinary employees (N). The sample size is determined based on Cochran formula. Considering the expected effect, α level and statistical power, it is estimated that at least 250 questionnaires are needed to ensure the reliability and representativeness of the research results. Finally, 256 valid questionnaires are collected, which meets the demand of sample size. After the preliminary design of the questionnaire, 20 professionals with relevant backgrounds are invited to fill it out, and the expression and order of the questions are adjusted based on their feedback to improve the clarity and logic of the questionnaire.

In order to ensure the validity and reliability of the questionnaire, this paper refers to the published related research and builds a measurement tool based on the indicators used in these studies. By using the online survey platform to distribute questionnaires and setting up a reminder mechanism, the response rate is improved, and small rewards are provided to participants who complete the questionnaires to ensure the data quality. In order to verify the consistency and reliability of data, Cronbach's α coefficient and exploratory factor analysis are used for internal consistency test, and Pearson correlation coefficient is also used to evaluate the correlation among variables. The questionnaire is distributed to 297 respondents by e-mail or online survey platform. Two hundred and fifty six valid questionnaires are collected.

The questionnaire is divided into six sections. The first section is basic information statistics, including gender, working years, education level and occupation. The second section is the development level of environmental science, which mainly focuses on the degree of attention paid by enterprises to the development of environmental science and whether enterprises are developing or applying related technologies of environmental science. The third section is the application level of digital platform, knowing the application of digital platform in the enterprise where the interviewee works, including: the experience of using digital platform, whether the enterprise widely uses digital platform to support business operations, and whether the enterprise uses digital platform to monitor and manage data related to environmental protection and social responsibility. The fourth section is the environmental behavior of enterprises, mainly including whether enterprises have taken measures to reduce carbon emissions and whether enterprises actively participate in resource management and sustainable practice. The fifth section investigates the respondents' questions about CSR activities, and whether they hold positions related to environmental protection or social responsibility, including: whether enterprises actively participate in social responsibility activities, such as charitable donations and community support. Whether the enterprise has social responsibility report or traceable social responsibility record. The sixth section is the intermediary role of digital platform in environmental behavior and social responsibility, mainly including whether enterprises use digital platform to monitor and report environmental behavior and social responsibility activities. In the definition of variables and the construction of measurement scale, this paper defines "corporate social responsibility" as that enterprises voluntarily assume social and environmental responsibilities while pursuing economic benefits. "Digital platform usage" refers to the degree to which enterprises integrate and use digital technology platforms in their operations and management. "Environmental protection behavior" covers all practical actions taken by enterprises to reduce environmental impact and promote sustainable development. The measurement of these variables is based on the previous literature review, combined with expert opinions and pretest results, forming a set of scales containing multiple items, aiming at comprehensively and accurately capturing the core content of each variable. Table 2 shows the definition and selection basis of research variables:

According to the intermediary effect analysis method mentioned by Alfons et al. (44), Pearson correlation coefficient and Bootstrap method are used in this paper to evaluate the relationship among digital platform usage, CSR policy implementation and corporate environmental behavior. This method is widely recognized and used in social science research, and has been recognized by academic circles for its robustness and applicability. Pearson correlation coefficient is used to analyze the correlation among different variables, and the calculation is shown in Equation (1):

$$r = \frac{n(\Sigma xy) - (\Sigma x)(\Sigma y)}{\sqrt{\left[n\Sigma x^2 - (\Sigma x)^2\right]\left[n\Sigma y^2 - (\Sigma y)^2\right]}} \quad (1)$$

In Equation (1), r represents the correlation coefficient. x and y represent two variables respectively, and n represents the sample size. Using Baron and Kenny's mediation effect analysis method, Equations (2–4) shows the calculation of intermediary effect:

$$a = \frac{X - M}{X} \quad (2)$$

$$b = \frac{Y - X}{Y - M} \quad (3)$$

$$c' = \frac{Y - M}{X} \quad (4)$$

In the above equations, a stands for total effect, b stands for direct effect, c' stands for indirect effect, X stands for intermediary variable (application level of digital platform), M stands for the influence of intermediary variable on dependent variable, and Y stands for dependent variable (environmental protection behavior or social responsibility activities of enterprises).

4 Results and discussion

4.1 The results of reliability and validity test and descriptive statistical analysis of the questionnaire

The reliability and validity of the questionnaire are shown in Figure 4. It shows that each factor has a high reliability coefficient (greater than 0.84), the factor load (greater than 0.75) indicates that there is a correlation between the problem and each factor, and the KMO value shows that the data is applicable in factor analysis.

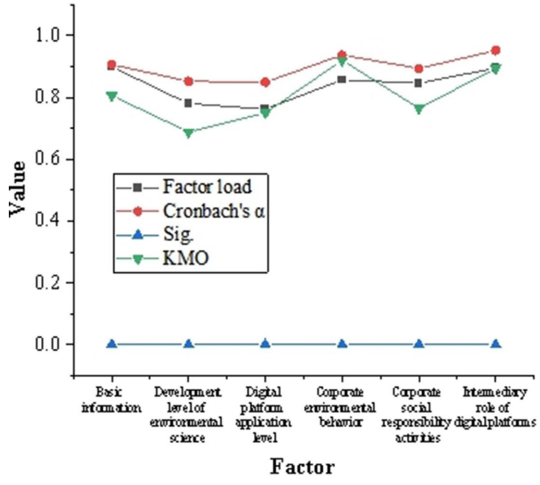

FIGURE 4
Results of reliability and validity test of questionnaire.

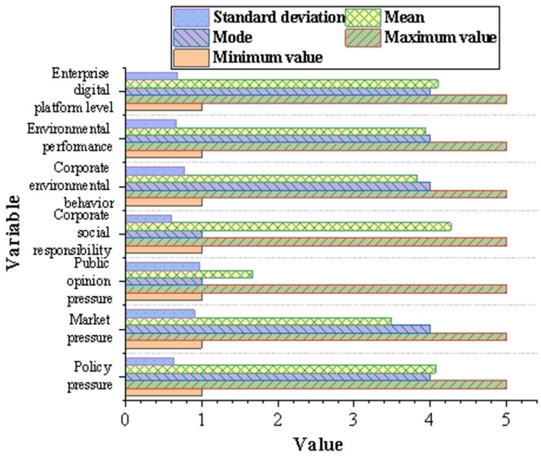

FIGURE 5
Descriptive statistical analysis results of the questionnaire.

Figure 5 shows the descriptive statistical analysis results of the questionnaire. According to the descriptive statistical results, the respondents' average scores on policy pressure, market pressure, CSR, environmental performance, and enterprise digital platform level are 4.07, 3.49, 4.27, 3.93, and 4.1, respectively. The evaluation results are relatively consistent. However, there are great differences in the evaluation of public opinion pressure and corporate environmental protection behavior.

4.2 The correlation between the usage of digital platform and the environmental protection behavior of enterprises

Figure 6 shows the results of correlation analysis between the usage of digital platform and the environmental protection behavior of enterprises. Pearson correlation coefficient shows that there is a moderate positive correlation between the use of digital platforms and corporate environmental behavior (correlation coefficient is 0.523). The Sig. value of correlation analysis is 0.001 (<0.05), which indicates that this correlation is significant. The correlation between the usage of digital platform and enterprise's environmental behavior is 5.367, Sig. = 0.000 ($p < 0.05$), which verifies hypothesis 1.

Figure 7 shows the intermediary analysis of the usage of digital platform. The intermediary analysis shows that the intermediary effect ratio (a * b/c) is 55.31%, and the 95% Bootstrap CI range does not include 0, which indicates that the usage of digital platform plays a significant intermediary role between digital platform and corporate environmental protection behavior.

4.3 The influence of digital platform on CSR policy and practice

Figure 8 shows the results of correlation analysis between digital platform and CSR. Pearson correlation coefficient shows that there is

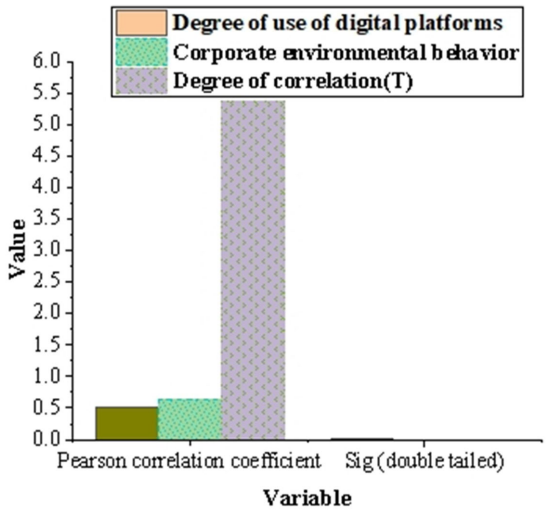

FIGURE 6
The results of correlation analysis between the use of digital platform and the environmental protection behavior of enterprises.

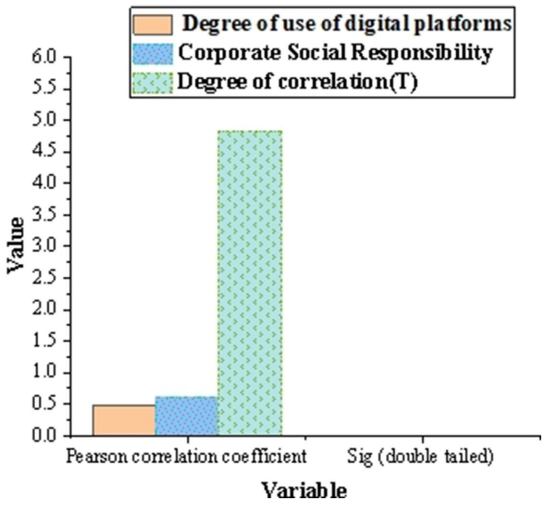

FIGURE 8
Correlation analysis results between digital platform and CSR.

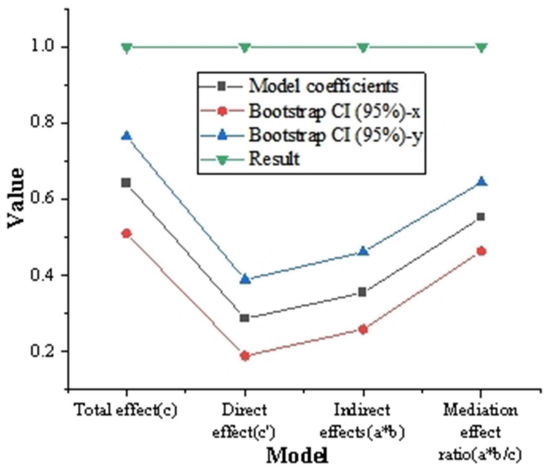

FIGURE 7
Intermediary analysis of the usage degree of digital platform.

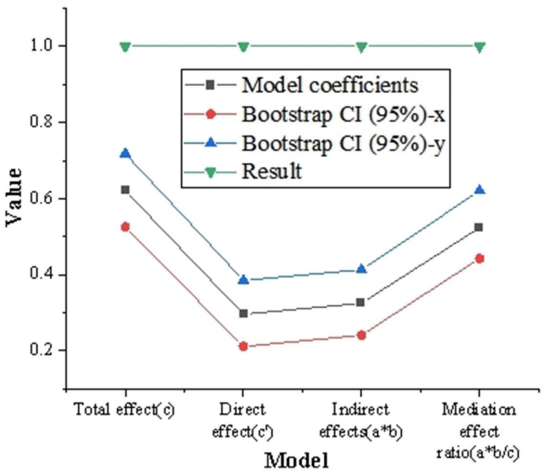

FIGURE 9
Intermediary analysis of digital platform on CSR policy and practice.

a moderate positive correlation between the use of digital platforms and CSR policies and practices (correlation coefficient is 0.481). The Sig. value of correlation analysis is 0.003, which is less than the significance level of 0.05, indicating that this correlation is significant. The correlation T between digital platform and CSR is 4.825, Sig. = 0.000 ($p < 0.05$), which shows that there is a positive correlation between digital platform's social responsibility tools and CSR activities, and supports hypothesis 3.

Mediating analysis shows that the mediating effect ratio (a * b/c) is 52.40%, and the 95% Bootstrap CI range does not include 0, indicating that the usage of digital platforms plays a significant mediating role between digital platforms and CSR policies and practices. Figure 9 shows the intermediary analysis of digital platform on CSR policy and practice.

4.4 Mediating and regulating functions of digital platform and enterprise's environmental protection behavior

Figure 10 shows the analysis results of the intermediary role and regulatory role of digital platform on enterprise environmental protection behavior. The total effect (a) of digital platform on corporate environmental behavior is 0.627, the total effect (b) of intermediary variable CSR policy implementation is 0.452, and the total effect (b) of intermediary variable environmental innovation technology is 0.313. The mediating effect and 95% confidence interval calculated by Bootstrap method show that the mediating variable CSR policy implementation and environmental protection innovation technology significantly mediate the influence of digital platform on

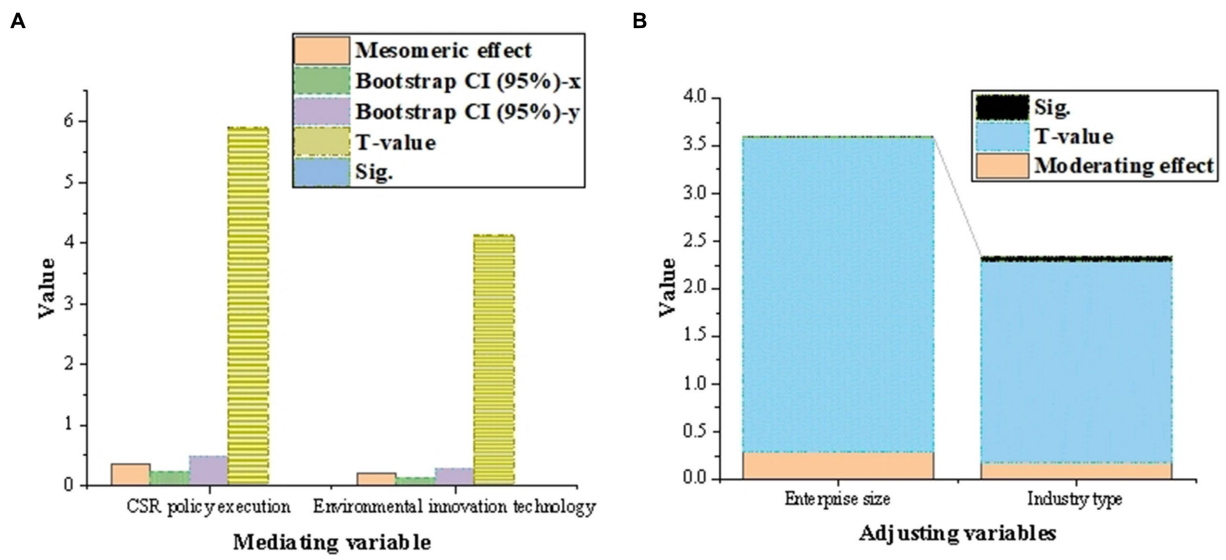

FIGURE 10
The analysis results of the mediating and regulating effects of digital platform on enterprise's environmental protection behavior [**(A)** the mediating effect; **(B)** for regulatory purposes].

TABLE 3 Results of SEM and multiple regression analysis.

Variable	Coefficient (β)	Standard error	*T* value	*p*-value
Use of digital platform	0.623	0.041	15.21	<0.001
Implementation of CSR policy	0.457	0.038	12.03	<0.001
Environmental innovation technology	0.342	0.045	7.60	<0.001
Enterprise scale (adjusting variable)	0.198	0.052	3.81	<0.001
Industry type (adjustment variable)	0.162	0.055	2.95	0.003

$p < 0.05$ indicates that the result is statistically significant.

corporate environmental protection behavior, because their confidence intervals do not include 0. *T*-value and Sig. value also support the significance of these mediating effects. The moderating effect of moderating variable enterprise scale is 0.284, and that of moderating variable industry type is 0.179. The *t*-value and Sig. value of the regulatory effect show that both the scale of enterprises and the types of industries have a significant regulatory effect on the impact of digital platforms on corporate environmental behavior.

In order to further explore the potential causal relationship between the use of digital platforms and the environmental behavior of enterprises, Structural Equation Modeling (SEM) is introduced for analysis. In addition, through the analysis of mediating and moderating effects, it further analyzes how the digital platform affects the CSR practice and environmental behavior of enterprises through different mediating variables (environmental innovation technology) and moderating variables (enterprise scale and industry type). Firstly, a structural equation model is established to evaluate the direct and indirect relationship between digital platform use (independent variable) and enterprise environmental behavior (dependent variable). As a part of indirect relationship, two intermediary variables are considered: CSR policy implementation and environmental innovation technology. Meanwhile, enterprise scale and industry type are regarded as moderating variables to test whether they will change the correlation between the main variables. The hypothesis is tested by multiple regression analysis. This analysis helps to verify the correlation between the use of digital platform, the implementation of CSR policy, environmental innovation technology and corporate environmental behavior, and also examines the regulatory role of enterprise scale and industry type. Table 3 shows the results of multiple regression analysis, which is used to test the direct impact of the use of digital platforms on corporate environmental behavior and its indirect impact through intermediary variables.

In Table 3, the use of digital platform has a significant positive impact on corporate environmental behavior ($\beta = 0.623$, $p < 0.001$), and CSR policy implementation and environmental innovation technology both show significant positive effects as intermediary variables. In addition, as moderating variables, enterprise scale and industry type have a significant moderating effect on the relationship between the main variables. Through the structural equation model and the results of multiple regression analysis, it is confirmed that there is a significant positive relationship between the use of digital platforms and corporate environmental behavior. Environmental innovation technology and the implementation of CSR policy have played an important intermediary role in this relationship. In addition, the analysis also reveals the moderating role of enterprise scale and industry type in the relationship between digital platform use and enterprise environmental behavior. This emphasizes the need to consider the specific background and characteristics of enterprises when encouraging enterprises to take digital measures to improve their environmental performance. The above findings have important implications for decision makers and policy makers. They emphasize the necessity of supporting enterprises to adopt

digital technology to improve environmental protection behavior and CSR practice, and suggest the importance of considering enterprise scale and industry characteristics when designing relevant policies and interventions.

The findings of this paper provide valuable insights for decision makers and policy makers. Firstly, the paper emphasizes the core role of digital platform in promoting corporate environmental behavior and social responsibility practice. The application of digital technology can help enterprises to manage resources more efficiently and formulate environmental protection strategies, thus promoting sustainable development. It is suggested that policy makers should support and encourage enterprises to adopt digital technology to improve their environmental friendliness and social responsibility practice. Secondly, future policy planning needs to take into account the differences in the influence of enterprise scale and industry type on digital platforms. Enterprises of different scales and industries may face different challenges and opportunities in digital transformation, so customized guidelines are needed to guide them to make rational use of digital platforms. Policymakers can formulate targeted policies and measures according to the characteristics of different enterprises to promote the combination of digitalization and sustainable development. Finally, it is suggested that further research should pay attention to the differences in the impact of digital platforms on corporate social responsibility and public health in different regions and cultural backgrounds. Different regions and cultures may have different degrees of acceptance and practice of digitalization, which will have different degrees of impact on corporate social responsibility and public health. In-depth study of the mechanism of digital platforms in different contexts will help to better guide enterprises and policy makers in their decision-making and practice in different environments. Through these suggestions and research directions, people can better promote the goals of corporate social responsibility and sustainable development with the help of digital platforms.

5 Conclusion

The purpose of this paper is to explore the influence of digital platform on corporate environmental behavior and social responsibility, and to deeply understand how digital platform shapes the sustainable development practice of enterprises. Through comprehensive analysis of questionnaire survey data and various research methods, it is found that digital platform plays an active role in the sustainable development of enterprises. There is a positive correlation between the wide application of digital platform and corporate environmental behavior and social responsibility, which shows that digital platform helps enterprises to participate in environmental protection and social responsibility activities more actively and promote sustainable development. Secondly, the environmental protection innovation technology of digital platform has a positive impact on the implementation of environmental protection policies of enterprises. Environmental protection innovation technology plays an intermediary role between digital platform and enterprise environmental protection behavior, which strengthens the influence of digital platform on enterprise environmental protection behavior. In addition, the scale of enterprises and the types of industries plays a regulatory role in the influence mechanism of digital platforms. Enterprises of different scales and industries have different responses to digital platforms, which requires individualized consideration when formulating environmental protection policies and strategies. However, there are some shortcomings in this paper. The research sample has limitations and may not fully represent enterprises of other industries and scales. Future research can expand the sample range, deeply analyze the relationship between digital platform and sustainable development of enterprises, and consider more regulatory factors.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MW: Conceptualization, Data curation, Validation, Writing – review & editing. RY: Conceptualization, Formal analysis, Writing – original draft. XG: Investigation, Methodology, Writing – original draft. ZW: Formal analysis, Methodology, Visualization, Writing – review & editing. YZ: Investigation, Software, Writing – review & editing. TL: Funding acquisition, Project administration, Resources, Software, Supervision, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Effects of internal migrants' health on economic resilience in China's Yangtze River Delta urban agglomeration: moderating effects of basic public health services

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Introduction: Internal migrants constitute a significant generality in the socioeconomic development of developing countries. With the frequent occurrence of major public health emergencies, obstacles to labor supply due to health issues among internal migrants not only affect their livelihood stability but also urban economic resilience. Moreover, the design of basic public health service systems tends to favor local residents over internal migrants, further exacerbating the health and employment risks of internal migrants. As a result, urban economic resilience faces significant challenges.

Objective: The objective of this study was to deconstruct economic resilience into economic resistance and recovery abilities, investigate the net effect and its heterogeneity of internal migrants' health on economic resilience in China's Yangtze River Delta urban agglomeration (CYRD), and the mediating effect from labor participation rate and labor time supply, as well as the moderating effect of basic public health services.

Methods: Based on the China Migrants Dynamic Survey data (CMDS), the study empirically estimated the effects of internal migrants' health on economic resilience in CYRD through microeconometric analysis methods, mediating and moderating effect model.

Results: Our findings indicate that internal migrants' health has a positive effect on economic resilience in CYRD. For each unit increase in migrants' health, it will drive up the average economic resistance ability by 0.0186 and the average recovery ability by 0.0039. Secondly, the net effects of migrants' health on economic resilience show significant structural differences, industry and city heterogeneity. The effect of migrants' health on economic resistance ability is significantly higher than that on economic recovery ability; The effect of migrants' health on economic resilience of the secondary industry is higher than that of the tertiary industry; The cities with high economic resistance and recovery abilities have more prominent positive effect from migrants' health. Thirdly, migrants' health not only has a direct effect on the economic resistance and recovery abilities, but also has a mediating effect on which through labor participation rate and labor time supply.

Discussion: Enhancing the accessibility and quality of basic public health services is beneficial for enhancing the positive effects of internal migrants' health on economic resilience.

KEYWORDS

internal migrants, health performance, economic resilience, basic public health services, Yangtze River Delta urban agglomeration

1 Introduction

Economic resilience is an important focus for urban agglomerations to address challenges from internal and external environmental changes and to move toward high-quality economic development (1). It is also a key support to avoid a hard landing of the national economy and to solidify the foundation for economic recovery under the pressure of a global macroeconomic downturn. As the main carriers of urbanization and national economic, also the strategic pivot of national economic development and regional development strategy, urban agglomerations is conducive to breaking administrative barriers, enhancing industrial agglomeration and connectivity (2), thus accelerating the aggregation of population and factor resources, providing employment opportunities, and promoting regional economic development (3). However, with risks such as natural disasters, economic crises, trade frictions, and major public health incidents continuously accumulating, urban agglomerations has entered a period of frequent internal and external shocks (4, 5). The ability of urban agglomerations to provide a endogenous driving force for regional and national economic development is facing great challenges (6). In this grim reality, economic resilience can help the economic entity withstand external shocks and recover quickly (7). Therefore, it becomes crucial for urban agglomeration economic systems to break through predicaments, get rid of the downward economic trajectory, and achieve steady economic growth.

Internal migrants also provides important support for urbanization advancement and social-economic development, and it helps promote factor agglomeration, industrial transfer, and equalization of public services, driving balanced regional economic development and social integration (8). The laws of world economic development indicate that the economic takeoff of any country inevitably accompanies the process of urbanization, which is particularly prominent in China as a populous and economically influential country (9). According to China's population census data, urbanization rate increased from 36.5% in 2000 to 63.89% in 2020, with the urban population increasing from 460 million to 900 million.[1] Among them, the contribution of population mobility to the increase in urbanization level is about 45%, higher than the contribution of urban areas expansion, which accounts for 35% of the urbanization rate.[2] According to the United Nations *World Population Prospects*' forecast, by 2030, China's urbanization rate will reach about 71%, corresponding to 1.03 billion urban residents, an increase of about 130 million from 2020. About 50% of the newly added urban population comes from rural-urban migration, and about 80% of the new urban population will be distributed in 19 major urban agglomerations.[3] Moreover, this spontaneous migration of population between rural and urban areas driven by market forces has shown certain positive effects in optimizing social resource allocation and regional technological exchanges (10), stimulating consumption (11), and narrowing regional income gaps (12), and has been recognized by domestic and foreign scholars. It can be seen that such large-scale population mobility is not only an important factor affecting China's urbanization, industrialization, and modernization but also a major variable that cannot be ignored in the development of regional relations.

However, as an important part of the economic development of urban agglomerations, the risk resistance ability of the internal migrants is much lower than that of the local population when facing internal and external shocks to cities. Taking public health emergencies as an example, the sudden outbreak of the COVID-19 pandemic in 2021 brought about huge economic losses and employment shocks to countries around the world (13, 14), including China. And the restrictions on labor mobility caused by epidemic prevention measures led to a continuous expansion of the gap between labor supply and demand in cities, resulting in a sharp increase in the unemployment rate among migrant workers (15, 16). China's urban labor market is also facing unprecedented pressure, with difficulties in recruiting workers and employment being reinforced. The temporary and informal employment for migrant workers makes the risks of unemployment and disease particularly severe (17). The hindrance to labor supply caused by health problems among migrant workers not only affects their own livelihood stability but also affects the sustainability and resilience of urban economic development (18). Moreover, the design of an urban public health service system tends to favor local urban residents rather than migrant workers, further exacerbating the health and employment risks of migrant workers, thus posing significant challenges to the resilience of urban economic development. Therefore, systematically exploring the impact of migrant workers' health on the economic resilience of CYRD and the regulatory effects from public health services not only provides new perspectives for studying the economic resilience, but also brings breakthroughs for enhancing economic resilience.

Existing literature closely related to this study mainly includes two branches. The first branch explores the disadvantaged position of migrant workers in terms of health and employment. For a long time, a large number of studies on migrant workers in the United States have pointed out a significant positive correlation between low socioeconomic status and health disadvantages among non-Hispanic whites and blacks (19). A series of studies based on the theory of dual labor markets also indicate that migrant workers, especially those who move across national borders, tend to engage in dangerous and demeaning work (20). Furthermore, research suggests that due to disadvantages such as lack of medical insurance, migrant workers tend to return to their places of origin after falling ill, which may reduce the labor supply in destination cities and the social welfare of migrant workers themselves (21). The second branch discusses the factors influencing economic resilience. Factors such as centrality and diversity of industrial linkages and entrepreneurial vitality are important factors affecting urban economic resilience (22). For example, industrial diversification can provide a favorable environment for technological innovation, effectively promote the enhancement of urban innovation capability and structural adjustment, and thereby enhance urban economic resilience (23). Enhanced innovation capability can also effectively drive the improvement of urban economic resilience (24), mainly through strengthening talent reserves, upgrading industrial structure, and

1 The data is sourced from the National Bureau of Statistics of China (https://www.stats.gov.cn/sj/sjjd/202302/t20230202_1896485.html).

2 http://politics.people.com.cn/n/2013/0204/c70731-20426975.html

3 https://m.thepaper.cn/baijiahao_8705887

optimizing resource allocation efficiency (25). In addition, existing research have explored the effect of different factors on economic resilience from various aspects such as psychological expectations (26), labor skills (27), economic agglomeration level (28), economic structure (29), transportation infrastructure (30), and spatial structure (31). In summary, existing literature has conducted a series of studies on migrant workers' health and economic resilience separately, but literature attempting to explore the relationship between the two is rare.

This study selects the CYRD, one of the six largest urban agglomerations in the world and the main gathering place of internal migrants in China, as a typical case. According to China's national population census in 2020, the total number of internal migrants in CYRD is 73.573 million, accounting for 19.6% of the country's internal migrants and ∼42% of the total local population. It can be said that migrants constitute the backbone of the local labor systems (LLS) in CYRD, serving as the main force driving its socioeconomic development and urban construction. Based on micro-sample data from CMDS, this paper investigates the effect of internal migrants' health on the economic resilience of CYRD, the mechanisms of action, and the policy regulatory effects. The marginal contribution are 2-fold: firstly, it decomposes economic resilience into economic resistance and recovery abilities, explores the factors influencing urban agglomeration economic resistance and recovery abilities from the perspective of migrant workers' health in an innovative way, expands the research scope of factors influencing urban agglomeration or urban economic resilience, and opens up new perspectives for the study of economic resilience. Secondly, it systematically analyzes the logical mechanisms by which migrant workers' health affects the economic resilience from the dimensions of labor participation rate and labor supply, and further explores the regulatory effects of urban public health services on migrant workers' health and the economic resilience, providing new ways for enhancing the economic resilience.

This study is structured as follows: the identification method for economic resilience and the identifying equations of internal migrants' health on economic resilience are presented in Section 2. The regression estimation results and the results of the mediating and moderating effects tests are presented in Section 3. Section 4 draws conclusions and policy implications. The research framework is shown in Figure 1.

2 Methodology

2.1 Case

As one of the fastest-growing regions in both China and the world in terms of economic growth and urbanization, CYRD plays a demonstrative role in the construction of urban agglomerations in China. It holds significant strategic importance in opening-up development and modernization construction, and provides a lot of replicable and promotable experiences for the development of other regions. At present, CYRD includes Shanghai and 26 other cities from Jiangsu, Zhejiang, and Anhui. In Figure 2, CYRD covers an area accounting for about 2.2% of China's territory. However, it hosts ∼16.7% of China's population, nearly 25% of its total economic output, and 33.3% of its total import and export volume. Therefore, studying the impact of migrants' health on the economic resilience of CYRD has significant practical implications.

2.2 Economic resilience identifying

Economic resilience refers to the ability of an economy to effectively respond to external disturbances, resist risk shocks, and achieve economic autonomy and sustainable development. From existing literature, there appear to be two main methods for identifying economic resilience (32, 33). One approach involves constructing a multidimensional indicator system for economic resilience, assigning weights to each indicator, and then calculating a composite index of urban economic resilience (34). The other approach is to build a sensitivity index based on core variables to identify urban economic resilience (35, 36). Due to the lack of universally recognized indicators and weights for economic resilience in the academic community, as well as the lack of precision and universality in the indicator systems constructed for measuring the economic resilience of different types of regions, this study adopts the approach of Faggian et al. (33) to construct a Sensitivity Index (*SI*) based on the core indicator of employment level for identifying urban economic resilience.

$$SI_{it} = \frac{employment_{i,t}/employment_{i,t-k}}{employment_{n,t}/employment_{n,t-k}} \quad (1)$$

Where $employment_{i,t}$ is total employment in city i during period t, $employment_{n,t-k}$ is total employment in the country during period $t-k$. The SI index is similar to the location entropy index and is centered around 1. When the SI is >1, it indicates that the employment growth of city i is faster compared to the national average during the $t-k$ to t period, suggesting relatively strong economic resilience. When the SI is <1, it indicates that the employment growth of city i is slower compared to the national average during the $t-k$ to t period, indicating relatively weak economic resilience.

Similar to the study by Fingleton et al. (35) in the UK, this paper distinguishes between two types of economic resilience: recover ability, which refers to the economic recovery ability of cities during a period of stable economic growth, and resistance ability, which refers to the ability to withstand shocks during an economic downturn. According to Figure 3, the GDP of CYRD and the GDP per capita growth rates reached a peak in 2017 and then began to decline. Specifically, the main reason for the slowdown in the economic growth is the declining growth rates of the total output value of the secondary and tertiary industries, which together account for about 90% of the GDP. Therefore, this study sets the period from 2017 to 2020, before the widespread outbreak of the COVID-19 pandemic, as the

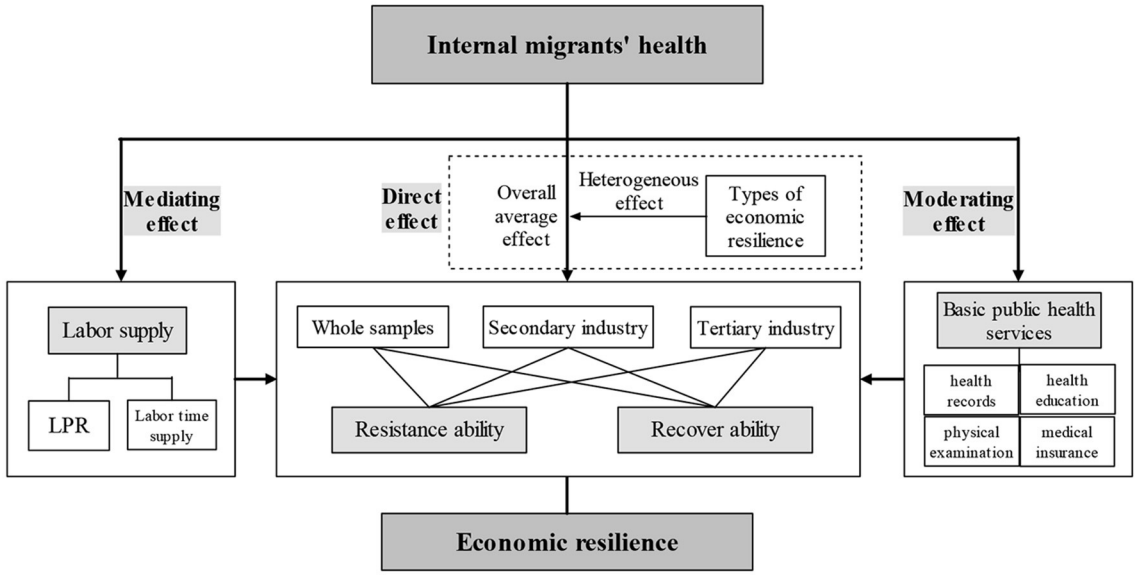

FIGURE 1
A research framework for this study.

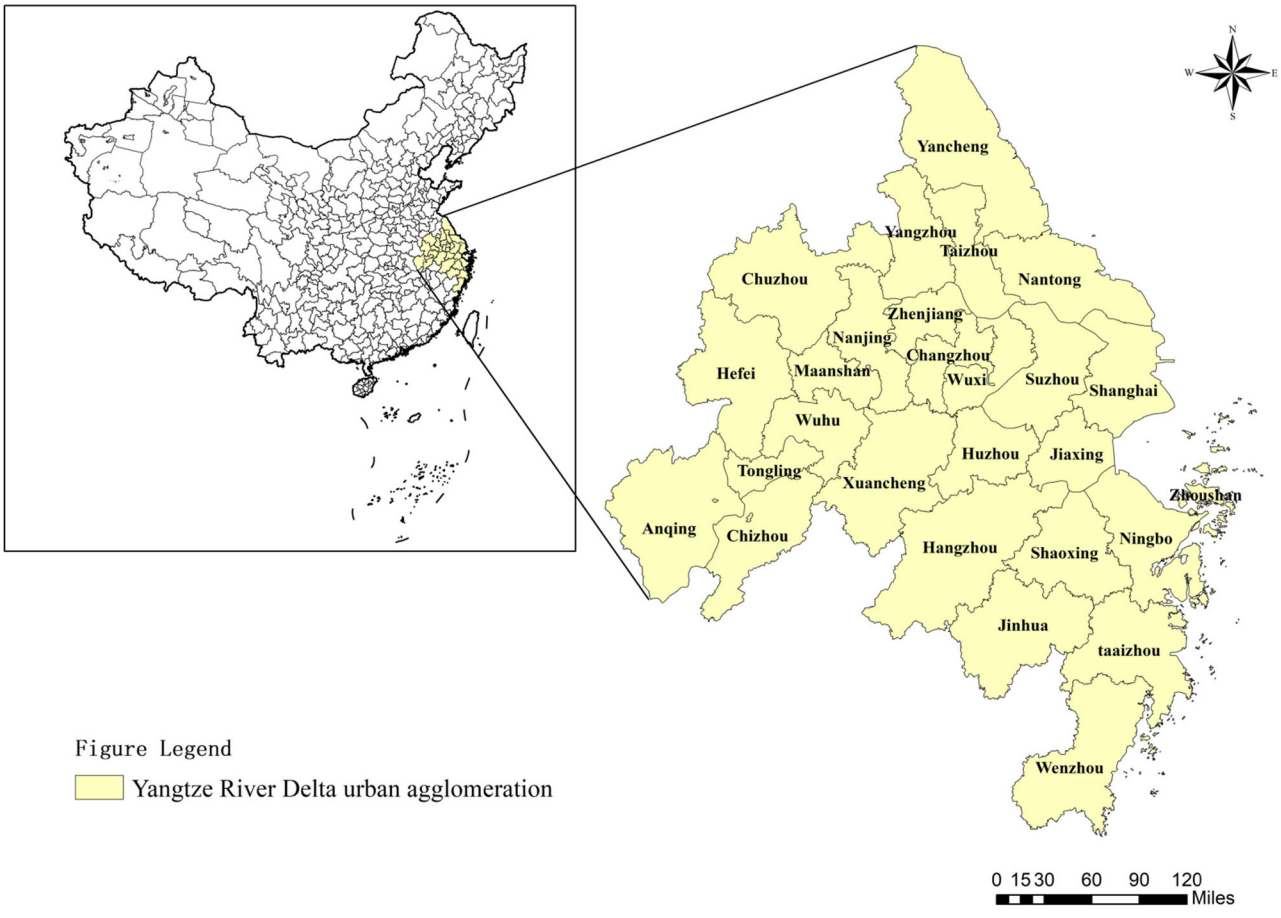

FIGURE 2
The spatial distribution of the samples in this study.

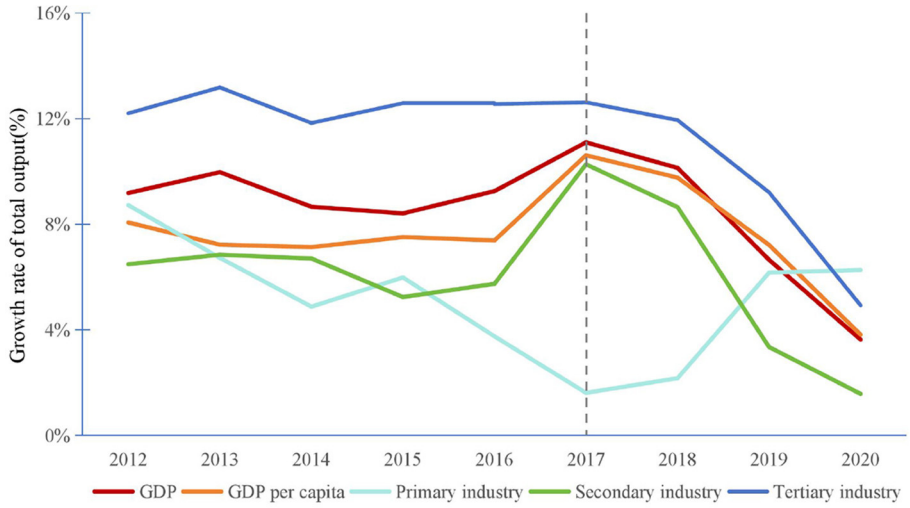

FIGURE 3
Economic performance of CYRD.

TABLE 1 Economic resilience classification.

Groups	Types of economic resilience	Classification criteria
Group I	High resistance	Resistance ability >1
Group II	Low resistance	Resistance ability <1
Group III	Fast recovery	Recovery ability >1
Group IV	Slow recovery	Recovery ability <1

recessionary period for CYRD, and the period from 2012 to 2017 as the pre-recessionary period.[4] Additionally, the economic recovery ability is measured by the economic sensitivity index from 2017 to 2019, while economic resistance ability is measured by the economic sensitivity index from 2015 to 2017. The reason for only examining the period from 2015 to 2017, the pre-recessionary period, is to maintain consistency with the length of the recessionary period after 2017. Meanwhile, based on the recovery and resistance indexes, the economic resilience is classified into four types (Table 1).

2.3 Econometric model setting

2.3.1 Identification of the effect of internal migrants' health on economic resilience

The effect of internal migrants' health on economic resilience has been supported by theoretical research. To further verify the response of economic resilience to internal migrants' health, this paper constructs the following econometric model:

$$resistance_{i,2017-2019} = \alpha + \beta health_{ijt} + \gamma_1 X_{it} + \gamma_2 M_{it} + \gamma_3 Z_{it} + \varepsilon_{it} \quad (2)$$

$$recovery_{i,2015-2017} = \alpha + \lambda health_{ijt} + \gamma_1 X_{it} + \gamma_2 M_{it} + \gamma_3 Z_{it} + \varepsilon_{it} \quad (3)$$

Where, the dependent variables *resistance* and *recovery* represent the resistance ability index and recovery ability index of city *i*, respectively. The independent variable $health_{ijt}$ represents the health performance of internal migrants *j* in city *i*. β and λ are the net effects of internal migrants' health on the resistance ability and recovery ability of the urban economic, respectively. *X*, *M*, *Z* are used to control social factors, economic factors, and institutional factors that affect economic resilience.

According to data from China's NBS, the proportion of employment in the three industries for the internal migrants changed from 2.54%, 29.06%, 68.4% in 2015 to 2.36%, 9.28%, 88.36% in 2017, and further to 2.24%, 26.13%, 71.63% in 2018. The employment of the internal migrants is concentrated in the secondary and tertiary industries. Therefore, in addition to examining the overall economic resilience, this paper further distinguishes industry heterogeneity and explores the effect of migrants' health on economic resilience of the secondary and tertiary industries. Furthermore, to overcome potential reverse causality between economic resilience and migrants' health and obtain more robust estimation results, this paper sets the value of t in the econometric model at the initial period. In other words, the t value for Model (3) is set to 2017, and for Model (4) it is set to 2015. This is because the health status during the initial period is considered a predetermined variable, and will not be influenced by subsequent stages of economic resilience.

4 The reason for not considering the period after 2020, during the COVID-19 pandemic, is that the Chinese and global economies faced significant external shocks during the pandemic, making it difficult to accurately test the impact of migrants' health on economic resilience during this period.

2.3.2 Identification of the mediating effect of internal migrants' labor supply

How internal migrants' health affects economic resilience is the focus of this paper. Existing literature indicates that labor supply is one of the important factors influencing regional economic vitality and resilience. For CYRD, internal migrants constitute the main body of local labor resource supply, so the economic resilience will be affected by the labor supply status of internal migrants. Specifically, internal migrants' health will indirectly affect the economic resilience by influencing the labor supply of internal migrants.

To test the above-mentioned mediation mechanism, this paper constructs a mediating effect model based on the labor supply of internal migrants. According to the identification strategy, we first construct an econometric Model (5) to test whether the prerequisites for the existence of the mediating effect are met, which is whether the explanatory variable, internal migrants' health, significantly affects the mediator variable, the labor supply of migrants. If the estimation results of Model (5) are prominent, we further construct econometric Models (6) and (8) to test the existence of the mediating effect, that is, to test whether the mediator variable, the labor supply of internal migrants, significantly affects economic resilience. If the mediating effect exists, we finally include both the independent variable and the mediator variable in the baseline regression equation and construct econometric Models (9) and (10) to test the mediation effect of migrants' health on the economic resilience through its effect on the labor supply of internal migrants.

$$labor\_\sup ply_{ijt} = \alpha + \beta health_{ijt} + \gamma Z_{it} + \varepsilon_{it} \quad (4)$$

$$resistance_{i,2017-2019} = \alpha + \beta labor\_\sup ply_{ijt} + \gamma_1 X_{it} + \gamma_2 M_{it} + \gamma_3 Z_{it} + \varepsilon_{it} \quad (5)$$

$$recovery_{i,2015-2017} = \alpha + \lambda labor\_\sup ply_{ijt} + \gamma_1 X_{it} + \gamma_2 M_{it} + \gamma_3 Z_{it} + \varepsilon_{it} \quad (6)$$

$$resistance_{i,2017-2019} = \alpha + \beta_1 health_{ijt} + \beta_2 labor\_\sup ply_{ijt} + \gamma_1 X_{it} + \gamma_2 M_{it} + \gamma_3 Z_{it} + \varepsilon_{it} \quad (7)$$

$$recovery_{i,2015-2017} = \alpha + \beta_1 health_{ijt} + \beta_2 labor\_\sup ply_{ijt} + \gamma_1 X_{it} + \gamma_2 M_{it} + \gamma_3 Z_{it} + \varepsilon_{it} \quad (8)$$

Where, the mediating variables $labor\_\sup ply_{ijt}$ represent the labor supply performance of internal migrants j in city i, measured by the individual labor participation rate (LPR) and labor time supply of the internal migrant.

2.3.3 Identification of the moderating effect of basic public health services

Existing studies indicate that the health status of the internal migrants is closely related to the accessibility and quality of urban basic public health services. This suggests that adjustments to urban basic public health service policies will indirectly impact the correlation between internal migrants' health and urban economic resilience. To verify this inference and determine the optimal strategy for optimizing urban basic public health services, this paper constructs a moderation effect model. In this model, influencing economic resistance and recovery abilities, an interaction term between basic public health services and internal migrants' health is introduced. The extended econometric model is set as follows:

$$resistance_{i,2017-2019} = \alpha + \beta health_{ijt} + \phi health_{ijt} \times public\_service_{ijt} + \gamma_1 X_{it} + \gamma_2 M_{it} + \gamma_3 Z_{it} + \varepsilon_{it} \quad (9)$$

$$recovery_{i,2015-2017} = \alpha + \lambda health_{ijt} + \varphi health_{ijt} \times public\_service_{ijt} + \gamma_1 X_{it} + \gamma_2 M_{it} + \gamma_3 Z_{it} + \varepsilon_{it} \quad (10)$$

Therefore, after introducing the interaction term between urban basic public health service variables and migrants' health variables, the moderating effect coefficients are as follow:

$$\frac{\partial \ln(resis\tan ce_{i,2017-2019})}{\partial health_{ijt}} = \beta + \phi \times public\_service_{ijt} \quad (11)$$

$$\frac{\partial \ln(re\,cov\,ery_{i,2015-2017})}{\partial health_{ijt}} = \lambda + \varphi \times public\_service_{ijt} \quad (12)$$

In the equations (11) and (12), $public\_service_{ijt}$ is the moderating variable. The estimated parameters ϕ and φ characterize the moderating effects of basic public health services on internal migrants' health and the economic resilience. In the above equation, if the estimated parameter $\phi > 0$, it indicates that enhancing urban basic public services contributes to strengthening the positive effect of migrants' health on economic resilience. If the estimated parameter $\varphi > 0$, it indicates that enhancing urban basic public services contributes to strengthening the positive effect of migrants' health on urban economic recovery.

2.4 Variable section and data sources

(1) Dependent variable: The dependent variable is economic resilience, characterized specifically through economic resistance and recovery abilities, as detailed in Section 2.2. The raw data for urban economic resistance and recovery abilities primarily come from various editions of the *China Urban Statistical Yearbook*.

(2) Independent variable: The key independent variable is urban internal migrants' health, mainly measured through self-assessment of their health conditions. According to the questionnaire in CMDS, the response options regarding health conditions include "healthy," "basically healthy," "unhealthy but able to manage life," and "unable to manage life". To facilitate quantitative analysis of migrant health variables, this study uses the Likert scale method to assign values of 4, 3, 2, and 1, respectively, based on the degree of health. The data on migrants' health conditions are sourced from the CMDS, a nationwide annual survey conducted by the National Health Commission of China, concentrating on areas with a significant influx of internal migrants. The survey includes 1,459 county-level units, 3,776 townships, and 8,993 neighborhood committees across the country. CMDS samples nearly 200,000 households each year, covering information on internal migrants, household members, migration patterns, employment, income and housing, health, marriage and fertility, etc.

(3) Control variables: In the control variables, social factors include population density (*density*) and its quadratic term, urbanization rate (*urbanization*); economic factors include per capita GDP (*rjgdp*) and its quadratic term, trade dependence rate (*trade*); institutional factors include government expenditure (*expenditure*) and its quadratic term, innovation ability (*innovation*). Population density is measured by the permanent population size per unit area, and urbanization rate is measured by the proportion of urban population. Trade dependence is measured by the proportion of international trade to GDP. Government expenditure level mainly refers to the scale of government fiscal public expenditure, and innovation ability is measured by the number of authorized patents. The raw data for all control variables are also sourced from various editions of *China Urban Statistical Yearbook*, with occasional supplementation from individual city's *Yearbooks* to address missing data.

(4) Mediating variable: The mediating variable in this study is the labor supply of internal migrants, primarily measured through two dimensions: individual labor participation rate and labor time supply. Firstly, the individual labor participation rate is measured using a dummy variable, indicating whether internal migrants have participated in work in the past week for at least 1 h with income ($LFP = 1$) or not ($LFP = 0$). However, according to Heckman (37), the change in individual labor supply includes both changes in work participation (breadth) and changes in working hours (depth). Therefore, this study also considers the labor time supply variable, measured by the weekly working hours of internal migrants.

(5) Moderating variable: The moderating variable in this paper is basic public health services, comprising two dimensions: accessibility and quality. The public health services' accessibility is reflected through indicators such as *health records* (*health_records)*, *health education (health_education)*, etc. The public health services' quality is measured by indicators such as *physical examinations* for major diseases *(Physical_examination)*, *urban medical insurance (medical_insurance)*, etc. For ease of quantitative analysis, all the above variables are set as 0–1 binary dummy variables. Regarding the indicators for basic public health services' accessibility, options such as "heard about the national basic public health service project," "established resident health records," and "received health education for major diseases" in the questionnaire are set to 1, while other options are set to 0.[5] Regarding public health services' quality, options such as "received follow-up assessment and health examination for major diseases" and "participated in urban resident or employee medical insurance" in the questionnaire are set to 1, while other options are set to 0. The original data for the moderating variable of basic public health services are sourced from CMDS.

3 Results

3.1 Baseline regression

3.1.1 The net effect of internal migrants' health on economic resilience

Based on the identification strategy outlined earlier, this paper decomposes economic resilience into economic resistance and recovery ability, and empirically estimates the overall average effects of internal migrants' health on the economic resilience of CYRD. From the estimation Equations (1, 4) in Table 2, the net effects of internal migrants' health on economic resistance ability and recovery ability are both significantly positive, with marginal coefficients of 0.0186 and 0.0039, respectively. This indicates that migrants' health has a positive effect on economic resilience. Furthermore, for each one unit increase in internal migrants' health, the average of economic resistance ability and recovery ability increases by 0.0186 and 0.0039, respectively. Therefore, enhancing the health level of internal migrants in CYRD has significant effects on improving both economic resistance and recovery abilities. Comparatively speaking, the promotion effect of internal migrants' health on the economic resistance is particularly prominent.

As one of the most dynamic economic regions in China, CYRD accommodates a large number of internal migrants, totaling 73.573 million, accounting for 19.6% of the national internal migrants. The significant presence of internal migrants enriches the labor resources and human capital, driving concentrated economic development and ensuring the sustained and rapid advancement of urbanization. As a crucial component of the labor supply in CYRD, whether internal migrants can provide a continuous labor output becomes an important factor influencing the sustained and stable economic development and resilience of urban agglomerations, with labor supply being constrained by individual health levels. Therefore, enhancing the health level of internal migrants can inject new impetus into economic resilience.

The overall average effect estimation confirms that enhancing internal migrants' health significantly promotes the economic resilience of CYRD. However, since the employment sectors of internal migrants are mainly concentrated in the secondary and tertiary industries, further exploration of the heterogeneous effect of internal migrants' health on the economic resilience of different industries is of practical significance. To address this, this paper replaces the overall economic resilience variable with secondary and tertiary industry economic resilience variables,

5 The important diseases in the options mainly include occupational diseases, sexually transmitted diseases, AIDS, tuberculosis, chronic diseases, etc.

TABLE 2 Baseline regression estimation results.

	Dependent variable: resistance			Dependent variable: recovery		
	(1)	(2)	(3)	(4)	(5)	(6)
Health	0.0186***	0.0287***	0.0156***	0.0039*	0.0053*	0.0019
	(0.0009)	(0.0014)	(0.0007)	(0.0021)	(0.0028)	(0.0023)
Density	2.7961***	4.8351***	1.4841***	4.6642***	7.6793***	2.4146***
	(0.0907)	(0.1409)	(0.0677)	(0.3931)	(0.4581)	(0.3882)
Density* density	−9.9479***	−9.9813***	−2.8623***	−23.3391***	−35.7448***	−8.8158***
	(0.4598)	(0.7143)	(0.3429)	(2.0378)	(2.3746)	(2.0124)
Urbanization	1.0037***	0.4297***	0.1519***	−0.0134***	−0.0187***	−0.0060***
	(0.0140)	(0.0217)	(0.0104)	(0.0007)	(0.0008)	(0.0007)
Lnrjgdp	−1.6432***	−2.3943***	−1.0716***	0.3231***	0.0028	0.8226***
	(0.0137)	(0.0212)	(0.0102)	(0.0586)	(0.0683)	(0.0579)
Lnrjgdp* lnrjgdp	0.3767***	0.5715***	0.2597***	−0.1350***	−0.0597***	−0.2514***
	(0.0032)	(0.0050)	(0.0024)	(0.0154)	(0.0179)	(0.0152)
Trade	−0.0402***	−0.1789***	−0.0681***	−0.0818***	−0.1072***	−0.0041
	(0.0020)	(0.0030)	(0.0015)	(0.0048)	(0.0055)	(0.0047)
Lnfinance	−0.8760***	−1.8247***	−0.0261	−0.4994***	−0.8545***	−0.6401***
	(0.0195)	(0.0303)	(0.0145)	(0.0898)	(0.1047)	(0.0887)
Lnfinance*lnfinance	0.0539***	0.1216***	0.0010	0.0484***	0.0794***	0.0496***
	(0.0015)	(0.0024)	(0.0011)	(0.0074)	(0.0087)	(0.0073)
Lninnovation	0.0941***	0.1954***	0.0101***	0.1627***	0.1783***	0.1505***
	(0.0012)	(0.0019)	(0.0009)	(0.0052)	(0.0061)	(0.0052)
_Cons	4.6638***	8.3276***	1.9174***	1.4373***	2.8473***	−2.4392***
	(0.0611)	(0.0950)	(0.0456)	(0.2815)	(0.3281)	(0.2780)
F stats.	5704.1140***	3920.3034***	4590.4027***	384.5057***	384.0409***	359.8270***
R^2	0.6712	0.6838	0.6216	0.7578	0.7576	0.7454
Obs.	27960	27960	27960	1240	1240	1240

***P < 0.01, *P < 0.1, robust standard errors in parentheses. Equations (1, 4) represent the full sample estimation results; Equations (2, 5) represent the estimated results of the secondary industry sample; Equations (3, 6) represent the estimated results of the tertiary industry sample (the same below).

and re-conducts regression estimations to examine the industry heterogeneity of the effect of migrants' health on economic resistance and recovery abilities. The results of the other estimation equations in Table 2 show that, on the one hand, internal migrants' health positively promotes the economic resistance of both the secondary and tertiary industries, with marginal effects of 0.0287 and 0.0156, respectively. On the other hand, higher migrants' health levels also contribute to the improvement of economic recovery ability in the secondary industry, with a marginal effect of 0.0053. However, the effect of migrants' health status on economic recovery ability of the tertiary industry is not obvious. Comparatively, the effects of migrants' health on economic resistance of both the secondary and tertiary industries are significantly higher than that of economic recovery ability. Additionally, whether from economic resistance or recovery, the secondary industry economic resilience of CYRD is more sensitive to internal migrants' health.

Table 2 also presents the net effects of social, economic, and institutional factors on the economic resilience. From the estimation results of social factors, both for the overall sample and the secondary or tertiary industry samples, population density shows an inverted U-shaped trend in its impact on the economic resistance and recovery abilities. This indicates that increasing population density contributes to enhancing the economic resistance and recovery abilities of the urban agglomeration when population density is low. However, further increases in population density lead to congestion effects, weakening the economic resistance and recovery abilities. Thus, an appropriate level of population density is conducive to economic resilience. Additionally, the increase in urbanization rate has a promoting impact on the economic resistance ability, but suppresses economic recovery ability. The estimation results of economic factor control variables show that the effect of regional economic development level on the economic resistance ability exhibits a U-shaped trend, while its impact on economic recovery ability shows an inverted U-shaped trend. Moreover, the growth of foreign trade dependence is unfavorable for the economic resistance

TABLE 3 Heterogeneity analysis of resistance.

	High resistance (Resistance ability>1)			Low resistance (Resistance ability<1)		
	(1)	(2)	(3)	(4)	(5)	(6)
Health	0.0110*** (0.0007)	0.0037*** (0.0007)	0.0016*** (0.0007)	0.0001 (0.0004)	0.0070*** (0.0006)	0.0011*** (0.0004)
Control	Yes	Yes	Yes	Yes	Yes	Yes
_cons	2.1775*** (0.0959)	−4.5903*** (0.0863)	3.1543*** (0.1542)	14.9872*** (0.0861)	−23.7494*** (0.6312)	0.6999*** (0.0431)
F Stats.	5393.8901***	23287.9210***	10453.2312***	12038.4810***	3045.6910***	3240.3420***
R^2	0.7417	0.9202	0.7034	0.9294	0.7972	0.7705
Obs.	18,800	20,200	11,873	9,160	7,760	9,660

***P < 0.01.

TABLE 4 Heterogeneity analysis of recovery.

	High recovery (Recovery ability>1)			Low recovery (Recovery ability<1)		
	(1)	(2)	(3)	(4)	(5)	(6)
Health	0.0025** (0.0012)	0.0051* (0.0027)	0.0009 (0.0014)	0.0003 (0.0014)	0.0002 (0.0017)	0.0001 (0.0011)
Control	Yes	Yes	Yes	Yes	Yes	Yes
_cons	−1.8099*** (0.2013)	−2.0022*** (0.3077)	−0.0813*** (0.1323)	0.4725*** (0.0251)	0.1211*** (0.0414)	0.1285*** (0.0434)
F Stats.	153.6602***	129.0410***	134.9310***	2409.8400***	11.650***	12.650***
R^2	0.7226	0.7260	0.6662	0.9383	0.2546	0.2705
Obs.	601	498	687	639	282	294

***P < 0.01, **P < 0.05, *P < 0.1.

ability together with recovery ability. The estimation results of institutional factor control variables show that there is a U-shaped relationship between government expenditure level and economic resistance ability together with economic recovery ability. Furthermore, increasing government expenditure levels further enhances economic resilience. Innovation capability has a promoting impact on both economic resistance and recovery abilities of CYRD. Finally, the significance tests of the model confirm that the econometric model is well-specified.

3.1.2 Heterogeneity analysis of economic resilience

Section 2.2 divides economic resilience into four groups based on the magnitude of economic resistance and recovery abilities: High resistance, Low resistance, Fast recovery, and Slow recovery. This section further investigates the heterogeneous effect of internal migrants' health on the economic resistance and recovery abilities of CYRD according to different groups of economic resilience. The estimation results in Table 3 demonstrate that, whether for the high economic resistance sample or the low economic resistance sample, internal migrants' health significantly enhances the overall economic resistance as well as economic resistance of the secondary and tertiary industries. However, comparatively, the positive effect of internal migrants' health levels is more prominent in high economic resistance city samples. Table 4 reports the heterogeneous analysis results according to the grouping of economic recovery ability. The estimation results show that the coefficient of the internal migrants' health is only significantly positive in high economic recovery city samples and not significant in low economic recovery city samples, indicating that improving internal migrants' health levels only has a positive effect on high economic recovery city samples. In summary, the heterogeneous effect of internal migrants' health on economic resilience provides guidance for the precise policy-making of local governments.

3.2 Mediating effect test

Before identifying the mediating effects, the paper first tests the prerequisites for the existence of mediating effects based on the econometric model (5), and then examines the existence of them based on econometric models (6) and (8). The test results in Table 5 show that internal migrants' health has a significant effect on their LPR and labor time supply, meaning that the prerequisites for the existence of mediating effects are met. Specifically, each increase in the health level of internal migrants will effectively increase the labor participation rate by 9% in 2017 and 6% in 2015, while increasing the labor time supply by 1.5% in 2017 and 1.8 in 2015.

Looking at the estimated Equations (1, 2) from Table 6, the labor participation rate and labor time supply of the internal migrants have a positive effect on economic resistance ability, indicating that internal migrants' health does indeed indirectly affect the economic resistance ability by influencing their labor participation rate and labor time supply. Looking at the estimated Equations (5, 6) from Table 6, the labor participation rate and labor time supply of the internal migrants also have a positive effect on economic recovery ability, indicating that internal migrants' health also indirectly affects the economic recovery ability of CYRD through their labor participation rate and labor time

TABLE 5 Prerequisite testing for mediating effects.

	2017		2015	
	LFP	LN (Working_hours)	LFP	LN (Working_hours)
	(1)	(2)	(3)	(4)
Health	0.0891*** (0.0045)	0.0147*** (0.0050)	0.0553*** (0.0172)	0.0180** (0.0072)
Control	Yes	Yes	Yes	Yes
_cons	0.9691*** (0.0229)	4.4508*** (0.0150)	1.9171*** (0.0911)	4.2844*** (0.0991)
F Stats.	559.021***	540.020***	149.090***	9.0900***
R^2	0.7006	0.7111	0.6984	0.6230
Obs.	30000	25928	1358	827

tIn regression Equations (1, 2), individual attribute factors such as gender, age, education, marriage, Hukou status, and other personal characteristics that influence the labor participation rate and labor time supply of the floating population are controlled for. ***P < 0.01, **P < 0.05.

supply. In summary, the mediating effects based on the labor participation rate and labor time supply of the internal migrants significantly exist.

Subsequently, the paper further estimates the mediating effects based on econometric models (9) and (10). The estimated Equations (3, 4) in Table 6 show that, in addition to the direct effect on economic resilience of CYRD, the health of the internal migrants also has a mediating effect on economic resilience through influencing the labor participation rate and labor time supply. Specifically, the mediating effect of the labor participation rate on economic resilience is 0.01, and the mediating effect of labor time supply on economic resilience is 0.9%. Furthermore, according to the estimated Equations (7, 8) in Table 6, in addition to the direct effect on the economic recovery capability, the health of the internal migrants also has a mediating effect on the economic recovery capability through influencing the labor participation rate and labor time supply of internal migrants. Among them, the mediating effect of labor participation rate on economic recovery capability is 0.002, and the mediating effect of labor time supply on economic recovery capability is 0.6%. Thus, it is evident that the mediating effects of the labor participation rate and labor time supply on economic resilience are more pronounced.

3.3 Moderating effect test

Since the migrants' health status is related to the basic public health services of the city to which they belong, will basic public health services have a moderating effect on the health and economic resilience? For that, this paper further identifies the moderating effect based on econometric models (11) and (12). The moderating variables are public health services' accessibility and quality. The accessibility of public health services is characterized by residents' health records and health education, while public health services' quality is expressed by physical examinations of major diseases and urban medical insurance. The specific method for estimating the moderating effects is as follows: first, in the baseline regression direction, the interaction terms of internal migrants' health and the public health services' accessibility and quality are added separately for regression estimation; then, the interaction terms are simultaneously included in an analytical framework for regression estimation (Table 7).

The estimated Equations (1–3) have reported the moderating effects of public health services on the economic resilience. The results indicate consistent estimation results for the interaction terms between internal migrants' health and the accessibility and quality variables of basic public health services in three regression equations mentioned above. Therefore, this paper only analyzes the total regression estimation (Equation 3). On the one hand, the moderating effect mechanism of the basic public health services' accessibility has played a significant role, as enhancing public health services' accessibility helps strengthen the positive effect of internal migrants health on economic resilience. Specifically, the moderation effect of establishing residents' health records is 0.0129, and the moderation effect of conducting health education is 0.0029. On the other hand, the moderating effect mechanism of basic public health services' quality also partly plays a positive moderating role. Implementing crucial illness examinations can significantly enhance the positive effect of internal migrants' health on economic resilience, with a moderation effect of 0.0106. However, increasing urban medical insurance cannot significantly enhance the positive moderating effect of internal migrants' health on economic resilience.

Meanwhile, this paper also estimates the moderating effects of public health services on the economic recovery of CYRD. Considering that the interaction terms between internal migrants' health and public health services' accessibility and quality also yield consistent estimation results in regression (Equations 4 6), this section also only elaborates on the estimation results of Equation (6). Overall, both the mechanisms of the basic public health services' accessibility and quality play positive moderating roles. Enhancing the accessibility and quality of public health services is beneficial for strengthening the positive effect of migrants' health on economic resilience. For basic public health services' accessibility, the moderation effect of establishing residents' health records is 0.0029, and the moderation effect of conducting health education is 0.0098; for public health services' quality, the moderation effect of implementing important disease health examinations is 0.0061, and the moderation effect of increasing urban medical insurance is 0.0060.

4 Conclusions

This study deconstructed economic resilience into resistance ability and recovery ability, analyzed the net effect and its heterogeneity of internal migrants' health on economic resilience in CYRD, and further investigated the mediating effect from labor participation rate and labor time supply of the internal migrants, as well as the moderating effect of public health services. The following findings were obtained: firstly, internal migrants' health has a significant positive effect on the economic resilience of CYRD. Specifically, for each unit increase in the health status of internal migrants, the average growth of economic resilience increases by 0.0186, and the average growth of economic recovery increases

TABLE 6 Regression results of mediating effects.

	Dependent variable: resistance				Dependent variable: recovery			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Health			0.0174*** (0.0009)	0.0228*** (0.0109)			0.0036*** (0.0013)	0.0020* (0.0013)
LFP	0.0134*** (0.0012)		0.0105*** (0.0012)		0.0033*** (0.0009)		0.0020* (0.0013)	
LN (Working_hours)		0.0086*** (0.0013)		0.0092*** (0.0013)		0.0050*** (0.0011)		0.0055* (0.0036)
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
_cons	4.6717*** (0.0614)	4.6256*** (0.0667)	4.6526*** (0.0611)	4.6033*** (0.0662)	0.8768*** (0.0494)	0.3587*** (0.0552)	1.4398*** (0.2816)	1.4610*** (0.3483)
F Stats.	5624.600***	4808.560***	5208.210***	4488.800***	10571.220***	9295.060***	349.440***	183.820***
R^2	0.6680	0.6647	0.6721	0.6706	0.7454	0.7496	0.7579	0.7326
Obs.	27960	24262	27960	24262	36120	31059	1240	750

***P < 0.01, *P < 0.1.

TABLE 7 Regression estimation results of moderating effects.

	Dependent variable: resistance			Dependent variable: recovery		
	(1)	(2)	(3)	(4)	(5)	(6)
Health	0.0098*** (0.0015)	0.0055** (0.0023)	0.0067** (0.0030)	0.0035** (0.0015)	0.0075* (0.0040)	0.0059* (0.0034)
Health_records	0.0063** (0.0031)		0.0263** (0.0120)	0.0069*** (0.0023		0.0110*** (0.0007)
Health_education	0.0052** (0.0024)		0.0053*** (0.0009)	0.0423** (0.0218)		0.0110*** (0.0007)
Physical_examination		0.0054*** (0.0010)	0.0159* (0.0101)		0.0192*** (0.0032)	0.0110*** (0.0007)
Medical_insurance		0.0035*** (0.0009)	0.0016*** (0.0009)		0.0078** (0.0033)	0.0110*** (0.0007)
Health*health_records	0.0001 (0.0026)		0.0129** (0.0069)	0.0029* (0.0016)		0.0039** (0.0017)
Health*health_education	0.0150*** (0.0020)		0.0029** (0.0013)	0.0098* (0.0061)		0.0105* (0.0063)
Health*physical_examination		0.0106** (0.0057)	0.0159*** (0.0061)		0.0041** (0.0019)	0.0061** (0.0033)
Health*medical_insurance		0.0047 (0.0054)	0.0039 (0.0054)		0.0052** (0.0024)	0.0060* (0.0034)
Control	Yes	Yes	Yes	Yes	Yes	Yes
_cons	4.6776*** (0.0652)	4.7733*** (0.2676)	5.0269*** (0.2881)	1.5026*** (0.2826)	2.2471*** (0.3550)	2.2809*** (0.3599)
F Stats.	3681.3601***	234.6330***	174.8310***	276.2303***	124.4710***	96.7220***
R^2	0.6746	0.7016	0.7088	0.7594	0.7314	0.7324
Obs.	24871	1412	1312	1240	1655	655

***P < 0.01, **P < 0.05, *P < 0.1.

by 0.0039. Secondly, the net effect of internal migrants health on economic resilience exhibits significant structural differences, industry disparities, and regional heterogeneity. Among them, the impact of internal migrants health on the economic resilience is significantly higher than on economic recovery; the marginal effect of internal migrants health on the resilience of the secondary industry economy is significantly higher than that on the tertiary industry; and cities with high economic resilience and recovery demonstrate a more prominent promotion effect of internal migrants health levels. Thirdly, apart from directly affecting the economic resilience and recovery, the health of internal migrants also exerts indirect effects through their impact on labor force participation rates and labor supply hours, thereby influencing economic resilience and recovery. The mediating effects of labor force participation rates on economic resilience and recovery are 0.01 and 0.002 respectively, while the mediating effects of labor supply hours on economic resilience and recovery are 0.009 and 0.006 respectively. Fourthly, basic public health services have a significant positive moderating effect on the relationship between internal migrants' health and economic resilience. Enhancing the basic public health services accessibility and quality contributes to strengthening the positive effects of internal migrants' health on economic resilience.

Improving the resilience of urban or urban agglomeration economies is not only an intrinsic requirement for enhancing urban competitiveness but also a necessary path to achieve high-quality and sustainable urban development. Currently, external shocks represented by public health emergencies frequently occur,

severely affecting the health status and labor supply levels of urban labor forces, thereby weakening the risk resistance capabilities of urban and urban agglomeration economies. Therefore, efforts to enhance urban and urban agglomeration economic resilience should not only focus solely on upgrading economic and industrial structures, optimizing infrastructure, and increasing the number of labor forces but also address health issues among urban labor forces, especially internal migrants. Firstly, community and public health service centers are the most direct, effective, and economical ways for internal migrants to obtain health resources. Establishing health education points in communities and public health service centers can help improve the health awareness and disease prevention capabilities of internal migrants. Secondly, internet digital platforms and face-to-face education should be fully leveraged and new media such as the Internet, WeChat public accounts, and mobile apps can be ways to broaden the channels and methods of health education dissemination. Thirdly, improve the health records management, strengthen the dynamic monitoring of health data for internal migrants, and help them improve their health literacy and health levels. Finally, expand the coverage of important disease health examinations and urban medical insurance to benefit all internal migrants, thereby increasing their health levels while reducing health expenditures. In summary, enhancing the basic public health services can increase labor supply by improving the health levels of internal migrants, thereby consolidating the economic resilience of cities.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the (patients/ participants OR patients/participants legal guardian/next of kin) was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

SZ: Conceptualization, Supervision, Visualization, Writing – original draft. YD: Data curation, Formal analysis, Methodology, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Does the digital economy improve comprehensive total factor productivity in China?

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Total factor productivity is an important symbol of high-quality economic development. At present, the question of whether the digital economy can infuse fresh impetus into enhancing total factor productivity has emerged as a prominent concern in China. This paper constructs a new undesirable output to measure comprehensive total factor productivity (CTFP) with the slack-based measure (SBM) undesirable Malmquist-Luenberger index by using 2011-2020 Chinese provincial panel data. Then, this paper explores the impact of the digital economy (DIG) on CTFP with a fixed effects (FE) panel model and a mediating effect model. The results show that CTFP increases by an average of 3.9%, technical efficiency contributes -1.1%, and the contribution rate of technological progress is 5.0%. Technological progress is the main source of CTFP growth. The empirical findings show that the DIG has a positive and significant impact on CTFP. This paper conducts various robustness tests, and the results remain consistent with the previous conclusion. Moreover, mechanism tests suggest that the promoting effect of the DIG on CTFP can be attributed to three main effects: technological innovation, the factor endowment structure and the educational level. Furthermore, the results of heterogeneity analysis demonstrate that the promoting effect of the DIG on CTFP exists in China's eastern, central and western regions. The findings of this research can serve as a valuable reference for informing decision-making processes related to environmental governance and high-quality economic development in China.

KEYWORDS

digital economy, technological innovation, factor endowment structure, human capital, comprehensive total factor productivity, mediating effect model

1 Introduction

Since the 1970s, China's annual economic growth of 10% has been accompanied by environmental pollution, ecological degradation and an excessive consumption of resources (1, 2). However, the report of the 20th National Congress of the Communist Party of China pointed out that promoting green and low-carbon economic and social development is a key link in achieving high-quality development. As an important engine of economic growth, total factor productivity incorporating environmental factors has increasingly become a core indicator in measuring the quality of national or regional economic growth (3, 4). This paper refers to total factor productivity in terms of comprehensive total factor productivity (CTFP), which is the measure of total factor productivity when the comprehensive environmental pollution index is included as an undesirable output.

At present, many countries worldwide regard improving the level of digital economy (DIG) development as one of the paths for high-quality economic development, and China is one such

country. The "White Paper on the Development of China's Digital Economy (2023)" pointed out that the scale of the DIG reached 50.2 trillion RMB in 2022, accounting for 41.5% of GDP, and the DIG has made an enormous contribution to the growth of China's national economy. The DIG has distinctive features, such as high speed, high innovation, low cost, low pollution, replicability, and shareability. With data elements as the core, the DIG has played a critical role in stimulating consumption and investment and in promoting technological change. The production link has greatly changed the mode of production and consumption as well as people's way of life, and the DIG is a new engine for improving the efficiency of overall social resource allocation (5, 6).

The literature on total factor productivity measurement with data envelopment analysis (DEA) is mainly divided into two types. On the one hand, some authors treat environmental pollution factors as input factors, but this method does not conform to the actual production process (7, 8). On the other hand, other scholars treat environmental pollution as an undesirable output to measure total factor productivity. The main difference is the choice of the elasticity of environmental pollution variables, such as an environmental pollutant (9, 10), two environmental pollutants (11, 12), three types of industrial waste (13), and a variety of environmental pollutants (14). The research above has not reached a unified conclusion; if the undesirable outputs (the selected environmental pollutants) are different, the measurement results of total factor productivity will also be different.

The academic community presents three different views on the impact of DIG development. First, some scholars believe that digital transformation promotes the economic benefits of real enterprises by reducing costs, improving asset utilization efficiency, and enhancing innovation capabilities. The DIG is characterized by low energy consumption and low pollution emissions. Meanwhile, the characteristics of reproducibility and shareability make data resources overcome the limitations of the traditional law of diminishing marginal returns. The DIG may also reduce environmental pollutants in various ways, thereby improving total factor productivity and ultimately promoting high-quality economic development (15–18). Second, the DIG may have a negative impact on total factor productivity. The application of artificial intelligence technology has a complex effect on total factor productivity. An overreliance on artificial intelligence technology will inhibit total factor productivity growth. Meanwhile, digitization has intensified the competition among enterprises and increased the cost pressure. Some studies have pointed out that the excessive use of artificial intelligence technology will have a certain substitution effect on low-end labor, resulting in an improper allocation of capital and labor and thus damaging production efficiency (19, 20). A third view holds that there is no linear effect between the DIG and total factor productivity. In the early stage of economic development, the technological progress brought by the DIG causes enterprises to reset their production equipment and increase their production by increasing resource extraction and energy consumption. Information technology and the real economy are not fully integrated, and the effect of the DIG cannot be effectively released (21, 22). However, most current studies focus on the impacts of the DIG on total factor productivity, with the combined impact being neglected.

The marginal contributions of this research are mainly as follows. First, this paper constructs a comprehensive environmental pollution index as a new undesirable output to measure CTFP in China with the slack-based measure (SBM) undesirable Malmquist–Luenberger index. Second, this paper clarifies the mechanisms of the direct and indirect effects of the DIG on CTFP, which is a useful supplement to existing research. Third, to explore the specific ways in which the DIG affects CTFP, a mediating effect model including technological innovation, the factor endowment structure and human capital is constructed to explore the transmission mechanisms.

The remainder of this study is organized as follows. Section 2 proposes the theoretical analysis and hypotheses. Section 3 presents the research design, including the samples, data, variables, and methods. Section 4 discusses the empirical results. Section 5 draws the conclusions and policy implications. The technical roadmap of this study is shown in Figure 1.

2 Theoretical analysis and hypothesis development

2.1 Direct impact of the dig on CTFP

The theoretical logic based on which the DIG drives up CTFP is mainly reflected in the three important aspects. First, the DIG is a new

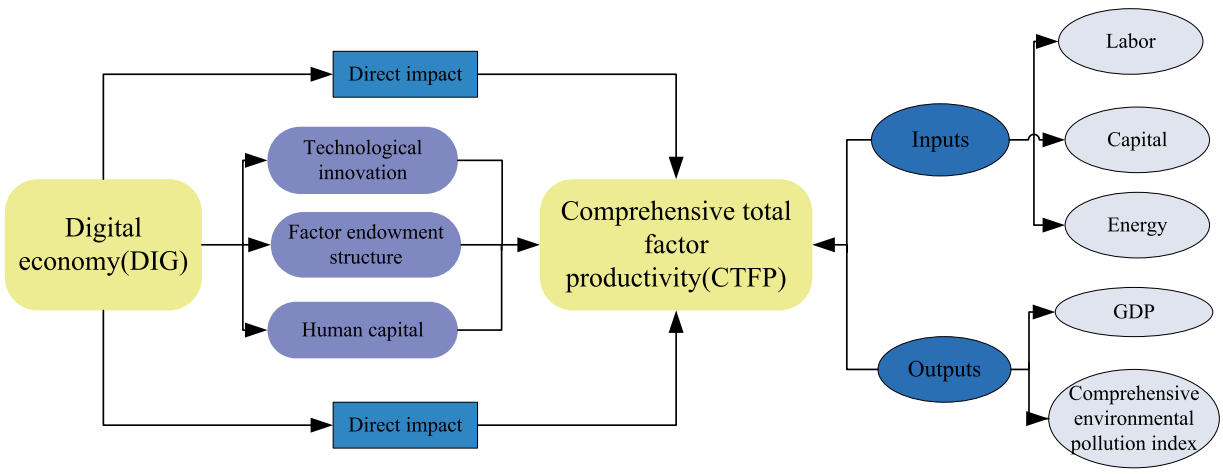

FIGURE 1
The technical roadmap.

economic model that expands and extends the boundaries of production possibility, changes the constraints of the scale economy under the traditional model, makes new assumptions regarding factors such as labor and capital, and reduces the excessive consumption of factors such as resources and the environment, which ultimately improves the production efficiency of enterprises (4). Second, the DIG itself has spawned a series of innovative technologies, such as artificial intelligence and cloud computing, which have minimized the intermediate links of transactions and reduced transaction costs. At the same time, digital platforms and data analysis can enhance the interaction between producers and consumers, alleviate the mismatch between supply and demand, and thus improve CTFP (23). Third, the traditional economic development model characterized by energy depletion and environmental degradation will lead to high pollution and high energy consumption, which is contrary to the connotation of high-quality economic development. Data elements in the DIG can replace traditional labor and capital, reduce environmental pollution and energy consumption, and are one of the important ways to improve total productivity (16). Therefore, based on the analysis above, this paper proposes the following hypothesis:

> *H*1: The DIG will improve CTFP.

2.2 Mechanisms of the effect of the dig on CTFP

The digital economy, as a permeable factor, not only directly impacts overall green productivity but also potentially exerts an indirect influence. Solow (24) defined total factor productivity as the economic growth rate after accounting for labor and capital contributions. Technological innovation, factor endowment structure, and human capital are considered crucial factors affecting total factor productivity. Additionally, DIG may impact CTFP through other unobservable channels. Due to data availability and the definition of total factor productivity, this paper focuses on three specific channels through which DIG affects CTFP: technological innovation, factor allocation structure, and human capital.

2.2.1 Technological innovation effect

Technological innovation holds great significance for improving CTFP. Technological innovation plays an important role in environmental protection and sustainable development and provides a valuable way to reduce carbon emissions (25). Big data technology can track the flow of financial resources, weaken adverse selection and moral hazard, promote the output of innovative achievements, realize process re-innovation, transform polluting enterprises with high losses and low output, and realize pollution reduction and carbon reduction. Furthermore, big data, cloud computing, etc., can conduct for an integrated analysis of green product information and consumption preferences, which not only directly improves the production capacity of enterprises but also reduces the energy consumption per unit product by improving the energy efficiency of products and processes. Digital technology can also help make manufacturers' innovation be data driven, improve the efficiency of green technology research and development (R&D) decision-making, and effectively reduce environmental pollution and carbon emissions (26). Hence, this paper proposes the following hypothesis:

> *H*2: The DIG promotes CTFP by driving technological innovation.

2.2.2 Factor endowment structure effect

The DIG may promote CTFP by optimizing the factor endowment structure. The emergence of DIG platforms can effectively alleviate the information asymmetry problem in the market, effectively reducing search, matching, transaction and replication costs (27). Furthermore, the DIG accelerates the cross-regional flow of production factors, leading to the gradual transfer of production factors to enterprises or departments with high productivity and high marginal returns. In particular, it guides the flow and concentration of production factors to green and low-carbon enterprises under the background of increasingly stringent environmental regulation, improves the efficiency of resource allocation, promotes the transformation of resource-consuming enterprises to technological innovation-driven enterprises, and ultimately improves total factor productivity (28). Hence, this paper proposes the following hypothesis:

> *H*3: The DIG promotes CTFP by driving the factor endowment structure.

2.2.3 Human capital effect

The development of the DIG has enabled online platform activities to continuously supplement offline agglomeration activities, which not only overcomes the geographical limitations of offline human capital agglomeration but also maintains the online agglomeration activities of human capital. The industrial agglomeration and coordinated development driven by the DIG attract more high-tech enterprises and high-skilled talent, and the resulting scale economies can further reduce the R&D costs of enterprises and promote an improvement in the level of innovation and R&D. Digital platforms have accelerated the spillover and diffusion of cutting-edge technologies in the industrial network, ultimately improving total factor productivity (4). Digital platforms bring a rapid flow of human capital, which can effectively guide the operation of material capital so that high-tech material capital can match the high-level labor force. Human capital can greatly affect technology R&D and application to promote the development of productivity and an improvement in labor productivity. Hence, this paper proposes the following hypothesis:

> *H*4: The DIG promotes CTFP by driving human capital.

3 Research design

3.1 Methods

To examine the impact of DIG development on CTFP, the basic regression model of the relationship between the DIG and CTFP is constructed, as shown in Equation (1):

$$CTFP_{it} = \alpha_0 + \alpha_1 DIG_{it} + \alpha_2 \mathrm{Cont}_{it} + \varepsilon_{it} \quad (1)$$

In Equation (1), i and t represent the region and year, respectively; ε is the error term; and α is the coefficient. CTFP represents the dependent variable, DIG represents the level of DIG development, and Cont represents all the control variables. The first hypothesis suggests that a one-unit change in DIG will result in α_1 corresponding unit change in CTFP, assuming all other variables remain constant in Equation (1).

In addition to the total effect embodied in Equation (1), the DIG may have an indirect impact on CTFP through some mediating mechanisms. According to the research hypotheses above, the DIG may improve CTFP through technological innovation, the factor endowment structure and human capital. Therefore, the following mediating effect model is established in this paper:

$$M_{it} = \beta_0 + \beta_1 DIG_{it} + \beta_2 Cont_{it} + \varepsilon_{it} \tag{2}$$

$$CTFP_{it} = \gamma_0 + \gamma_1 DIG_{it} + \gamma_2 M_{it} + \gamma_3 Cont_{it} + \varepsilon_{it} \tag{3}$$

M represents the mediating variables, which are technological innovation (RD), the factor endowment structure (KL) and human capital (HC). The other variables are defined the same as in Equation (1). Based on hypotheses 2–4, the study initially assesses the impact of DIG on the mediating variables, as depicted in Equation (2). Significance of coefficient β_1 indicates a substantial influence of DIG on the mediating variables. Subsequently, both DIG and the mediating variables are integrated into the model, as illustrated in Equation (3). If coefficients γ_1 and γ_2 are significant, it suggests that DIG affects CTFP through intermediary variables.

3.2 Variables

3.2.1 Dependent variable

When DEA is used to measure CTFP, the Luenberger productivity index can compensate for the shortcomings of the Malmquist index and Malmquist–Luenberger productivity index. The decrease in "bad" output and the increase in "good" output fit the farthest-point distance function. Therefore, this study selects a model that combines the SBM undesirable model containing undesirable output and the Luenberger productivity index to calculate CTFP.

For a specific $DMU_0\left(x_0, y_0^g, y_0^b\right)$, Tone (29) proposed an SBM undesirable model including both "good" and "bad" outputs. This model solved the slack problem of input–output variables. The model is shown in Equation (4):

$$\vec{S}_C^{\,t}\left(x_k^t, y_k^t, b_k^t\right) = \rho^* = min \frac{1 - \frac{1}{m}\sum_{i=1}^{m} \frac{s_i^-}{x_{i0}}}{1 + \frac{1}{s_1 + s_2}\left(\sum_{r=1}^{s_1} \frac{s_r^g}{y_{r_0}^g} + \sum_{r=1}^{s_2} \frac{s_r^b}{y_{r0}^b}\right)}$$

$$s.t. \begin{cases} x_0 = X\lambda + s^- \\ y_0^g = Y^g\lambda - s^g \\ y_0^b = Y^b\lambda + s^b \\ \lambda \geq 0, s^- \geq 0, s^g \geq 0, s^b \geq 0 \end{cases} \tag{4}$$

where t is the period (2011–2020), k is 30 Chinese provinces, s^g is the expected output shortage, and s^- and s^b represent the excess of inputs and the excess of undesirable outputs, respectively. The objective function ρ^* is strictly decreasing with respect to s^-, s^g, and s^b.

On the basis of Equation (4) and the ideas of Chambers et al. (30), the CTFP index is constructed from period t to period t + 1 (see Equation 5):

$$\begin{aligned} CTFP(x^{t+1}, y^{t+1}, f^{t+1}; x^t, y^t, f^t) &= \left(\frac{\vec{S}_C^{\,t}(x^{t+1}, y^{t+1}, b^{t+1})}{\vec{S}_C^{\,t}(x^t, y^t, b^t)} \times \frac{\vec{S}_C^{\,t+1}(x^{t+1}, y^{t+1}, b^{t+1})}{\vec{S}_C^{\,t+1}(x^t, y^t, b^t)} \right)^{1/2} \\ &= \frac{\vec{S}_C^{\,t+1}(x^{t+1}, y^{t+1}, b^{t+1})}{\vec{S}_C^{\,t}(x^t, y^t, b^t)} \times \left(\frac{\vec{S}_C^{\,t}(x^{t+1}, y^{t+1}, b^{t+1})}{\vec{S}_C^{\,t+1}(x^{t+1}, y^{t+1}, b^{t+1})} \times \frac{\vec{S}_C^{\,t}(x^t, y^t, b^t)}{\vec{S}_C^{\,t+1}(x^t, y^t, b^t)} \right)^{1/2} \\ &= TEC\left(x^{t+1}, y^{t+1}, b^{t+1}; x^t, y^t, b^t\right) \times EFF\left(x^{t+1}, y^{t+1}, b^{t+1}; x^t, y^t, b^t\right) \end{aligned} \tag{5}$$

where EFF and TEC represent the changes in technical efficiency and technological progress from t to t + 1, respectively. If the values of CTFP, EFF and TEC are greater than 1, they mean CTFP growth, technical efficiency growth and technological progress improvement, respectively; if the values of CTFP, EFF and TEC are less than 1, they mean CTFP decline, technical efficiency deterioration and technological regression, respectively.

Three inputs and two outputs are selected for measuring CTFP: the three inputs are employed persons, the capital stock and total energy consumption, and the two outputs are desirable and undesirable outputs. The desirable output is regional GDP (13). To remove the effects of inflation, GDP is measured in 2010 constant prices. The undesirable output is the comprehensive environmental pollution index, which uses the entropy method to combine $PM_{2.5}$ pollution with wastewater emissions, general solid waste production, sulfur dioxide emissions, nitrogen oxide emissions, and smoke dust emissions. Employed persons are measured as the number of employees at the end of the calendar year (12). The capital stock is the total existing capital resources of each province, and it is calculated by the perpetual inventory method (11). The equation is $K_{it} = I_{it} + (1 - \delta_{it})K_{it-1}$, where K_{it} represents the actual capital stock of province i in year t and I_{it} represents fixed asset investment in province I in year t. In addition, considering the comparability problem, the total fixed asset investment in each province is deflated using the fixed asset investment price index, with 2010 as the base period. At the same time, the initial capital stock in 2010 is represented by dividing fixed asset investment by 10%, and the depreciation rate δ_{it} is equal to 9.6% (31). Total energy consumption is the direct creator of environmental pollution and a major contributor to GDP growth (32).

3.2.2 Independent variable

The measurement of the DIG draws on the method of Zhao et al. (33) and involves relevant indicators from five levels: the internet penetration rate, the number of internet-related employees, internet-related output, digital financial inclusion development, and the number of mobile internet users (see Table 1).

The five-level indicators in Table 1 are dimensionally reduced by the entropy method and condensed into a comprehensive DIG index. The adoption of the entropy method in this paper is motivated by the following reasons: Firstly, it eliminates the need for expert scoring or subjective valuation, thereby mitigating the influence of human bias. Secondly, it enables analysis of the correlation between indicators and adjustment of weights

TABLE 1 Digital economy evaluation index system.

Secondary indicators	Tertiary indicators	Indicator explanation
Internet penetration rate	Internet users per 100 people	Reflects the internet penetration in each city
Number of internet-related employees	Proportion of employees in computer services and software	Reflects the degree of development of the digital economy
Internet-related output	Number of mobile Internet users	Reflects the degree of internet demand in each city
Digital financial inclusion development	China digital financial inclusion index	Reflects the degree of development of digital finance
Number of mobile internet users	Number of mobile phones per 100 people	Reflects the popularity of telecommunications

TABLE 2 Descriptive statistics of the digital economy.

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Average	0.131	0.197	0.263	0.293	0.341	0.344	0.409	0.501	0.590	0.657
Min	0.077	0.139	0.196	0.233	0.280	0.287	0.352	0.428	0.504	0.556
Max	0.314	0.399	0.479	0.521	0.586	0.565	0.639	0.773	0.895	0.982
Stedv.	0.052	0.057	0.062	0.062	0.066	0.059	0.063	0.076	0.085	0.089

Calculated based on the entropy method combined with the index system in Table 1.

accordingly, thus enhancing the accuracy of comprehensive evaluation. The calculation process for the entropy method is illustrated in formulas (6)–(11). The comprehensive DIG index of each province from 2011 to 2020 is calculated; Table 2 presents the descriptive statistics of the DIG. The table shows that from 2011 to 2020, the level of DIG development was very different, and the level of DIG development showed an upwards trend over time. We take 2011 and 2020 as examples. In 2011, the top five provinces were Beijing, Shanghai, Guangdong, Zhejiang and Fujian, while the bottom five were Yunnan, Henan, Jiangxi, Gansu and Guizhou. In 2020, the top five provinces were Beijing, Shanghai, Zhejiang, Guangdong, and Tianjin, while the bottom five were Jilin, Hunan, Jiangxi, Hebei and Heilongjiang. Comparing 2011 and 2020, the level of DIG development of the top-ranked provinces changed slightly, while the level of DIG development of the bottom-ranked provinces changed greatly. These findings indicate that provinces with a good foundation for DIG development give full play to their own advantages and widen the gap with other provinces.

$$x_{ij} = \frac{x_{ij} - \min\{x_j\}}{\max\{x_j\} - \min\{x_j\}} \tag{6}$$

Where $\max\{x_j\}$ is the maximum value of the indicator in all years; $\min\{x_j\}$ is the minimum value of the indicator in all years; x_{ij} is the result of dimensionless.

$$w_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{7}$$

Where w_{ij} represents the proportion of j indicators in year i.

$$e_j = -\frac{1}{lnm}\sum_{i=1}^{m}\left(w_{ij} \times \ln w_{ij}\right) \tag{8}$$

Where e_j represents the information entropy of the indicator.

$$d_j = 1 - e_j \tag{9}$$

Where d_j represents the information entropy redundancy.

$$\varphi_j = \frac{d_j}{\sum_{i=1}^{m} d_j} \tag{10}$$

Where φ_j represents the index weight.

$$DIG_i = \sum_{j=1}^{m} \varphi_j \times w_{ij} \tag{11}$$

Where DIG_i represents digital economy development level of each province.

3.2.3 Control variables

Referring to the literature (1–3, 32), this study controls for the following variables that may affect CTFP. (i) Economic development level (PGDP). This variable is expressed by *per capita* GDP, which is used to measure the impact of regional economic development on CTFP (9). (ii) Population agglomeration (POP). This variable is expressed by the population per unit area, and the square term of POP is introduced to investigate whether there is a non-linear relationship between population agglomeration and CTFP (12). (iii) Environmental regulation (ENVR). This variable is expressed by the proportion of environmental governance investment in GDP. It is used to measure the impact of the level of environmental regulation on CTFP (18). (iv) Economic openness (FDI). This variable is expressed by the proportion of the actual use of foreign direct investment in GDP and is denoted by FDI. It is used to examine the impact of

foreign direct investment on CTFP (32). (v) Industrial structure (ST). This variable is expressed by the ratio of the added value of the secondary industry to the added value of the tertiary industry. It is used to verify the influence of the rationality of the industrial structure on CTFP (32).

3.2.4 Mediator variables

Based on the theoretical analysis above, this paper selects the following mediator variables. (i) Technological innovation (RD). This variable is expressed by the ratio of R&D expenditure to GDP. It is mainly used to examine the impact of the level of expenditure on science and technology on CTFP (16). (ii) Factor endowment structure (KL). This variable adopts the ratio of the capital stock to the number of laborers in each province. Its purpose is to examine the influence of the rationality of factor endowments on CTFP to further optimize resource allocation (17). (iii) Human capital (HC). This variable is expressed by the *per capita* years of education (34). The calculation method is as follows: *per capita* years of education = (the number of illiterate people * 1 + the number of people with a primary school education * 6 + the number of people with a junior high school education * 9 + the number of people with a high school and technical secondary school education * 12 + the number of people with a college degree or above *16)/the total population older than 6.

3.2.5 Data and statistical description

The data on the three inputs as well as GDP, wastewater emissions, general solid waste production, sulfur dioxide emissions, nitrogen oxide emissions, and smoke dust emissions are from the China Statistical Yearbooks (2012–2021), the China Energy Statistics Yearbooks (2012–2021) and the China Environmental Statistical Yearbooks (2012–2021). PM2.5 pollution concentration data are obtained from the International Geoscience Information Network Center of Columbia University and processed with ArcGIS 10.0 software (1, 32). The CTFP indicator is calculated by the CTFP model. The DIG indicator is from the China Statistical Yearbook and the Digital Finance Research Center of Peking University and is calculated by the entropy method. The data on other control variables are from the 2012–2021 China Statistical Yearbook and provincial statistical yearbooks. The descriptive statistics are shown in Table 3.

4 Results and discussion

4.1 Measurement of CTFP and the decomposed effects

MaxDEA 6.16 software is combined with Equation (5) to measure the CTFP and decomposed effects of 30 Chinese provinces from 2011 to 2020. The results are provided in Table 4.

(1) Changes in and decomposed effects on China's CTFP. Table 4 shows that from 2011 to 2020, the average growth rate of the CTFP index was 7.82%, of which EFF contributed 0.18% and TEC contributed 7.77%. From the perspective of the decomposed effects, both EFF and TEC could improve China's CTFP, but TEC was the main source of power.

TABLE 3 Descriptive statistics of the variables.

Variable	Variable	Unit	Mean	SD	Min	Max
Input	Employed persons	10,000 persons	2703.55	2155.50	279.00	7150.25
	Capital stock	100 million	106786.50	90953.48	10512.23	298851.11
	Total energy consumption	10,000 tce	15200.83	12119.25	1601.00	41826.80
Desired output	GDP	100 million yuan	23589.36	18439.97	1519.23	93014.74
Undesired output	Environmental pollution comprehensive index	–	48883.38	40979.25	6557.08	181211.54
Dependent variable	CTFP	–	1.43	0.467	0.91	5.14
Independent variable	DIG	–	0.37	0.17	0.08	0.98
Control variables	PGDP	RMB	8920.77	13908.29	160.82	127760.7
	POP	Person/ square kilometer	466.50	697.17	7.89	3922.86
	ENVR	%	1.32	0.77	0.22	4.24
	FDI	%	0.02	0.02	0.00	0.08
	ST	%	0.93	0.33	0.06	1.90
Mediator variables	RD	%	1.62	1.07	0.33	6.01
	KL	RMB/person	42.77	17.39	19.16	116.65
	HC	year	9.32	0.89	7.68	12.78

"–" means there is no unit, and the result is calculated by the entropy method.

TABLE 4 Descriptive statistical results of CTFP and the decomposed effects.

Regions/ Variables		2011–2012	2012–2013	2013–2014	2014–2015	2015–2016	2016–2017	2017–2018	2018–2019	2019–2020	Avg.
China	CTFP	1.077	1.085	1.049	1.079	1.077	1.039	1.129	1.059	1.110	1.078
	TEC	1.071	1.071	1.057	1.084	1.081	1.035	1.123	1.089	1.088	1.078
	EFF	1.006	1.013	0.993	0.996	0.998	1.004	1.005	0.978	1.021	1.002
ERC	CTFP	1.096	1.081	1.069	1.104	1.101	1.058	1.140	1.051	1.153	1.095
	TEC	1.094	1.083	1.063	1.108	1.099	1.047	1.148	1.057	1.078	1.086
	EFF	1.001	0.998	1.005	0.997	1.003	1.011	0.994	0.995	1.070	1.008
CRC	CTFP	1.071	1.105	1.020	1.053	1.065	1.043	1.113	1.084	1.081	1.070
	TEC	1.061	1.075	1.054	1.083	1.060	1.020	1.128	1.074	1.071	1.070
	EFF	1.010	1.028	0.968	0.975	1.005	1.022	0.986	1.009	1.009	1.001
WRC	CTFP	1.064	1.074	1.050	1.072	1.060	1.018	1.130	1.050	1.088	1.067
	TEC	1.054	1.057	1.052	1.059	1.079	1.033	1.096	1.133	1.110	1.075
	EFF	1.009	1.017	0.999	1.011	0.987	0.985	1.030	0.938	0.982	0.995

Data source: Calculated using MaxDEA 6.16 software.

TABLE 5 Benchmark regression results.

Variable	Dependent variable: CTFP		
	(1)	(2)	(3)
Estimation method	OLS	RE	FE
Constant	−0.050 (−0.34)	0.052 (0.23)	7.456** (2.18)
LnDIG	0.344*** (12.99)	0.330*** (13.89)	0.319*** (12.37)
LnPGDP	0.056*** (5.40)	0.045*** (4.31)	0.041*** (3.69)
LnPOP	0.061 (1.40)	0.063 (0.78)	−3.030** (−2.56)
$LnPOP^2$	−0.004 (−0.99)	−0.004 (−0.51)	0.299*** (2.83)
LnENVR	−0.035* (−1.72)	−0.059*** (−2.60)	−0.065*** (−2.65)
FDI	−1.936** (−2.25)	−3.074*** (−3.19)	−3.131*** (−2.96)
LnST	0.081*** (2.93)	0.033 (1.10)	0.011 (0.34)
R2	0.584	0.675	0.687
OBS	300	300	300
F statistic	$F(29, 263) = 6.11$, Prob>F = 0.0000		
Hausman tests	chi2(8) = 55.64, Prob>F = 0.0000		

The values in parentheses are *t*-values; *, **, and *** indicate that the estimated coefficients are significant at the 10, 5, and 1% levels, respectively. OLS, RE, and FE represent mixed effects estimation, random effects estimation, and fixed effects estimation, respectively. The asterisks in the following tables have the same meaning as the notes here.

(2) The trend and decomposition of CTFP in different regions. From 2011 to 2020, the average growth rate of the CTFP index in the eastern region was 9.48%, of which the contribution rate of EFF was 0.84% and the growth rate of TEC was 8.63%. From 2011 to 2020, the average growth rate of the CTFP index in the central region was 7.05%, of which the contribution rate of EFF was 0.13% and the contribution rate of TEC was 6.97%. From 2011 to 2020, the average growth rate of the CTFP index in the western region was 6.74%, of which the contribution rate of EFF was −0.45% and the contribution rate of TEC was 7.48%. In general, the growth rates of CTFP in the eastern, central and western regions decreased in turn. The EFF of the eastern and central regions had a slight effect on improving their CTFP, while the TEC of the western region had a restraining effect. TEC was the main driving force behind the improvement in CTFP in the three regions.

4.2 Benchmark regression

In this paper, STATA 15.0 software is used for quantitative regression. To avoid heteroscedasticity, logarithmic processing is adopted for each variable. The variance inflation factor is employed to examine the presence of multicollinearity among the variables. The average value of the variance inflation factor is 1.54, significantly below 10, indicating the absence of multicollinearity. Equation (1) is estimated by using ordinary least squares (OLS), fixed effects (FE), and random effects (RE) models, which are shown in Table 5. The F test and Hausman test are performed for OLS, FE and RE models to select a suitable panel model. The results of the *F*-test are $F(29, 263) = 6.11$, Prob>$F = 0.0000$, and the results of the Hausman test are chi2(8) = 55.64, Prob>$F = 0.0000$. All of these results show that the FE model is the best model among

TABLE 6 Mediating effect test results.

Variable	Technological innovation	Comprehensive total factor productivity	Factor endowment structure	Comprehensive total factor productivity	Human capital	Comprehensive total factor productivity
	lnRD(1)	lnCTFP(2)	lnKL(3)	lnCTFP(4)	lnHC(5)	lnCTFP(6)
Constant	2.512 (0.94)	6.955** (2.06)	13.123*** (3.03)	6.021* (1.75)	2.857*** (5.56)	5.415 (1.51)
lnDIG	0.107*** (5.28)	0.298*** (11.09)	0.076** (2.33)	0.311*** (12.02)	0.043*** (11.04)	0.289*** (9.28)
lnRD		0.199** (2.56)				
lnKL				0.109** (2.27)		
lnHC						0.714** (1.75)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.270	0.694	0.081	0.693	0.573	0.690
N	300	300	300	300	300	300

the three. Therefore, the analysis of the results is conducted based on the results of the FE model.

As shown in Table 5, column (3) shows that the DIG has significantly improved the CTFP of Chinese provinces. The impact coefficient is 0.319 and is significant at the 1% level. With its continuous and rapid development, the DIG has continuously penetrated various fields through information technology, reduced the massive emission of environmental pollutants, improved the efficiency of utilization in the production sector, and thus improved CTFP. In addition, the underlying reason for the direct and positive impact of the DIG on CTFP is that the characteristics of replicability and shareability of the DIG make data elements overcome the traditional law of diminishing marginal returns (35). The environmentally friendly features of consumption and low pollution emissions, as well as the features of low cost and high returns, have a positive effect on CTFP. This conclusion verifies that hypothesis 1 is correct. Regarding the other control variables, the coefficient of PGDP is positive and significant at the 1% level, indicating that the increase in PGDP is conducive to improving CTFP. The first-order coefficient of POP is negative, the second-order coefficient is positive, and both are significant. These results indicate that there is a U-shaped curvilinear relationship between population agglomeration and CTFP. In the initial stage, population agglomeration consumes more resources and energy and produces many environmental pollutants. When population agglomeration reaches a certain level, it can improve labor productivity, realize economies of scale, improve the utilization efficiency of resources and energy, and lead to an improvement in CTFP (36). ENVR inhibits an improvement in CTFP. The reason for this result may be that most enterprises across China passively accept environmental supervision. After raising production costs to meet the requirements of environmental regulatory policies, they must reduce their production input under capital pressure and reduce their investment in green technology. Technological innovation requires more investment and a long period of time to generate benefits. As a result, the cost of environmental regulation is greater than the benefits obtained, and CTFP declines (6). FDI negatively and significantly affects CTFP. One possible reason is that the entry of FDI may transfer a large amount of energy-intensive manufacturing or pollution-intensive industries to China, causing a considerable amount of environmental pollution and making the host country a "pollution paradise." It is also possible that enterprises in various regions of China become technologically dependent on foreign technology, inhibiting the independent innovation of Chinese enterprises (32). The coefficient of ST is positive but not significant. There is no evidence to show that ST has a significant impact on CTFP. One possible reason is that there is a non-linear relationship or other influence between ST and CTFP.

4.3 Mediating effect test

The previous estimation results confirm that the DIG plays a significant role in improving CTFP. Consistent with the previous theoretical analysis, this paper further explores the mechanisms of the impact of the DIG on CTFP through technological innovation (RD), the factor endowment structure (KL) and human capital (HC). The results are presented in Table 6.

4.3.1 Technological innovation effect

Column (1) reveals that the coefficient of the effect of the DIG on technological innovation is positive and significant at the 1% level. This result indicates that DIG development promotes technological innovation. Column (2) shows that the coefficient of the effect of DIG on CTFP is positive and significant at the 1% level. Additionally, the coefficient of the effect of technological innovation on CTFP is positive and significant at the 5% level. These results show that there is a mediating effect in which the DIG promotes CTFP through technological innovation, which is consistent with the analysis in Hypothesis 2. One possible reason for this conclusion is that the powerful financing ability of the DIG can provide a financial guarantee for the technological innovation of enterprises. Additionally, the green technological innovation of enterprises can reduce environmental pollution and improve CTFP, as supported by the studies conducted by Cheng et al. (37) and Zhao et al. (28).

4.3.2 Factor endowment structure effect

The estimates of the factor endowment structure effect are presented in Column (3) of Table 6. The coefficient of the effect of the DIG on the factor endowment structure is estimated to be 0.076 and is significant at the 5% level. This result implies that the DIG has a positive impact on the factor endowment structure. Column (4) shows that the coefficient of the DIG on CTFP is positive and significant at the 1% level. Additionally, the coefficient of the effect of the factor endowment structure on CTFP is positive and significant at the 5% level. These results show that there is a mediating effect in which the DIG promotes CTFP through the factor endowment structure. This conclusion verifies that hypothesis 3 is correct. One possible reason is that under the background of the DIG, each region will monitor the factor endowment in each detail and evaluate the local factor endowment structure. Then, industries will adjust based on the structure in a timely manner, open up the industrial chain, realize the connection between the bottom production factors and the top final product demand, and realize the upgrading of the factor endowment structure. The whole region will combine production factors and the industrial structure to meet market demand. In this process, the optimal allocation of the factor endowment structure will be realized through the DIG, and CTFP will ultimately be improved (38).

4.3.3 Human capital effect

The estimates of the human capital effect are presented in Column (5) of Table 6. The coefficient of the effect of the DIG on human capital is estimated to be 0.043 and is significant at the 1% level. This result implies that the DIG has a positive impact on human capital. Column (6) shows that the coefficient of the effect of the DIG on CTFP is positive and significant at the 1% level. Additionally, the coefficient of the effect of human capital on CTFP is positive and significant at the 5% level. These results show that there is a mediating effect in which the DIG promotes CTFP through human capital. This conclusion verifies that hypothesis 4 is correct. The primary reason behind these findings is that online and offline agglomeration, information network sharing and the efficient matching of big data algorithms can quickly realize a transformation of human capital from agglomeration to sharing and improve the level of human capital agglomeration. The improvement in the human capital level will prompt people to raise their requirements for the quality of the surrounding environment, prompting a transition to green consumption behavior and the green production behavior of enterprises (39). This transition will produce a reduction in environmental pollution and, in turn, a promoting effect that further improves CTFP.

4.4 Endogeneity tests

Considering the potential endogeneity problems in the model, this paper further uses the instrumental variable estimation method to test the impact of the DIG on CTFP. The selection of instrumental variables should meet the two conditions of being "independent of dependent variables" and "related to endogenous variables" (38, 40). (1) Referring to Zhao et al. (28), this paper takes the DIG (L.DIG) as the instrumental variable. The results of the two-stage regression are presented in columns (1) and (2) of Table 7. The F-statistic values of the weak instrumental variable tests in the first stage are all significant at the 1% level, indicating that the estimation results of the instrumental variables are valid. The estimation results of the second stage reveal that the coefficients of L.DIG align closely with the findings in the baseline regression results, reflecting that the impact of the DIG on CTFP is robust and credible. (2) With reference to relevant literature (41, 42), this paper additionally incorporates two other instrumental variables of the digital economy: the interaction term obtained by multiplying the number of fixed telephones per 100 individuals in 1984 with the national information technology service income (Lntel), and the interaction term derived from multiplying the number of post offices per million individuals in 1984 with the national information technology service income (Lnpost). The results are presented in columns (3) and (4) of Table 7. The coefficient of the Lntel's effect on CTFP exhibits a positive and statistically significant association at the 1% level, as does the coefficient of the Lnpost's effect on CTFP. These findings align with benchmark regression results, indicating that the effect of the DIG on CTFP remains robust.

4.5 Robustness tests

4.5.1 Quantile regression method

Quantile regression was conducted to examine the robustness of the findings. The results of quantile regression at 75 and 90%

TABLE 7 Endogeneity test results.

Variable	(1)	(2)	(3)	(4)
	First stage	Second stage	LnCTFP	LnCTFP
LnDIG			0.354*** (7.64)	0.325*** (13.73)
L.LnDIG	0.747*** (44.68)	0.300*** (10.06)		
LnTel			0.281*** (14.46)	
LnPost				0.268*** (13.24)
Control variables	YES	YES	YES	YES
R2	0.959	0.633	0.705	0.701
N	270	270	300	300
F-value	775.33			

TABLE 8 Robustness test results.

Variable	(1)	(2)	(3)	(4)
	LnCTFP(Quantile = 0.75)	LnCTFP(Quantile = 0.90)	LnCTFP	LnTEC
LnDIG	0.332*** (5.54)	0.341*** (2.70)	0.354*** (7.64)	0.325*** (13.73)
L.LnCTFP			0.122* (1.73)	
Control variables	YES	YES	YES	YES
R2			0.657	0.729
N	300	300	270	300

TABLE 9 Heterogeneity analysis results.

Variable	ERC(1)	CRC(2)	WRC(3)
constant	20.961 (1.09)	7.741 (0.72)	9.988** (2.44)
LnDIG	0.495*** (7.56)	0.358*** (6.72)	0.261*** (5.39)
Control	YES	YES	YES
R2	0.712	0.779	0.693
N	110	80	110

are presented in columns (1) and (2) of Table 8, respectively. Notably, all coefficients associated with the digital economy in quantile regression passed the significance test level of 1%, indicating that the impact of digital economy on CTFP remains robust.

4.5.2 Replacing the explained variable

This paper performs a robustness test by substituting the explained variable, CTFP. First, the first-order lag of CTFP (L.LnCTFP) is added to the measurement model as an explanatory variable for re-estimation. The results are presented in Column (3) of Table 8. The coefficient of the effect of the DIG on CTFP is positive and significant at the 1% level, and the coefficient of L.LnCTFP on CTFP is positive and significant at the 10% level. This conclusion is consistent with the results of the basic regression. Second, the TEC index, the decomposed index of CTFP, is used as a proxy variable for empirical testing, and the results are presented in Column (4) of Table 8. The coefficients of the DIG are positive and significant; thus, they are in line with the findings in the baseline regression results. These tests suggest a certain degree of robustness and reliability in the basic regression results.

4.6 Heterogeneity analysis

To investigate the heterogeneity between the DIG and CTFP in regional development, the research sample is divided into three regions according to the standards of the National Bureau of Statistics of the People's Republic of China: eastern region of China (ERC), central region of China (CRC), and western region of China (WRC). The heterogeneity test results are shown in Table 9. Columns (1), (2), and (3) reveal that the regression coefficients of the DIG are 0.495, 0.358, and 0.261, respectively, indicating that the impact of the DIG on CTFP decreases in turn from the ERC to the CRC and WRC. Meanwhile, the regression coefficients of the DIG are all positive and significant at the 1% level. These results indicate that the DIG can significantly improve the level of CTFP in the three major regions of China.

5 Conclusion and policy recommendations

5.1 Conclusion

The DIG has become one of the important ways to drive high-quality economic development in China, and CTFP is an important manifestation of high-quality economic development. The impact of the DIG on CTFP and the transmissions mechanisms have not been fully discussed. For this reason, this paper constructs a new undesirable output to measure the CTFP of China and empirically examines the effect of the DIG on CTFP and the mechanisms of this effect. Panel data covering 30 Chinese provinces and spanning from 2011 to 2020 are employed for analysis. The main conclusions drawn are as follows:

First, CTFP increased by an average of 3.9% in China. Technical efficiency contributed −1.1%, and the contribution rate of technological progress was 5.0%. Technological progress was the main source of total factor productivity growth.

Second, from a regional perspective, the growth rates of CTFP in the ERC, CRC, and WRC decreased in turn. The technical efficiency of the ERC and CRC had a slight effect on improving their CTFP, while the technical efficiency of the WRC had a restraining effect. Technological progress was the main driving force behind the improvement in CTFP in the three regions.

Third, the DIG had a positive and significant impact on CTFP, and this impact was significant in the ERC, CRC, and WRC. These findings remain consistent with the previous conclusion after endogeneity tests and various robustness tests.

Finally, mechanism tests suggest that the promoting effect of the DIG on CTFP can be attributed to three main effects: technological innovation, the factor endowment structure and human capital.

5.2 Policy recommendations

Several policy implications can be drawn from the conclusions above.

First, the governments of various regions in China should clearly see the differences between regions and formulate development strategies that correspond to them to promote haze governance between regions as well as CTFP convergence and balance. They should also make efforts to build regional comparative advantages, give full play to the orderly and free flow of various elements, and form a regional development pattern with benign interactions between regions. For regions with a high level of digital economy development, they should capitalize on their advantages by allocating sufficient research and development funds to foster the advancement of digital technology, thereby expediting the evolution of hardware infrastructure. Simultaneously, it is imperative for them to establish a core data platform that serves as the central engine driving data-centric elements. For regions with a lower level of digital economy development, the government should initially provide substantial foundational data to facilitate the growth of digital technology and stimulate its positive impact on traditional markets. Additionally, authorities should enhance support for such cities through research and development subsidies, preferential tax rates, and other measures aimed at guiding their sustainable development.

Second, all localities should use digital transformation to drive the transformation of traditional modes of production and governance as well as traditional ways of life, realize energy conservation, emission reduction and resource utilization efficiency improvement, fully release the role of the DIG in promoting green economic efficiency, and achieve high-quality economic development in China. The formulation of relevant policies and systems, such as the implementation of open market access policies, should be undertaken by all regions. It is essential to ensure compliance while striving for maximum cross-regional and cross-industry flow of production factors in order to achieve a more extensive allocation of resources. Additionally, establishing a production factor information sharing platform can effectively reduce information asymmetry by providing comprehensive data on talent demand, market demand, investment opportunities, etc. This will contribute to the creation of a favorable information environment in China that promotes the realization of digital economy system dividends. Consequently, it will facilitate better matching between production factors and market demand while enhancing resource allocation efficiency.

Third, the government should pay attention to optimizing the structure of foreign investment. While expanding the scale of foreign investment, the government should strengthen the assessment of the quality of foreign investment, guide the transfer of foreign investment to new high-tech industries, reduce investment in high-pollution, high-emission and high-energy-consuming industries, give full play to the "pollution halo effect" of foreign direct investment in various regions of China, realize more technology spillover effects, and improve total factor productivity. On one hand, it is imperative for all regions to enhance environmental standards, refine the negative list for foreign investment access, optimize the structure of attracting foreign investment, and augment the proportion of technology-intensive foreign-funded enterprises. Simultaneously, relevant departments should bolster supervision to curb rent-seeking activities, rigorously regulate environmental standards for attracting FDI, curtail the entry of high-energy consumption and highly polluting foreign enterprises, thereby achieving the objective of enhancing the quality of attracting foreign investment while stimulating industrial upgrading and technological innovation in existing foreign investments.

Finally, all localities should improve the quality and skills of human capital in society as a whole, especially the cultivation of cross-border, integrated and practical talent under the "industry-university-research" system. All regions should also actively cultivate high-tech industries and knowledge-technology-intensive industries and realize the overall transformation of the industrial chain with digital technology. Digital technology should be used to improve the technological innovation system, enhance the independent innovation capabilities of market entities, and promote the green transformation and development of China's economy. The government should enhance investment in education, technology research and development, and other related fields, while reallocating more fiscal expenditure toward education and scientific research. This will foster the cultivation of a greater number of innovative talents, enabling them to assume leadership roles as well as exert influence over innovation processes, thereby elevating the level of regional innovation. Simultaneously, it is imperative to augment investment in innovative human capital by offering higher wages to professionals engaged in higher education compared to ordinary employees. This will attract a larger pool of innovative talents while establishing a mechanism for joint talent training within the region to ensure effective flow and allocation.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

DM: Conceptualization, Formal analysis, Funding acquisition, Investigation, Software, Writing – original draft, Writing – review & editing. GL: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Research on the coupling and coordinated development of Guangxi's tourism industry, new urbanization and environmental health system in the post-epidemic era

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As one of China's sunrise industries, tourism has always been the engine to promote the development of the national economy, and in 2018, the annual income of China's tourism industry exceeded 5 trillion yuan unprecedentedly. In recent years, the traditional extensive production mode has inevitably brought about problems such as environmental pollution and public health threats, while helping the development of new urbanization, thus triggering a series of challenges in the environmental health system. The tourism industry, new urbanization, and environmental health system three cooperate and promote each other, the coordinated development between them for economic growth, new urbanization development, environmental protection, and public health play a vital role, in the post-epidemic era is a special period of historical opportunities, the public's focus from the original sacrifice of environmental health in exchange for economic growth model began to green, low-carbon sustainable development mode, Guangxi Zhuang Autonomous Region as a tourism resource endowment rich region, It is of positive significance to explore the coupling degree and coordination between the tourism industry, new urbanization and environmental health system, and put forward targeted practical enlightenment, which is of positive significance for promoting the sustainable development of tourism industry. Taking Guangxi Zhuang Autonomous Region as a case study, this paper constructs three comprehensive evaluation index systems of the tourism industry, new urbanization and environmental health system, and analyzes and compares the weights of various indicators in the three fields of tourism economy, new urbanization and environmental health system in Guangxi by using the entropy weight TOPSIS method. The coupling coordination model was used to measure the coupling degree and coordination degree of the tourism industry, new urbanization and environmental health system construction in Guangxi Zhuang Autonomous Region from 2009 to 2021. The empirical results show that the weights of various indicators change with the development of the social economy. The comprehensive efficacy index of Guangxi's tourism industry has increased year by year for 11 consecutive years; At the end of the evaluation period, after the outbreak of the new crown epidemic, the evaluation index of the tourism industry, new urbanization and environmental health system all showed a downward trend to varying degrees. Before the pandemic, the coupling coordination type of the three subsystems generally experienced a transformation of "moderate dissonance-reluctant coordination-primary coordination-intermediate coordination," but the overall development level was still poor. After the outbreak of the new crown epidemic,

the coupling and coordination between the three has been reduced to a state of poor coordination. Because of the above research conclusions, this study proposes to make full use of the important time node of the post-epidemic era and proposes to actively promote the development of the tourism industry, promote the upgrading of the industrial structure, use digital empowerment of the economic form, optimize the environmental health system and other targeted countermeasures to keep the coupling degree and coordination between the three within a reasonable range. This ensures the sustainable development of social systems in the region. This study has made some contributions to the development of high-quality tourism and a healthy environment. First of all, it enriches the content of the environmental health system. This study takes the ecological environment and atmospheric environment in the environmental health system as the entry point and adds the index content of the environmental health evaluation system, which provides a certain supplement for the relevant research on the environmental health system strength. Secondly, the relationship between the tourism industry, new urbanization and environmental health is analyzed and into a unified theoretical framework. This study takes the Guangxi Zhuang Autonomous Region, which is rich in tourism resources, as a case study site, and innovatively explores the coupling and coordination relationship among the tourism industry, new urbanization and environmental health system in the case site. Finally, it provides targeted countermeasures for the sustainable development path of the three systems of tourism industry, new urbanization and environmental health in the case site in the future. It is of positive practical significance to compare the coupling and coordination degree between the three, realize the coordinated, orderly, and healthy development of the three in the region, and provide operational suggestions for the upgrading of the tourism industry structure, the benign development of new urbanization, and the formulation of environmental health system policies.

KEYWORDS

post-epidemic era, Guangxi, tourism industry, new urbanization, environmental health, coupling and coordination

1 Introduction

At the end of 2019, an outbreak of novel coronavirus pneumonia ("NCP") occurred quietly and swept the world rapidly. The outbreak of NCCP is not only a "black swan" event in public health but also has a profound impact on air pollution. China has entered the post-epidemic era after an all-out effort by all sectors of society to "fight" the epidemic. It is obvious that environmental issues have become a major problem for all countries in the world, and it has become a consensus to protect and improve the environment and protect public health. How to achieve rapid economic and social development while keeping environmental health risks within an acceptable range requires our continuous efforts in practice. The 14th Five-Year Plan period is an important strategic opportunity period for China's tourism development. With the opening up to the outside world and the construction of "One Belt, One Road," China and ASEAN have established a strategic partnership of mutual trust, mutual understanding, mutual benefit, and mutual assistance. Now ASEAN has become China's largest trading partner, and China-ASEAN relations have become the most successful and dynamic model of regional cooperation in the Asia-Pacific region. Guangxi is at the intersection of the three national strategies of "One Belt and One Road," Yangtze River Economic Belt, and Beibu Gulf Economic Zone, and has the unique location advantage of "one bay with eleven countries, benign interaction between East and West," and is an important window of China to ASEAN, and has good tourism resources and development conditions. In the key period of the most active development of Guangxi's export-oriented economy, the development of the tourism industry as a sunrise industry is particularly important. Industrialization and urbanization are the basic driving forces of China's sustained economic growth (1). It is important to go deeper within the tertiary industry and explore the construction path of new urbanization with the modern service industry as the core, especially to play and realize the synergistic development between the service industry and new urbanization (2). In recent years, environmental pollution, air quality decline, and ecological damage have also been gradually highlighted, and strengthening environmental protection has become necessary for development and desired by people's livelihood. Economic development and environmental health are complementary to each other and can be transformed into each other, just as it is often said that "green water and green mountains are golden mountains." Therefore, it is of certain strategic significance to explore the coupled and coordinated development of the tourism industry, new

urbanization, and environmental health in Guangxi, to build a green and sustainable development model and to realize the benign development of the tourism industry.

By reviewing the relevant literature, we found that the development level of the tourism industry in Guangxi Zhuang Autonomous Region is relatively low on the whole, and some counties and cities have imperfect transportation networks and unsystematic protection of resources and environment, etc., which all impose certain restrictions on the development of tourism industry, and also cause a series of problems such as single employment structure and low-income level of residents. Few studies have been conducted in the Guangxi Zhuang Autonomous Region on the coupled and coordinated development of the tourism industry, new urbanization, and environmental health systems. Based on this, this paper uses the entropy-weighted TOPSIS method, which combines the entropy value method and TOPSIS method, to explore the development level of the comprehensive evaluation indexes of the three subsystems of tourism industry, new urbanization and environmental health in Guangxi Zhuang Autonomous Region from 2009 to 2021 using Guangxi Zhuang Autonomous Region as a case study site, aiming to quantitatively and objectively evaluate the development level of tourism industry, new urbanization and environmental health. The aim is to quantitatively and objectively evaluate the development levels and development history of the tourism industry, new urbanization and environmental health. Subsequently, the coupling coordination degree model is adopted to give specific measurement values for quantitative analysis of the coupling coordination relationship among the tourism industry, new urbanization and environmental health systems, thus providing a quantitative reference basis for decision-making on the coordinated development of the tourism industry, new urbanization and environmental health in Guangxi.

The tourism industry is rich in elements, intertwined and combined, constituting a closely integrated industrial chain, which is based on the industries contained in tourism itself and associated with the primary industry, secondary industry, and health, sports, culture and arts, finance, public services and other industries in the tertiary industry (3). The study of the coupled and coordinated relationship between tourism and other industries has a positive significance for promoting the healthy and sustainable development of tourism.

Foreign studies on the relationship between the ecological environment, tourism industry, and urbanization are more mature. The type of research is mostly single-factor analysis of tourism, urbanization and ecological environment, and the research on the correlation between multiple systems is less, and among the research on the correlation between multiple systems, the empirical research on the interaction between two systems is more common, and the research on the interaction between multiple systems is less than the former. Mullins proposed the concept of "tourism urbanization" for the first time in 1991, and subsequently, tourism urbanization has become a hot topic of research for scholars and governments at all levels at home and abroad (4, 5). Mullins argues that the mechanisms of tourism urbanization are mainly manifested in the fact that tourism can cause the expansion of the urban population, the restructuring of urban industries, and the change of urban class structure, especially the emergence of modern services and the prominence of the petty bourgeoisie as the main signs of the influence of tourism on urbanization (6). Thays analyzed the impact of tourism-led urbanization on the ecosystem environment around the Araruma Lagoon in Brazil (7). Ozturk used the environmental Kuznets curve hypothesis to study the interaction between tourism and ecological footprint (8). Izza Mafruhah studied the causal relationship between tourism development and marine ecological sustainability (9). Achmad Fandi researches the role of stakeholders in increasing tourism potential to support tourism industry activities, especially in a dynamic environment. The main objective of this study was to identify the factors that influence the improvement of the tourism industry and to produce strategies for the tourism industry (10). Genjin Sun et al. analyze the impact mechanism of environmental regulation on China's tourism development from the perspective of the integration of institutional and environmental economics (11). Dan Yuan studied How to coordinate the relationship between tourism and ecology (12). Qin Yang Research on the coupling and coordinated development of the tourism industry and regional economy in the economic circle of the Sichuan-Chongqing region in southwest China (13). Wei Yang studied whether the tourism industry and technological progress affect ecological economic development (14). Yu Zhang analyzed how to coordinate the tourism industry with the ecological environment (15). Muhammad Irfan's research unleashes the dynamic impact of the tourism industry on energy consumption and environmental sustainability (16). Xiao Yu's study on coupling coordination of the human settlement environment and tourism industry (17). Fengting Zhang's research on coupling coordination of the regional economy, tourism industry, and the ecological environment (18). Yufeng Cheng explored the ecological performance of China's tourism Industry (19). Liranran research on understanding and handling the relationship between the tourism industry, ecological environment, and regional economy correctly (20). Aiqin Ding analyzed the coupling effect measure of the tourism industry and new urbanization (21). Fengtai Zhang analyzed how new urbanization affects tourism Eco-Efficiency in China (22). Ming Hao et al. research a coupling relationship between New-Type urbanization and tourism resource conversion efficiency (23). Xingyu Yang's research on coupling and interaction between tourism eco-efficiency and new urbanization in the Yangtze River economic belt (24). Dongmin Zhang's research on uncoordinated coupling assessment of new urbanization and ecological carrying capacity in the Yellow River Basin (25). Shuwang Yang and Jing Li analyzed whether new-type urbanization curbs haze pollution (26, 27). Le Ma's research on the spatiotemporal evolution of urban carbon balance and its response to new-type urbanization (28). Haitao Wu analyzed whether environmental pollution inhibits urbanization in China (29). Yazhen Zhang's research on spatial and nonlinear effects of new-type urbanization and technological innovation on industrial carbon dioxide emission in the Yangtze River Delta (30). Kanda Xue studies the coupling coordination between New-Type Urbanization and Water Ecological Environment and its driving factors (31).

A review of the relevant literature revealed that the discussion of the two industrial systems seen through coupled coordination degree models is relatively common in China. For example, Li Mengcheng conducted a BP neural network model measurement and coupled coordination analysis of tourism development and ecological environment in 12 island counties in China (32); Xiong Jianxin analyzed the coupled coordination relationship between tourism and urbanization in the Dongting Lake area (33); Qu

Xiaoshang studied the coupled coordination degree between tourism economy and ecological environment in the provincial capitals of the Yellow River Basin region (34); Zhang Changcheng studied the Chengdu-Chongqing region's coupled coordination between tourism and new urbanization (35). While there are fewer discussions between the three industrial systems, for example, Geng Nana studied the coupled coordination among ecological environment, tourism industry, and urbanization in the Yellow River Basin (36); Gao Dongmei studied the coupled coordination among the three subsystems of tourism, economy, and ecological environment in Chinese provinces (37); Weng Gangmin studied the coupled coordination among tourism, ecology, and urbanization in the Beijing-Tianjin-Hebei region (38); Yang Xiuping studied the coupled coordination relationship of tourism environmental carrying capacity from three subsystems: natural, economic, and social (39); Luo Xue made a coupled coordination analysis of urbanization and ecological environment based on urban functional areas (40); Zhang Jiajie made a study on the coupling degree of ecological environment quality and urban development in Chengdu-Chongqing economic circle based on Google Earth Engine platform (41); Shi Zhiyu analyzed the Yangtze River Delta urban agglomerations and its coupling and coordination with urbanization (42); Wenjia Li studied the local coupling and remote coupling of urbanization and eco-environmental quality based on multivariate remote sensing data (43).

After systematically combing the existing literature, we found that although previous studies have included three systems, tourism, urbanization, and ecological environment, the relationship between them has also shifted from one-way influence research to two-way interaction research, and the use of coupled coordination degree, synergy degree, VAR and other econometric models and grayscale analysis, regression analysis and other research methods to quantitatively present the degree of coordinated development between the systems in different regions, the research. The theoretical basis and data analysis methods have become increasingly mature. However, most of them are still exploring the interaction between two of them or combining other subsystems, and there is still a lack of integration tourism industry, new urbanization and environmental health into a unified theoretical structure, and there is even less research on the coupled coordination relationship among tourism, new urbanization and environmental health systems in Guangxi Zhuang Autonomous Region, the case study of this paper. In conclusion, the study of the coupling and coordination relationship among tourism, new urbanization and environmental health in Guangxi Zhuang Autonomous Region is of great significance, which can better promote the coordinated and healthy development among the three, and thus promote the economic development in the whole region of Guangxi.

2 Materials and methods

2.1 Constructing the index system of tourism industry, new urbanization and environmental health system

This paper follows the evaluation principles of scientificity, systematization, accessibility, and comparability, and draws on the existing research results (1, 39, 44–46) to determine the following items as relevant industry evaluation indicators. it includes seven evaluation indexes of the tourism industry, 16 evaluation indicators of new urbanization, and 10 evaluation indexes of the environmental health system.

2.2 Research method

This paper adopts the entropy weight TOPSIS method as the main method and technique for the comprehensive development level of the tourism industry, new urbanization and environmental health system in Guangxi Zhuang Autonomous Region, and measures the coupling degree and coordination degree among tourism industry, new urbanization and environmental health system in Guangxi Zhuang Autonomous Region through the coupling coordination degree model. To avoid the influence of subjective factors in the process of weight determination, we choose to use the entropy TOPSIS method to assign weights to the system indicators first and use the comprehensive score to represent the system.

2.2.1 Entropy TOPSIS method

2.2.1.1 Entropy TOPSIS method meaning

The entropy method is a mathematical method used to determine the degree of dispersion of a certain indicator. The greater the degree of dispersion, the greater the influence of that indicator on the overall evaluation. The traditional "double basis point method," also called TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method, can be used to solve the problem of evaluating and ranking multiple solutions with multiple indicators in the socio-economic field. In the alternative solution set, a set of best indicator data is used as a virtual positive ideal solution, and a set of worst indicator data is used as a virtual negative ideal solution according to the nature and data of the indicators, and the superiority of the evaluated solution is judged by comparing the distance of the solution points from the positive and negative ideal points (46). Its general determination of weights based on expert opinion leads to the evaluation results being susceptible to human subjective factors, the determination of weights using the TOPSIS method is an important link, and the use of the information entropy method can effectively eliminate the influence of subjective factors (47). The entropy TOPSIS method is essentially an improvement of the traditional TOPSIS evaluation method, in which the weights of evaluation indexes are determined by the entropy method, and then the ranking of evaluation objects is determined by the TOPSIS method using the technique of approximating ideal solutions. In this paper, based on the improved entropy method to measure the weights of index order parameters, the TOPSIS method is used to measure the Euclidean distance, to reveal the closeness of the real state of the system to the ideal state, which can objectively measure the comprehensive efficacy index of the three systems of tourism and, new urbanization and ecological civilization system, and then scientifically evaluate the comprehensive development level of tourism and, new urbanization and ecological civilization system.

2.2.1.2 Entropy TOPSIS method-specific steps

The main calculation steps of the entropy TOPSIS method are as follows (47–51):

(1) Assuming that objects are being evaluated and n evaluation indexes for each object being evaluated, the judgment matrix is constructed as follows:

$$X = \left(X_{ij}\right)m \times n \left(i = 1,2, \ldots, m; j = 1,2, \ldots, n\right) \quad (1)$$

(2) Normalization of the judgment matrix.

$$X_{ij} = \frac{X_{ij}}{X_{\max}} \left(X_{\max} \text{ is the maximum value under the same indicator}\right) \quad (2)$$

(3) Calculate the information entropy.

$$H_{j=-K\sum_{i=1}^{m}P_{ij}} \ln P_{ij}$$

$$\text{In the formula, } P_{ij} = \frac{X_{ij}}{\sum_{i=1}^{m} X_{ij}}; k = \frac{1}{\ln m} \quad (3)$$

(4) The weights of indicator j are determined.

$$\omega_j = \frac{1 - H_j}{\sum_{j=1}^{n}\left(1 - H_j\right)} \quad (4)$$

In the formula, $\omega_j \in [0,1]$, and $\sum_{j=1}^{n}\omega_j = 1$.

(5) Calculate the weighted normalization matrix.

$$R = \left(r_{ij}\right)_{m \times n,} \; r_{ij=}\omega_j \cdot X_{ij} \left(i = 1,2, \cdots, m; j = 1,2, \cdots, n\right) \quad (5)$$

(6) Determine the optimal solution S_j^+ and the inferior solution S_j^-.

$$S_j^+ = \max\left(r_{1j}, r_{2j,} \cdots, r_{nj}\right), \; S_j^- = \min\left(r_{1j}, r_{2j,} \cdots, r_{nj}\right) \quad (6)$$

(7) Calculate the Euclidean distance between the evaluation object and the optimal and inferior solutions.

$$sep_i^+ = \sqrt{\sum_{j=1}^{n}\left(S_j^+ - r_{ij}\right)^2}, sep_i^- = \sqrt{\sum_{j=1}^{n}\left(S_j^- - r_{ij}\right)^2} \quad (7)$$

(8) Determine the relative proximity C_i to characterize the composite evaluation index:

$$C_i = \frac{sep_i^-}{sep_i^+ + sep_i^-}, C_i \in [0,1] \quad (8)$$

Where, the larger the value of C_i, the better the evaluation object is.

2.2.2 Coupling coordination degree model

Through the analysis of the relationship between the tourism industry, urbanization and environmental health in the previous paper, it is seen that there is a coupling and coordination phenomenon among these three. Referring to the research results of Xiaolin et al. (52), an index system reflecting the structural characteristics of the three is established to quantitatively analyze the coupling degree of the ternary system, and the coupling coordination results are used to judge the coupling coordination degree between tourism industry development, new urbanization construction and environmental health system in Guangxi Zhuang Autonomous Region. System (53), "financial system-industrial structure" system (54), and "innovation capacity-economic development" system (55), In recent years, the model has also been used in tourism research, including the "tourism-ecological environment" system (56), the "tourism-urbanization" system (57) and the "tourism-regional development" system (58).

2.2.2.1 Coupling and coordination model

In this paper, we borrow the concept of coupling degree in physics and refer to the research results of Cong Xiaonan (58) to give the measurement model of coupling degree using the method of characterizing the deviation formula between multiple systems.

$$C_k = \left\{\left(U_1 \times U_2 \times \cdots U_k\right)\prod\left(U_i + U_j\right)\right\}^{1/k} \quad (9)$$

According to Equation (1), the coupling degree model of the triadic system of tourism industry, new urbanization and ecological civilization construction is established:

$$C_3 = \left\{\left(U_1 \times U_2 \times U_3\right) / \left(U_1 + U_2 + U_3\right) \times \left(U_1 + U_2 + U_3\right)\right\}^{1/3} (10)$$

Among them, C_3 represents the coupling degree, U_1, U_2 and U_3 represent the comprehensive evaluation indices of the tourism industry, new urbanization and ecological civilization system, respectively. Since the tourism industry, new urbanization and ecological civilization systems all have different differences in their respective development history (59), to avoid deviating from reality, a coupling coordination degree model (60) is constructed by drawing on the research results of scholars such as:

$$D = \sqrt{C \times T}, \text{其中} \alpha U_1 + \beta U_2 + \gamma U_3 \quad (11)$$

Where, D is the coupling coordination degree of the tourism industry system, new urbanization and ecological civilization city system, T is the comprehensive evaluation index of the tourism industry, new urbanization and ecological civilization city, and α, β and γ are coefficients to be determined. Through the calculation of Equations (3)-(11), the coupling coordination among the three systems is eventually determined.

TABLE 1 Evaluation Index of the tourism industry and new urbanization.

Subsystem	The name of the metric	Unit	Attribute
Tourism industry	Total tourism spending	100 million yuan	+
	Domestic tourism consumption	100 million yuan	+
	Foreign exchange consumption for international tourism	$10,000	+
	The number of domestic tourists received	10,000 people	+
	The number of inbound tourists received	1	+
	Turnover of accommodation and catering services above the designated size	100 million yuan	+
	Number of star-rated hotels	1	+
The new type of urbanization	Proportion of urban population	%	+
	Population density	Person/per square kilometer	+
	Natural population growth rate	%	+
	Proportion of employed population in secondary and tertiary industries	%	+
	GDP per capita	Yuan	+
	The output value of secondary and tertiary industries accounts for the proportion of total output value	%	+
	Investment in fixed assets per capita	Yuan	+
	Per capita disposable income of urban residents	Yuan	+
	10,000 college students	1 person	+
	Number of health technicians per 1,000 people	1 person	+
	Number of buses for 10,000 people	Vehicle	+
	Postal and telecommunications business volume per capita	Yuan	+
	Built-up area per capita	Square meter	+
	Paved road area per capita	Square meter	+
	The area of garden green space per 10,000 people	Hectare	+
	Green coverage of built-up areas	%	+

2.2.2.2 Coupled coordination model data pre-analysis processing and partitioning criteria

The data are internalized before analysis, and the internalization formula is: $a+(b-a)\times(X-\min)/(\max-\min)$, where b is 0.99, a is 0.01, max and min denote, respectively, the maximum and minimum values of a term. All the data are between 0 and 1 after the internalization process (Tables 1–3).

The coupling degree is determined by the subsystem's integrated sequential covariates, which characterize how closely tourism, urbanization and environmental health interact with each other. When $C=0$, it means that the coupling degree is very low, the subsystems are irrelevant to each other, and the system develops in a disorderly way; when $C=1$, it means that the coupling degree is very high, the subsystems are closely cooperating, and the system moves in an orderly way. Using the median segmentation method, when $C\in[0, 0.3]$, the system is in the low-level coupling stage; when $C\in[0.3, 0.5]$, the system is in the fly-down grinding stage; when $C\in[0.5, 0.8]$, the system is in the benign coupling stage; when $C\in[0.8, 1]$, the system is in the high-level coupling stage.

2.3 Data sources

The data in the paper mainly come from Guangxi Zhuang Autonomous Region 2009–2021, Guangxi Statistical Yearbook, National Economic and Social Development Bulletin, and Ecological Environment Bulletin.

2.4 Empirical analysis

According to Equations (1) and (2), SPSS was used to process the basic data by means of the mean value in the standardized processing method, and then the weights of the evaluation indicators of the three subsystems of the tourism industry, new urbanization and environmental health from 2009 to 2021 were calculated (Tables 4–6).

2.4.1 Comprehensive system efficacy index

In this paper, based on the entropy method, the TOPSIS method is combined with the results of the entropy method, and the entropy

TABLE 2 Environmental health system evaluation indicators.

Subsystem	Level 1 indicators	Secondary indicators	Unit	Attribute
Environmental health	Ecological environment	Total amount of industrial wastewater discharged	10,000 tons	–
		Total industrial emissions	Cubic meters	–
		Comprehensive utilization rate of industrial solid waste	%	+
		Harmless treatment rate of domestic waste	%	+
		Green cover area	Hectare	+
		The area of green space in the park	Hectare	+
	Atmospheric environment	Excellent air quality rate throughout the year	%	+
		Annual average concentration of SO_2	$\mu g/m^3$	–
		Annual average concentration of NO_2	$\mu g/m^3$	–
		PM10 annual average concentration	$\mu g/m^3$	–

TABLE 3 Classification standard of coupling coordination degree.

Coupling coordination degree *D* value interval	Level of coordination	Degree of coupling coordination
[0.0–0.1]	1	Extreme dissonance
[0.1–0.2]	2	Serious dissonance
[0.2–0.3]	3	Moderate dissonance
[0.3–0.4]	4	Mild disorder
[0.4–0.5]	5	On the verge of disorder
[0.5–0.6]	6	Barely in tune
[0.6–0.7]	7	Primary coordination
[0.7–0.8]	8	Intermediate level coordination
[0.8–0.9]	9	Good coordination
[0.9–1.0]	10	Quality coordination

TABLE 4 Weights of tourism industry evaluation indicators.

Serial number	1	2	3	4	5	6	7	8
Evaluation indicators	Proportion of urban population	Population density	Natural population growth rate	The proportion of the employed population in the secondary and tertiary industries	Area of paved roads per capita	GDP per capita	Built-up area per capita	Landscaping area per 10,000 people
Weight	0.0035	0.0002	0.0168	0.0165	0.0099	0.4573	0.0074	0.0050
Serial number	9	10	11	12	13	14	15	
Evaluation indicators	The output value of secondary and tertiary industries accounts for the proportion of total output value	Investment in fixed assets per capita	Per capita disposable income of urban residents	10,000 college students	Number of health technicians per 1,000 people	Number of public cars per 10,000 people	Post and telecommunications business per capita	
Weight	0.0002	0.1379	0.0216	0.0339	0.0187	0.0130	0.2582	

TOPSIS method is used to calculate the relative proximity through the Euclidean distance, so as to reveal the proximity between the real state and the ideal state of the system, and thus more objectively measure the comprehensive efficacy index of tourism, new urbanization, and environmental health subsystems, and more scientifically It can reflect the comprehensive development level of tourism, new urbanization and environmental health. According to Table 7, from an overall perspective, the comprehensive efficacy index of tourism subsystem in Guangxi

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TABLE 5 Weight of evaluation indicators of new urbanization.

Serial number	1	2	3	4	5	6	7	8
Evaluation indicators	Proportion of urban population	Population density	Natural population growth rate	The proportion of the employed population in the secondary and tertiary industries	Area of paved roads per capita	GDP per capita	Built-up area per capita	Landscaping area per 10,000 people
Weight	0.0035	0.0002	0.0168	0.0165	0.0099	0.4573	0.0074	0.0050
Serial number	9	10	11	12	13	14	15	
Evaluation indicators	The output value of secondary and tertiary industries accounts for the proportion of total output value	Investment in fixed assets per capita	Per capita disposable income of urban residents	10,000 college students	Number of health technicians per 1,000 people	Number of public cars per 10,000 people	Post and telecommunications business per capita	
Weight	0.0002	0.1379	0.0216	0.0339	0.0187	0.0130	0.2582	

TABLE 6 Weight of environmental health evaluation indicators.

Serial number	1	2	3	4	5
Evaluation indicators	Total amount of industrial wastewater discharged	Total industrial exhaust emissions	Comprehensive utilization rate of industrial solid waste	Harmless treatment rate of household waste	Green cover area
Weight	0.3826	0.0907	0.0230	0.0018	0.0699
Serial number	6	7	8	9	10
Evaluation indicators	Park green space	Excellent air quality rate throughout the year	SO_2	NO_2	PM10
Weight	0.1920	0.0015	0.2165	0.0102	0.0118

showed a rising trend year by year during the 10 years from 2010 to 2019, with an average growth rate of 26.87% and a good development momentum, and the tourism industry was hit hard by the New Crown epidemic in 2020, and the comprehensive efficacy index of tourism also decreased by 52.07% compared with 2019, and in 2021, because the In 2021, the epidemic is effectively controlled, tourism industry has warmed up and increased by 15.19% compared with 2020; the comprehensive efficacy index of Guangxi's new urbanization subsystem fluctuates up and down between 2009 and 2013, but the overall change is not significant. 2014–2020 increases year by year, with an average increase of 75.33 in 7 years, especially in 2020, the growth rate reaches 356.16%. It indicates that in the early period of the evaluation period, the foundation of new urbanization construction in Guangxi was slightly weak, and the development was constrained and restricted to a certain extent, while with the advantage of late development, the overall development process of new urbanization in Guangxi began to accelerate in the middle and late periods of the evaluation period, reflecting that the policies related to new urbanization construction introduced and implemented in Guangxi were implemented favorably, and the urbanization efficacy index in 2021 was 9.13% lower than that in the urbanization efficacy index in 2021 is 9.13% lower than that in 2020, indicating that the development of urbanization has slowed down due to a series of factors such as the new crown epidemic; the comprehensive efficacy index of environmental health subsystem in Guangxi showed a decreasing trend between 2009 and 2016, with an average decrease of 21.62%. 2017–2019 gradually rebounded, with an average increase of 41.29% in the 3 years. This reflects that due to the successive introduction of national policies and strong governance at the government level, the construction of ecological civilization in Guangxi has achieved a certain degree of success in recent years. 2020–2021 the efficacy index of the environmental health subsystem decreased slightly compared with 2019, but the overall fluctuation is small.

2.4.2 Coupling degree analysis

2.4.2.1 Analysis of coupling results from 2010 to 2014

According to Table 7, within the 5 years from 2010 to 2014, the system coupling degree of "tourism-new urbanization-environmental health system" at the Guangxi district level increased year by year, indicating that in these 3 years Guangxi district level "tourism-new urbanization-environmental health" in the growth process of low-level-high-level coupling, and the three subsystems gradually reach a benign high-level coupling state among themselves in the 5 years.

TABLE 7 Tourism industry, new urbanization, ecological environment system entropy weight TOPSIS results and coupling coordination degree results.

Systematic evaluation indicators		Annual												
		2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Comprehensive efficacy index of the tourism industry	Relative proximity	0.121	0.154	0.204	0.246	0.288	0.335	0.390	0.472	0.581	0.757	0.989	0.474	0.546
Comprehensive efficacy index of new urbanization	Relative proximity	0.032	0.042	0.039	0.048	0.048	0.055	0.066	0.071	0.085	0.136	0.203	0.926	0.081
Comprehensive efficacy index of ecological and environmental systems	Relative proximity	0.723	0.703	0.502	0.515	0.416	0.303	0.240	0.107	0.124	0.145	0.277	0.214	0.240
Results of coupling coordination calculations	Coupling degree *C* value	0.195	0.425	0.579	0.716	0.756	0.815	0.786	0.76	0.726	0.808	0.801	0.462	0.442
	Harmonized index *T* value	0.293	0.273	0.343	0.378	0.426	0.42	0.428	0.448	0.515	0.579	0.697	0.565	0.537
	Coupling coordination *D* value	0.239	0.341	0.445	0.52	0.567	0.585	0.58	0.583	0.611	0.684	0.747	0.511	0.487
	Coordination level	3	4	5	6	6	6	6	6	7	7	8	6	5
	The degree of coupling coordination	Moderate outrange	Mild disorders	On the verge of imbalance	Barely coordinated	Barely coordinated	Barely coordinated	Barely coordinated	Barely coordinated	Junior coordination	Junior coordination	Intermediate coordination	Barely coordinated	On the verge of imbalance

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2.4.2.2 Analysis of coupling results from 2015 to 2019

In the 5 years of 2015–2019, the system coupling degree of Guangxi district-level "tourism-new urbanization-environmental health system" decreases in fluctuation, but the decrease is not significant, and $C \in [0.7–0.8]$ in 5 years, which indicates that in these 5 years Guangxi district-level "tourism-new urbanization-environmental health New urbanization-environmental health" is in a fluctuating phase of friction and high-level coupling.

2.4.2.3 Analysis of coupling results from 2020 to 2021

In 2020–2021, the coupling between tourism-new urbanization-environmental health at the district level in Guangxi shows a decreasing trend, with a 42.32% decrease in 2020 and an average 4.33% decrease in 2021. The tourism-new urbanization-environmental health system has certain differences in terms of internal structure, functional positioning, and development speed, but there is a correlation between the three.

2.4.2.4 Comprehensive coupling results and cause analysis

The study of the results of coupling degree analysis reveals that tourism, new urbanization and environmental health subsystems in Guangxi do reflect a closely linked coupling relationship as a whole, and imply a strong influence relationship and high interaction intensity between tourism, new urbanization and environmental health. Tourism, as an effective industrial support for new urbanization, is a useful attempt to explore the new urbanization in multiple ways, and the concepts of ecological and environmental quality, social integration and harmony, and advanced lifestyles embodied in the new urbanization development create the necessary conditions and opportunities for tourism development. In addition, according to the table, the coupling degree of the "tourism-new-urbanization-environmental health" system in Guangxi also presents alternating changes of different degrees and modes. The reason is that the development of tourism in Guangxi is changing from traditional sightseeing tourism to health and leisure tourism, and the urbanization reform is just at an important historical stage of "overcoming difficulties." In addition to the other factors that affect the development of regional economic volume, the running-in smoothness between the evolution of each subsystem and the changes affected by external factors leads to a certain degree of fluctuations in the coupling degree of the system. From 2009 to 2021, the average coupling degree of the "tourism-new urbanization-environmental health" system in Guangxi was 0.636, indicating that the average coupling degree of the three subsystems was basically in the stage of integration during the evaluation period. However, in 2014, the coupling degree of the "tourism-new urbanization-environmental health" system reached the optimal state of 0.815, while the coupling degree of 2009 was the lowest state of 0.195. Taking 2014 as the cut-off point, the average coupling degree of the three subsystems in the region increased progressively from 2009 to 2014. The average coupling degree shows a progressive upward trend in 2009–2014, but in 2015–2019, it begins to show a slight decline accompanied by fluctuations, and a significant decline in 2020. In 2009–2014, the average composite efficacy index of the "Tourism-New Urbanization-Environmental Health" subsystem in the region increased at a low rate of −0.061, while the average efficacy index of the three systems increased from 2016 to 2019, with an average increase of 0.273. Among them, the tourism subsystem showed an increasing trend from 2010 to 2019, with an average efficacy index of 0.4416; the urbanization subsystem composite efficacy index fluctuated up and down from 2009 to 2013, with little overall change; it gradually increased from 2014 to 2020, with an average increase of 0.7533 over 6 years; the environmental health subsystem composite efficacy index showed a decreasing trend from 2010 to 2016, with an average decrease of −0.061. The average change in the composite efficacy index of tourism, new urbanization, and environmental health subsystems in the periods of 2009–2014 and 2015–2019 is also a major factor in the change of coupling degree. In contrast, the harm caused by the new crown epidemic in early 2020 to all sectors, especially tourism, is the direct cause of the significant decrease in the coupling degree in 2020.

2.4.3 Coordination degree analysis

2.4.3.1 Analysis of results

According to Table 7, on the whole, from 2009 to 2019, the coordination degree of the "tourism-new urbanization-environmental health" system in Guangxi shows an increasing trend year by year, with an average coordination degree of 0.537 and an average increase of 0.0508, indicating that the overall operation of the "tourism-new urbanization-environmental health" system in Guangxi is within the benign growth process of moderate disorder-intermediate coordination. The overall operation of the "tourism-new urbanization-environmental health" system is within the benign growth process of moderate disorder-medium level coordination. The change characteristics of the "tourism-new urbanization-environmental health" system coordination degree, which is a comprehensive index reflecting both the development degree and coupling degree of the tourism-new urbanization-environmental health subsystem, reveal that as the comprehensive development level of tourism, new urbanization, and environmental health in Guangxi gradually improves, the coupling degree of the three systems will increase in the 10 years from 2009 to 2019. Ten years, the coupling degree of the three gradually increases, and the coordination degree also achieves a benign transformation of moderate disorder – mild disorder – near disorder – barely disorder – preliminary coordination – intermediate coordination. From the comparison of the changes in system coordination degree and coupling degree, it can be seen that the changing pattern of the coordination degree is roughly the same as that of the coupling degree until 2020, but at the beginning of 2020, the coordination degree and coupling degree simultaneously undergo a significant decline and remain consistent with the change of development degree. This indicates that it is affected by a series of persistent adverse effects brought about by the new crown epidemic in late 2019, and also reflects the relatively strong influence of the integrated development level of tourism and new urbanization on the system coordination degree. In the post-epidemic era, the development level of each subsystem will continue to rebound as the new crown epidemic is transformed into regular management of category B. At this time, if we further expand the space for improving the system coordination, we should pay sufficient attention to improving the bridging of the subsystem coupling relationship to achieve a benign coordination state among the three.

2.4.3.2 Cause analysis

In the pre-evaluation period, the construction of new urbanization is in the exploration period, and the constraints it faces are varied and complex, involving a wide range of factors. Although there is a cross-sectional gap between tourism and new urbanization in terms of comprehensive development, according to the trend chart analysis (Figure 1), with the deep expansion of tourism and the release of energy level accumulation, the positive effect of tourism on new urbanization is continuously strengthened, contributing to the steady increase of the comprehensive development level of new urbanization. The development gap between the two gradually decreases, thus promoting the benign development of the coupling relationship and ultimately enhancing the coordinated interaction effect of the system. At the early stage of evaluation, the regional tourism industry in Guangxi is relatively weak in terms of development conditions, operational efficiency, and supporting guarantee, and the supply factors created by tourism to the new urbanization are not yet fully utilized, so the coordinated development level of the three subsystems in the whole region is low. In the later stage of the evaluation, as the new urbanization process progresses, its derivative demand for tourism development gradually grows, so the new urbanization, with its significant feed-back mechanism to tourism, accordingly widens the space of interaction and matching between the two, thus ensuring the dynamic improvement of the coordinated development of the system.

3 Results

The article takes the Guangxi Zhuang Autonomous Region as the research object, and takes the data from 2009 to 2021 as the research sample, through the index weight index of the three subsystems of the tourism industry, new urbanization and environmental health using the entropy weight TOPSIS method to derive the efficacy index of the three subsystems, on this basis, the coupling coordination degree model is used to quantitatively explore the coupling degree between Guangxi tourism industry, the coupling degree and its coordination level among the tourism industry, new urbanization and environmental health of Guangxi were explored quantitatively based on the coupling coordination degree model, and the following conclusions were drawn.

Firstly, the integrated development and virtuous cycle among the three subsystems of the tourism industry urbanization-environmental health can promote the integration within the three industries and finally achieve the sustainable development goal of mutual benefit and win–win.

Second, during the evaluation period, the weights of the indicators of the three subsystems of the tourism industry, new urbanization and environmental health in Guangxi Zhuang Autonomous Region have been changing with the socio-economic development: in the early period of the evaluation period, except for the tourism industry, which has been increasing year by year, the subsystems of new urbanization and environmental health have decreasing and fluctuating trends to different degrees; in the middle of the evaluation period, the evaluation indices of the three subsystems have shown good growth trend.

Third: before the outbreak of the new crown epidemic in late 2019, the coupling coordination types of the three subsystems of tourism industry, new urbanization and environmental health have generally experienced a "moderate disorder – barely coordinated – primary coordination – intermediate coordination" benign transformation, and in 2020–2021 the coordination degree is affected by the new crown epidemic and turns to a state of near disorder. Although the benign shift was shown before the epidemic, the overall development level is still poor.

Fourth, later in the evaluation period, the mutual integration among the three subsystems of the tourism industry, new urbanization and environmental health is reduced to a barely coordinated stage by the epidemic and other factors. In the post-epidemic era, there is still a long way to go to enhance the coupling and coordination between the three and to allow the integration and progress of the industries to develop together.

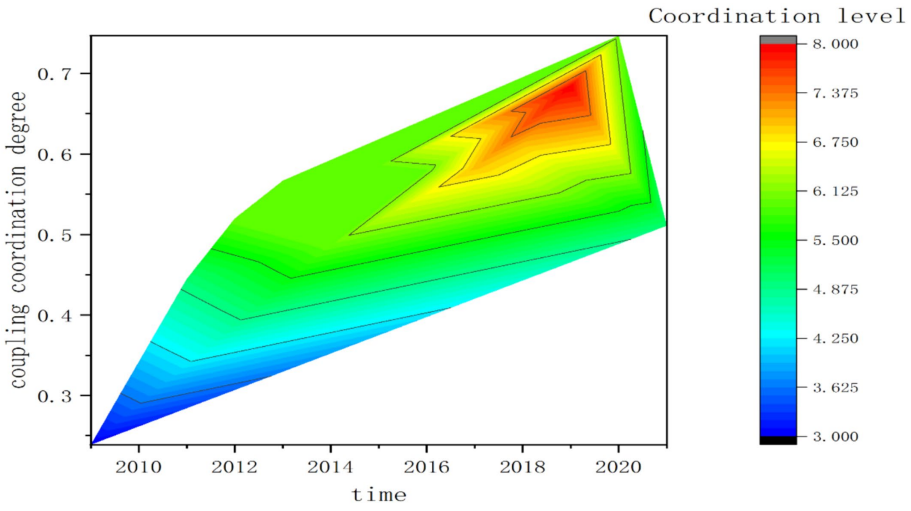

FIGURE 1
The trend of coupling coordination degree and coupling coordination level of tourism industry-new urbanization-environmental health subsystem in Guangxi Zhuang Autonomous Region from 2009 to 2021.

4 Discussion

To further deepen the development of tourism industry changes, accelerate the promotion of new urbanization construction, and actively promote the construction of ecological civilization based on vigorously maintaining the original ecology; at the same time to further strengthen the linkage of the three, fully create the "1 + 1 + 1 > 3" spillover effect, so that the three present a positive degree of coupling and coordination to promote the tourism industry, new urbanization and ecological civilization. The new epidemic, China's economic growth rate, and environmental health are constantly being tested, and the interaction between various factors has brought serious challenges to the sustainable development of China's tourism industry, new urbanization, and environmental health, and in the post-epidemic era, all industries have ushered in new development opportunities:

First, promote the low-carbon transformation of the industry and help upgrade the industrial structure.

In the field of new urbanization construction, from the government level, first, it should strengthen the control of energy consumption intensity and quantity, curb the blind development of high energy-consuming and high-emission industrial projects, and promote the optimization and upgrading of industrial structure; second, it should enhance the effect of energy utilization efficiency by implementing the amplitude saving of the secondary industry mainly in industry and construction, which can be done through the introduction of various award policies or tax incentives, etc. to Encourage localities to increase the consumption of renewable energy; third, it is necessary to coordinate the construction of new urbanization and the development plan of the tourism industry, avoid homogeneous development, eliminate the intensification of market competition caused by the waste of resources, and create favorable conditions for the formation of the core competitiveness of the tourism industry. Traditional industries are not the same as backward industries, as long as they continue to work on the word "reduction" and remove the label of high energy consumption and high emissions, they can be better integrated into the sustainable development process of the tourism industry and ecological environment.

Second, digital empowers the economy and creates new-quality productivity.

At present, the digital economy has penetrated one, two, and three industries, with intelligent technology as the engine of the new technology movement that is sweeping all walks of life. The most significant feature of the digital economy era is undoubtedly digitalization. Digital technology not only changes the traditional business model but also uses big data and Internet technology to enable a comprehensive industrial chain transformation of the traditional industrial economy, creating a deep integration of the digital economy and the traditional real economy. Starting from the government level, we should pay attention to the policy support and precise capital investment of the tourism industry, deepen the application of the digital economy in the tourism industry, and create new quality productivity, which can promote the structural upgrading of the tourism industry in a considerable period and drive the rapid development of the regional economy. At the same time, the construction of new urbanization also requires the development level of regional service industries, including tourism, to be upgraded, to boost development with domestic demand and enhance people's experience and identity by providing better services, thereby accelerating the construction of new urbanization and promoting the benign and coordinated development of the three.

Third, focus on green development goals, and maintain the sustainability of the environmental health system.

To promote healthy and coordinated development between the tourism industry, new urbanization, and environmental health, we should implement precise measures to promote the development level of the regional service industry. The improvement of the development level of the regional service industry will drive the development of the tourism industry and attract more tourists, which requires that the ecological environment should also be further improved to meet the growing demand of tourists for an ecological environment. Promote the integrated development of new urbanization, environmental health, and tourism industry with the concept of all-for-one tourism development, explore the depth and breadth of the environmental health system, and maintain the sustainability of the environmental health system. The regional economy and tourism industry are closely related to each other, and the ecological environment is the basis and long-term driving force for the development of the regional economy and tourism industry. China has been advocating the concept of a "community of human destiny," calling on all countries in the world to reduce disagreements, fight the epidemic together, protect the environment together, seek common development, and share the fruits. In the post-epidemic era, it is necessary to seize the favorable opportunity of the initial improvement of the ecological environment and make full use of the ecological environment to support and rely on the regional economy. "Green water and green mountains are the silver mountains of gold," a firm new development concept, fundamentally prevents the destruction of the ecological environment, increases the punishment for the destruction of the ecological environment, tries to maintain the original ecological environment, reduces automobile emissions, advocate new energy vehicles, maintain a good quality of the atmosphere, tourists will also be with the overall environmental health of the tourists will also travel and consume many times with the benign change of the whole environmental health, thus bringing more opportunities and positive orientation for the development change of tourism industry; meanwhile, the fundamental improvement of environmental health quality will also become the label of new urbanization construction.

5 Limitations and prospects

Based on the analysis of the tourism industry, new urbanization and environmental health system in Guangxi Zhuang Autonomous Region mainly from the perspective of economics, this study has some shortcomings in the details.

First, indicators of the tourism industry, new urbanization and environmental health systems. This study involves the construction of the three indicators in the index system and the selection of measurement methods and refers to the methods of some scholars, but the current academic community has not formed a consistent view on the construction and measurement methods of different indicator systems, and different scholars have different treatments and interpretations of related issues. Due to the complexity and diversity of the environmental health system, there are still some indicators that have not been included in the evaluation scope of the indicator system, and the process of empirical analysis, the quality of the indicators often determines the accuracy of the analysis results, so there may be a certain degree of imperfection in

the measurement of the indicators of the environmental health system.

Second, in terms of the choice of empirical methods, the entropy-weighted TOPSIS method and the coupling coordination model in quantitative analysis were used for analysis. In future research, the introduction of qualitative analysis, machine learning, and other methods may be able to increase the breadth of research argument perspectives.

Third, in addition to studying the coupling and coordination relationship between the tourism industry, new urbanization and environmental health system, there are still more systems that can be discussed, and they all have an impact on the overall development of the regional economy. In future research, we can not only study the relationship between more systems but also conduct more in-depth research on the subsystems in the tourism industry, such as catering, accommodation, transportation, etc., to increase the depth and comprehensiveness of the research.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/supplementary material.

Ethics statement

The studies involving humans were approved by Guangxi University for Nationalities. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

QM: Writing – original draft, Writing – review & editing. HP: Data curation, Methodology, Software, Writing – review & editing. YN: Writing – original draft, Writing – review & editing. JM: Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Economic policy uncertainty and corporate innovation-empirical evidence from Chinese pharmaceutical listed companies

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Introduction: Under the background that economic policy uncertainty tends to be normal, the innovation behavior of enterprises can cope with the cost impact brought by economic policy uncertainty.

Methods: Based on the relevant data of China's A-share pharmaceutical listed companies from 2015 to 2022, this paper empirically studied the relationship between economic policy uncertainty and firm innovation by using fixed-effect model, intermediary model, instrumental variable method and two-step method, and investigated the mechanism effects of financialization, executive compensation and government subsidies.

Conclusion: Economic policy uncertainty significantly increases the innovation intensity of enterprises. Enterprises with dual management, overseas background and non-state-owned ownership will increase their innovative behavior in the face of economic policy uncertainty. Further analysis shows that economic policy uncertainty increases the innovation intensity of enterprises through three mechanisms: increasing financial transformation, obtaining government subsidies and motivating management. Increasing the innovation intensity of enterprises can deal with the risk impact caused by economic policy uncertainty, but can not deal with the negative impact of cost increase. The transformation of financialization can help enterprises cope with the operational risks and later costs caused by economic policy uncertainty.

Discussion: This study provides empirical evidence for the theoretical inference that firms respond to the impact of economic policy uncertainty and thus increase their innovation behavior.

KEYWORDS

economic policy uncertainty, corporate innovation, financialization, listed pharmaceutical companies, cost

1 Introduction

In recent years, the external business environment of various enterprises has been characterized by instability, largely as a consequence of the impact of the global financial crisis, depressed international markets, low consumer dynamics, and public safety and health incidents. A comparison of the economic policy uncertainty index, as measured by Scott Baker, reveals that China's economic policy uncertainty index in 2022 is 12.8 times higher than that

of 2000.[1] Additionally, the team assesses the economic policy uncertainty of other countries. A comparison of the data reveals that the U.S. economic policy uncertainty index in 2022 is 1.17 times higher than that of 2000, while the world economic uncertainty index in 2022 is 3.78 times that of 2000. The gradual increase in economic policy uncertainty has had a detrimental impact on the normal functioning of the economy. This has manifested in various ways, including a negative effect on stock market returns (1, 61), a deterioration in market expectations (2), an exacerbation of capital outflows, and the triggering of economic turmoil in a number of countries, which has led to increased volatility in the food market (3). In order to circumvent the repercussions of the economic crisis, countries implement irregular adjustments to their economic policies in order to navigate the market turbulence, which in turn gives rise to an increase in the economic policy uncertainty index. In the context of rising economic policy uncertainty, the question of how enterprises can build their competitive advantage to cope with the various adverse effects has become a key research topic. Innovation is widely recognized as a driving force of development, and the ability to innovate is crucial to the sustainable development of enterprises. However, the continuous changes in economic development policies make the development environment of enterprises dramatically turbulent, which impacts the enterprises' R&D and innovation activities. The manner in which economic policy uncertainty affects enterprise behavior has become a topic of growing interest among scholars, who are engaged in research to elucidate the pathways of influence.

In previous studies, research on economic policy uncertainty has focused on economic activities such as trade and import/export, business transformation, and unemployment, while after the outbreak of the COVID-19 pandemic in 2020, economic policy uncertainty has increased dramatically worldwide, and the volatility of the macroeconomic environment has caused firms' strategic planning and resource allocation to be affected. The research focuses on how economic policy uncertainty affects corporate finance, capital flows, and investment, among others, in order to counteract the shocks caused by economic policy uncertainty. Enterprise innovation is the main way for manufacturing enterprises to develop their core business and enhance their competitiveness, but enterprise innovation is also accompanied by long cycles, high investments, and irreversibility, which is more obvious in the pharmaceutical field. With the increasing trend of aging and changes in the disease spectrum, products in the pharmaceutical manufacturing industry need to be constantly updated and iterated, and enterprises need to continuously invest in innovation to improve their competitiveness. To maintain competitiveness and market share, pharmaceutical companies must constantly seek new areas of growth. Innovation has become a key way for companies to manage uncertainty and achieve sustainable development. When the external economic environment is turbulent, companies will choose to tighten their capital, save money in all aspects of spending, and prioritize the allocation of funds to more promising projects, which will have an impact on the company's competitiveness.

For enterprises, on the one hand, economic policy uncertainty will promote enterprises to enhance their sense of crisis, actively save cash flow, avoid unnecessary expenses, and enhance innovation investment in their main business in order to increase their competitiveness; on the other hand, economic policy uncertainty will increase the difficulty of financing for enterprises, leading to an increase in enterprise risk, and enterprises will reduce their investment and innovation activities in order to avoid the risk. Therefore there are two views on economic policy uncertainty, one view is that firms' innovation activity is a continuous investment activity that requires high adjustment costs, and uncertainty can increase firms' resilience by actively saving cash in the early stage, making it possible to have enough funds to maintain R&D activities in uncertain times, so as to stay ahead of competing firms and gain an over-expected market share. In the case of economic policy uncertainty, pharmaceutical enterprises find it difficult to accurately predict the direction and impact of the policy, there may be huge risks, but due to the long cycle of pharmaceutical product innovation, the characteristics of continuous investment, pharmaceutical enterprises still need to maintain a continuous investment in technological innovation, through increasing R&D efforts, the introduction of advanced technology and management experience, enterprises can continue to enhance their innovation capabilities and core competitiveness to better cope with market changes and competitive challenges. The other view is that economic policy uncertainty makes it difficult for firms to meet their annual expectations, leading to fluctuations in firms' market expectations and inhibiting their innovative activities, which will lead to serious operational risks, reduced capital expenditure, and higher financing costs for firms. Economic policies uncertain policies may have an impact on market supply and demand, market prices, and the competitive landscape of the market, and pharmaceutical companies are often influenced by market expectations when making technology innovation decisions. Uncertain market expectations may make pharmaceutical manufacturing enterprises more cautious in technological innovation, thus affecting innovation effectiveness and market competitiveness. As a result of increased financing costs and risks, pharmaceutical manufacturing firms may make decisions to reduce investment in innovation.

One potential solution to the issue of financing difficulties in the process of financialization, which can be defined as the structural optimization of firms in order to mitigate the impact of external shocks. In the context of economic uncertainty, enterprises are compelled to adapt their internal strategies and structures in order to mitigate the impact of external environmental factors. The potential risks associated with production and operational challenges disrupted capital chains, and financing constraints provide enterprises with a compelling motivation to expedite the transformation of financialization. On the one hand, enterprises leverage the reservoir effect of financialization to accumulate and enhance their asset liquidity and liquid cash reserves, thereby reducing the capital breakage of enterprise-related activities (4, 5); alternatively, from a financing perspective, enhanced transparency of corporate information and increased financial investment can mitigate the risk of collapse (6) and alleviate constraints on financing (7). An increase in financial investment can alleviate constraints on financing and prompt enterprises to allocate more funds to the R&D process. The continuity of R&D funding enables enterprises to enhance their innovation capabilities, strengthen their product competitiveness, and improve their resilience to external environmental risks. This illustrates the efficiency of financialization in mitigating the impact of

1 The Baker team updated the economic policy uncertainty index based on the calculations of Baker (68), sourced from the economic policy uncertainty index on China at http://www.policyuncertainty.com.

business risks associated with economic policy uncertainty. Pharmaceutical companies, due to the distinctive characteristics of the industry, require sustained innovation to bolster enterprise competitiveness. Consequently, the demand for innovation is particularly high in this sector.

In addition to structural optimization, internal management optimization is also a strategy employed by firms to mitigate the impact of external shocks. Executive incentives represent a specific form of internal management optimization pursued by firms to enhance their resilience to external transformations. Prior research has demonstrated that executive incentives constitute a significant factor influencing managerial decisions to increase investment in corporate innovation. In the context of economic policy uncertainty, firms are exposed to a dual risk: that of their main business and that of changes in their own managers. On the one hand, executive compensation incentives can effectively address the principal-agent conflict, mitigate the risk-aversion tendency of management, and stimulate enthusiasm for venture capital projects, thereby increasing the innovation output of the enterprise (63). Conversely, executive compensation incentives can be viewed as a cost-effective internal governance mechanism. They have the potential to curtail the exploitative practices of senior managers with regard to resources, whilst simultaneously enhancing the efficiency of R&D activities (9). By implementing reasonable improvements to the executive incentive policy, it is more feasible to stabilize the internal governance of the firm and provide guidance against external risk shocks.

In the market mechanism, the enterprise's R&D and innovation activities are external, and the enterprise has to bear all the R&D costs in the R&D and innovation activities, in the background of the economic policy uncertainty, the impact brought by the external environment may make the enterprise to reduce the income that it should have, so as to reduce the enterprise's R&D enthusiasm. In this context, government subsidies will help enterprises get rid of financial difficulties and better deploy resources to innovative R&D (10). On the one hand, pharmaceutical enterprises are technology-driven, and such enterprises must provide sufficient funds for research to develop new products or services (11) to ensure the competitiveness of their own business, and government subsidies offset the financial constraints caused by market failures by compensating for innovation inputs (12); on the other hand, targeted government subsidies can help redistribute the labor force (8) and enhance the innovation efficiency of enterprises.

In light of the aforementioned analyzes, the objective of this research is to examine the impact of economic uncertainty on innovation in the pharmaceutical industry. To this end, the following questions will be addressed: firstly, how does economic policy uncertainty affect innovation in pharmaceutical manufacturing firms? Secondly, it is necessary to identify the mechanism through which economic policy uncertainty affects innovation in pharmaceutical manufacturing companies. Thirdly, what strategies can be employed to mitigate the impact of economic policy uncertainty fluctuations?

In order to respond to the aforementioned questions, this paper utilizes data from China's A-share listed pharmaceutical manufacturing firms from 2015 to 2022, with the objective of evaluating the influence of economic policy uncertainty on pharmaceutical manufacturing firms' innovation. This paper makes a number of contributions to the existing literature. Firstly, it explores the factors affecting corporate innovation from the perspective of economic uncertainty. While existing studies have explored the factors affecting corporate innovation from the perspective of policy incentives based on government subsidies (13), corporate governance (14), and internationalization (15), this paper explores the factors affecting corporate innovation from the perspective of macroeconomic uncertainty. This leads to the rise of economic policy uncertainty, which increases the willingness to innovate in response to external shocks, further expanding the study of corporate innovation from a macro perspective. This paper contributes to the existing literature on enterprise innovation by examining the willingness of enterprises to innovate in response to external shocks due to rising economic policy uncertainty from a macro perspective. Secondly, the mechanism of action is subjected to further examination. The extant literature on economic policy uncertainty has primarily focused on examining the impact of such uncertainty on investment risks, stock returns, and the financial industry as a whole. Additionally, studies on the relationship between economic policy uncertainty and innovation have predominantly concentrated on the industry as a whole or the manufacturing industry, with a comparatively limited number of studies examining the pharmaceutical manufacturing industry. In the context of the current era, which is characterized by unprecedented change, economic policy uncertainty is likely to persist for the foreseeable future. The pharmaceutical manufacturing industry is witnessing the emergence of an increasing number of innovative drugs, and economic policy plays an important role in guiding the strategic direction of enterprises. Consequently, it is becoming an increasingly influential factor. This paper examines the role of the enterprise in the innovation process from both internal and external perspectives. It confirms that reasonable financialization, executive incentives, and government subsidies can effectively enhance the enterprise's innovation ability, improve the enterprise's own ability to cope with the impact of economic policy uncertainty, and provide empirical evidence for the enterprise to enhance its innovation ability. Thirdly, the present study focuses on the pharmaceutical manufacturing industry. Currently, there is a paucity of research examining the nexus between economic policy uncertainty and enterprise innovation. The majority of extant studies tend to adopt a macro-level perspective, with scant attention paid to the pharmaceutical industry. In the current era, the pharmaceutical manufacturing industry has garnered considerable attention, particularly in light of the promotion of the strategy of Healthy China. The advent of innovative drug companies has underscored the necessity for pharmaceutical enterprises to prioritize innovation as a cornerstone of their organizational development. This paper will examine the influence of research and development (R&D) and innovation within the pharmaceutical industry through the lens of economic policy uncertainty, thereby addressing existing gaps in the literature and providing crucial insights for effectively navigating the impact of economic policy uncertainty on pharmaceutical manufacturing enterprises and enhancing their self-competitiveness. It offers a crucial point of reference for pharmaceutical manufacturing enterprises seeking to mitigate the impact of economic policy uncertainty and enhance their competitiveness. The contemporary global context is characterized by complexity and volatility, with the ascendance of uncertainty representing a pervasive challenge for humanity. This paper illustrates that, in the context of economic policy uncertainty, the utilization of appropriate tools is essential for enhancing enterprise resilience to external shocks and facilitating sustainable development.

This paper is divided into five sections, Section 1 is the introductory section; Section 2 is a summary of the relevant literature on economic policy uncertainty and the formulation of the research

hypotheses; Sections 3–5 are the modeling and data analysis; Section 6 is the conclusions and recommendations; and Section 7 is the shortcomings of the article.

2 Literature review and research hypotheses

2.1 Economic policy uncertainty and firms' R&D intensity

The concept of economic policy uncertainty can be defined as the inability of economic agents to accurately predict the timing, nature and extent of future changes to the government's current economic policy (16). For an extended period, scholars have engaged in the study of economic operations and market regulations. In the wake of the global economic crisis of 2008, countries have intervened in the real economy and modified economic policy on an ongoing basis in order to mitigate the risk of another crisis. However, this has led to an increase in economic policy uncertainty. China has been undergoing a critical period of economic development, progressing from a high-speed to a high-quality growth trajectory. This has entailed frequent adjustments to reform policies across a range of sectors, including finance, property, manufacturing and capital markets. While these measures have had discernible consequences, they have also heightened uncertainty. From an economic perspective, policy uncertainty has a significant impact on a number of key areas, including macroeconomic operations, monetary policy, and corporate behavior. In a study conducted in 2017, Knut Are Aastveit employed structural vector autoregression to examine the interaction between economic policy uncertainty and monetary policy shocks in the United States (17). The findings indicated that when uncertainty is elevated, the impact on investment behavior is particularly pronounced. In a similar study conducted in 2019, He Minyuan and colleagues observed that when economic policy uncertainty is higher, the tax burden on firms is heavier (18). Zheng et al. (2020) demonstrated that economic policy uncertainty has a detrimental impact on firms' innovation behavior. Conversely, economic policy uncertainty can affect the internal operations of firms. Sha et al. (19) investigated the relationship between economic policy uncertainty and mergers and acquisitions in China. Their findings suggest that Chinese firms are more likely to engage in acquisitions and increase the wealth of the acquirer during periods of high economic policy uncertainty. In a study conducted in 2019, Chen discovered a negative correlation between economic policy uncertainty and corporate risk-taking, among other factors (27). Zhang (20) and Qi et al. (21) demonstrated that economic policy uncertainty exerts an influence on investor sentiment and financial stability.

As noted by Nick (66), frequent alterations to macroeconomic policy can result in transient negative impacts on firms during periods of economic contraction. In response, firms may transition from short-term to long-term investments, aiming to secure more resilient economic returns. In accordance with the tenets of the growth option theory, it can be posited that when confronted with the specter of economic policy uncertainty, the prospective advantages of a firm's innovative conduct may be regarded as a growth option. It is further postulated that the ascendant uncertainty will engender a greater propensity to utilize the option, thereby enhancing the anticipated returns (22). It has been demonstrated that economic policy uncertainty engenders augmented profits and enhances the option value of the firm (23). As the value of the enterprise's options increases, so too does the benefit derived from innovation output, prompting the enterprise to increase the intensity of its innovation investment and thereby creating a positive feedback loop. The analysis of competitive analysis theory indicates that economic policy uncertainty will increase the information asymmetry of the enterprise, resulting in higher costs. However, the enterprise will seek to enhance its competitiveness and operational efficiency by increasing its innovation investment and market share (24, 25). In light of the aforementioned theory, the following hypothesis is put forth:

> *H1:* An increase in economic policy uncertainty has been observed to result in a heightened level of investment in innovation by firms.

2.2 Mechanisms by which economic policy uncertainty affects innovation intensity

2.2.1 Financialization of enterprises

The fundamental characteristics of continuous innovation are a lengthy cycle time, elevated risk, and a robust demand for capital. This implies that organizations must sustain their capital investments to maintain uninterrupted innovation and exhibit a heightened need for liquidity. It is not uncommon for non-financial firms to engage in financialization, which can be regarded as a normal investment activity that enables firms to pursue market profits and support their innovative behavior. Lee et al. (26) found that non-financial firms are motivated to hold financial assets mainly due to precautionary motives and to hold moderate holdings of financial assets against liquidity risk. The volatility of economic policies gives rise to an increase in market risk. In order to mitigate financing constraints and hedge risks, non-financial firms will hold more liquid financial assets for precautionary motives. By holding financial assets, firms can enhance their cash liquidity and ensure sufficient internal funding, while also mitigating the pressure and dependence on external financing. Hu et al. (7) posited that corporate financialization can satisfy the requirements of corporate innovation funds, thereby initiating innovative activities and enhancing corporate competitiveness. In the context of economic policy uncertainty, firms face heightened pressure to secure external financing, underscoring the need for sufficient cash reserves to support innovation. Corporate financialization serves as a reservoir, increasing corporate financial assets to satisfy corporate innovation activities, ensure innovation sustainability, and withstand negative shocks from economic policy uncertainty (59, 62). Concurrently, Jia (67) and other scholars posit that organizations should contemplate the prospective operational challenges and financial crises that they may encounter in the future. They advocate for an increase in liquid assets, such as financial assets that can be readily realized. In the event of insufficient funds for investment, production, and operational activities, and the capacity to provide financial support for continuous technological innovation, the enterprise may consider enhancing its innovation investment (28). This leads to the formulation of hypothesis two:

> *H2:* Economic policy uncertainty has a positive effect on firms' innovation inputs through the financialization mechanism.

2.2.2 Executive motivation

The R&D and innovation activities of enterprises are influenced by a range of internal and external factors. In addition to these external factors, managers represent another internal factor that affects the activities of enterprises (29). In accordance with the principal-agent theory, executives, in their capacity as agents of the enterprise, are driven by a combination of their own interests and those of the enterprise to pursue excess investment returns from the market (30). In accordance with the theory of high management, the actions of executives themselves can influence the enterprise's decision-making processes (31). It is inevitable that managers will be biased based on their interests. In selecting strategies for the short term, managers will favour those that benefit their interests, and will tend to avoid risky decisions such as high-risk research and development innovations (32). With regard to executive compensation, Zhou and Yang (33) posits that salary incentives for executives can foster convergence between personal and corporate interests, thereby enhancing their willingness to innovate and motivation to develop. Lu and Liang (34) and others contend that executive compensation incentives can improve corporate performance and significantly enhance the innovative performance of the enterprise, thereby improving business innovation. Dong and Qin (35) further argues that executive compensation incentives can promote innovation programs and the transformation of innovation results. It is thought that increased executive compensation incentives will produce an "innovation compensation effect," which will motivate executives to devote more time and energy to innovation management and reduce the tendency to avoid certain risky decisions. In the context of economic policy uncertainty, it is possible that executives may opt for more stable options. In the face of environmental uncertainty, employees may be driven to change jobs more frequently, thereby introducing significant internal instability into the enterprise. Moreover, an increase in executive incentive behavior may encourage executives to prioritise the company's innovative projects. When firms give more incentives to managers, it will encourage managers to care more about the long-term development of the firm, and it will also mean that firms will provide more attention and support to innovation activities, leading to hypothesis three in this analysis:

> *H3:* The uncertainty of economic policy has been demonstrated to stimulate corporate investment in innovation by enhancing the incentives for management.

2.2.3 Government subsidies

The theory of market failure posits that the state of perfect competition in the market represents an optimal structure for resource allocation. However, market regulation can be prone to blindness and may not fully account for the nuances of economic functions. Consequently, market failure is a phenomenon that exists (36). In the context of market uncertainty, the incentive effect of market competitiveness on innovation is diminished, whereas government subsidies have the potential to reinforce this effect (37). Government subsidies are important in promoting investment and economic growth, restructuring industries, guiding the economy's direction, maintaining social stability, and creating employment opportunities. By implementing a targeted subsidy policy, the government can effectively disseminate signals pertaining to industrial adjustment and market demand, thereby establishing a clear direction (38). This approach addresses the information asymmetry prevalent between enterprises and investors with regard to R&D and innovation activities, thereby stimulating enterprise innovation activities. The provision of government subsidies to relevant projects will assist enterprises in alleviating the immediate pressure on their investment resources, thereby facilitating the promotion of innovative activities. Consequently, enterprises will enhance their innovative activities in order to increase the likelihood of being awarded further government subsidies (39). In the case of insufficient endogenous financing and limited exogenous financing for enterprises, government subsidies are an important means of injecting capital into enterprises. In the context of economic policy uncertainty, the government provides subsidies to innovative enterprises as a means of conveying the message that innovation is encouraged by the government. This encourages enterprises to enhance their innovation intensity in order to mitigate the risk posed by environmental fluctuations. In light of the aforementioned analysis, the following hypothesis is proposed:

> *H4:* The uncertainty of economic policy has an enhancing effect on the investment of firms in innovation, due to an increase in the effectiveness of government subsidy mechanisms.

2.3 Manufacturing firms cope with operating costs and business risks

An increase in economic policy uncertainty will result in elevated operating costs and operational risks for enterprises, which will have a detrimental impact on their capacity to enhance innovation intensity and pursue financialization. The extant literature indicates that when economic policy uncertainty increases, enterprises will tend to increase their R&D intensity in order to achieve superior long-term returns and to withstand the impact of the external environment. Meng and Shi (40) posit that economic policy uncertainty will promote corporate innovation, while Xi and Zhang (41) has demonstrated that economic uncertainty has a positive impact on innovation investment through research. However, given the distinctive nature of pharmaceutical manufacturing companies' innovation activities, which entail a longer cycle and greater risk, the pharmaceutical industry's profit and revenue growth hinges on the development of proprietary products and innovative drugs. Consequently, enterprises will not curtail their innovation activities, forego necessary innovation costs, or reduce the negative impact of operating costs. Bu et al. (42) identified a discrepancy between the inputs and outputs of innovation. Yan and Hu (43) employed a multiple linear regression model to demonstrate that an increase in economic policy uncertainty prompts enterprises to enhance their innovation inputs. The specificity of pharmaceutical products enables them to reach a distinct consumer group. Consequently, when enterprises intensify their innovation inputs, they can elevate the quality of their pharmaceutical products and accelerate clinical enrolment, thereby enhancing their competitiveness and reducing operational risk. In light of the aforementioned analysis, the following hypotheses are put forth for consideration:

> *H5a:* An increase in innovation intensity can serve to mitigate the adverse effects of elevated operational risk faced by firms. However, it is not a panacea for the negative consequences of rising operational costs.

In regard to the financialization of firms, Michael (69) posits that economic policy uncertainty exerts an influence on bank credit, which in turn leads to a narrowing of bank credit, thus increasing the risk of external financing and operational risk for firms. Fatima and Waheed (44) employs a market analysis of Pakistan to demonstrate that economic policy uncertainty precipitates a deterioration in market investment and an increase in the risk of corporate finance. Conversely, policy uncertainty will also serve to increase the degree of information asymmetry between internal and external enterprises, which will produce the 'lemon effect' and increase the agency cost within the enterprise (45). Furthermore, it will intensify the discrepancy between the enterprise and the bank's information, thereby impairing the bank's capacity to accurately assess the enterprise's repayment capability (64). This often culminates in delayed or denied lending, which in turn leads to a reduction in operational efficiency and an increase in the enterprise's operating costs. In order to address the impact of risk and cost, enterprises frequently implement related strategies. Zheng (2021) and others have demonstrated that moderate financialization can stimulate enterprise investment in continuous innovation (65). Xu et al. (46) and others have proposed that financialization reduces the level of enterprise risk-taking, but it also results in the withdrawal of industrial capital from the real business, which has an adverse impact on competition for the enterprise's products and sustainable development. The process of financialization enables enterprises to increase their internal financing, reduce their dependence on external financing, and obtain excess returns. It also allows them to reduce their operating costs and increase their financial investment costs. However, there is a risk that if financialization is overused in the long term, it could result in a shift from the real economy to the virtual economy. An increase is to be expected. The following hypothesis is put forth for consideration:

> *H5b:* Financialization may continue to accommodate the risk implications of economic policy uncertainty; however, the response effect will be diminished with the escalation of financialization risk. Due to the lagged nature of the investment, financialization serves to mitigate the impact of cost shocks in subsequent periods; however, it is not a panacea for addressing cost shocks in the current period.

3 Research design

3.1 Model setting and sample selection

In order to identify the impact of economic policy uncertainty on enterprise innovation, this paper uses the fixed effect model to construct the following econometric model:

$$RD_{i,t} = \beta_0 + \beta_1 EPU_t + \delta Contral_{i,t} + \mu_i + \varepsilon_{i,t} \quad (1)$$

The subscripts i and t in its Equation 1 denote firms and years, respectively, with economic policy uncertainty as the explanatory variable and firm innovation as the explanatory variable, Control denotes the set of control variables, μ_i is the firms' individual fixed effect, and $\varepsilon_{i,t}$ is the random perturbation term. Referring to the approach of Wang and Tian (47). In this paper, we refrain from controlling for time-fixed effects due to the fact that the economic policy uncertainty index is a country-level time series, which would inevitably lead to the issue of multicollinearity if we were to control for time fixed effects. The regression coefficient β_1, as shown in the above regression equation, is of particular interest. A positive β_1 indicates that an increase in economic policy uncertainty encourages firms to pursue digital transformation, whereas a negative β_1 implies that it hinders such efforts.

In this paper, A-share listed companies in the pharmaceutical manufacturing industry from 2015 to 2022 are selected as the initial research sample to explore the relationship between economic policy uncertainty and corporate innovation and the relationship between financialization. In order to ensure the data validity, the sample is processed as follows: firstly, financial companies are excluded; secondly, samples with ST and period delisting are excluded; thirdly, samples of companies with missing key variables for three consecutive years are excluded, and finally, 1,128 observation samples are obtained. The raw data are all from the Cathay Pacific database (CSMAR) and the China Research Data Service Platform (CNRDS), and the relevant financial data are from the RESSET database.

3.2 Mechanism analysis model setting

In order to determine the impact of economic policy uncertainty on enterprise innovation, drawing on the idea of Jiang (60), this paper constructs the following model:

$$FIN_{i,t} / PAY_{i,t} = \alpha_0 + \alpha_1 EPU_t + \delta Contral_{i,t} + \mu_i + \varepsilon_{i,t} \quad (2)$$

$$RD_{i,t} = \omega_0 + \omega_1 EPU_t + \omega_2 FIN_{i,t} / PAY_{i,t} + \delta Contral_{i,t} + \mu_i + \varepsilon_{i,t} \quad (3)$$

Where (Equation 2) FIN, PAY denotes corporate financialization and executive incentives, Control denotes the set of control variables, μ_i is the firm's individual fixed effect, and $\varepsilon_{i,t}$ is the random perturbation term. The model allows for the verification of the impact of economic policy uncertainty on firms' innovation intensity. It is essential to ascertain whether the ω_1 and α_1 coefficients are statistically significant in order to determine whether the effect is positive or negative.

3.3 Definition of variables

3.3.1 Explained variables

Firm Innovation (RD). Academics divide the indicators for measuring enterprise innovation into R&D input and R&D output. The timeframe from R&D input to patent approval is very long. In contrast, the enterprise innovation studied in this paper is more interested in the enterprise's willingness to innovate in the case of economic policy uncertainty. Hence, this paper draws on the practice of Sun and Chen (49) and adopts the ratio of the enterprise's R&D investment in operating revenues as an indicator of enterprise innovation.

3.3.2 Explanatory variables

Economic policy uncertainty (EPU). The Baker et al. (68) team counted, developed, and published an index of China's economic policy uncertainty by searching for keywords on the South China Morning Post reports. The index is widely used in existing research,

TABLE 1 Definition of variables.

Variable name	Variable symbol	Description of variable
Firm innovation	RD	Firm's R&D investment as a percentage of operating income
Economic policy uncertainty	EPU	Statistics and formulation of SCMP reports by searching keywords
Firm size	SIZE	Natural logarithmic value of firm's total assets
Corporate debt ratio	LEV	Ratio of current year's liabilities to total assets of a company
TOP ratio of shares held by the largest shareholder	TOP	Ratio of the number of shares held by the largest shareholder to the total number of shares
Ratio of tangible assets	YX	Ratio of total tangible assets to total assets
Administrative expense ratio	GL	Administrative expense to total assets of the enterprise
Cash flow ratio	FCF	Ratio of cash flow to total assets
Operating income growth rate	YY	(Operating income current year current single quarter amount − Operating income previous single quarter amount)/Operating income previous single quarter amount
Tobin's Q	TQ	Ratio of firm's market capitalisation to total assets
Financialization	FIN	Ratio of financial assets to total corporate assets
Government subsidies	BT	Ratio of government subsidies to total assets or operating income
Executive incentives	PAY	The natural logarithm of the total compensation of the top three executives in the firm's payroll
Innovation output	PAT	The logarithm of the number of patent applications filed by the company in the year +1.
Cost	COST	Operating Costs to Operating Revenue Ratio
Operating risk	RISK	Three-year rolling standard deviation of total net asset margins

has been extensively tested and applied, and has been proven to have a certain degree of validity and stability. Since the index is a monthly index, this paper obtains the annual index by taking the arithmetic mean after summing the monthly data of each year and dividing the index by 100 to ensure the consistency of the data.

3.3.3 Control variables

The innovation of an enterprise is affected by the enterprise's own resources. In this paper, we adopt the following control variables: firm size (SIZE), defined as the natural logarithmic value of the enterprise's total assets; enterprise liability ratio (LEV), defined as the ratio of the enterprise's current year liabilities to total assets, which is used to measure the enterprise's level of financial risk. The proportion of the largest shareholder's shareholdings (TOP), defined as the ratio of the number of shares held by the largest shareholder to the total number of shares, the willingness of the largest shareholder exerts a significant influence on the implementation of the enterprise's innovation project and the importance of the project. The Tangible Assets Ratio (YX), defined as the total amount of tangible assets to the ratio of the total assets, provides insight into the structure of the enterprise. The Management Expense Ratio (GL) is defined as the ratio of management expenses to total assets and is used to reflect the management style of the company. The Cash Flow Ratio (FCF) is defined as the ratio of cash flow to total assets and shows the capital status of the company. Tobin's Q (TQ) is defined as the ratio of the company's market capitalization to total assets and is used to reflect the market value of the company. The growth rate of operating income (YY) provides insight into the growth trajectory of the firm. Table 1 delineates the variable definitions.

4 Analysis of empirical results

4.1 Descriptive statistics

The descriptive statistics of the variables are shown in Table 2. The mean value of the enterprise innovation R&D investment is 6.18%, and the standard deviation is 7.87%, which shows that the overall R&D investment among the sample enterprises is not high. The maximum and minimum values of the sample are a significant difference in R&D investment. From 2015 through 2022, the mean value of China's economic policy uncertainty is 5.17, and the standard deviation is 0.10, which shows that the degree of China's economic policy changes is noticeable. Meanwhile, the mean value of financialization is 7.60%, and the standard deviation is 10.41%. The overall degree of financialization is low, and the sample's maximum and minimum values can show a significant difference in financialization development between the samples.

4.2 Correlation analysis

Table 3 demonstrates the Spearman correlation coefficients between the variables. The VIF values are all less than 5, indicating no severe multicollinearity problem in the data.

4.3 Benchmark regression analysis

Table 4 reports the results of the benchmark regression of economic policy uncertainty on innovation in pharmaceutical manufacturing

TABLE 2 Results of descriptive statistics.

Variable	Sample size	Mean	Standard deviation	Minimum	Maximum
RD	1,128	0.0618	0.0787	0.0001	1.6700
EPU	1,128	5.1700	2.0360	1.8120	7.9190
SIZE	1,128	21.5437	1.1162	18.5786	24.9796
LEV	1,128	0.3217	0.1708	0.0143	0.8858
TOP	1,128	32.1247	13.0934	4.1800	69.1600
YX	1,128	0.8994	0.0977	0.4191	1.0000
GL	1,128	0.1013	0.0751	0.0054	1.3601
FCF	1,128	0.0694	0.6151	−0.1487	0.4706
YY	1,128	0.1831	1.0947	−1.6723	32.9643
TQ	1,128	2.5986	1.9424	0.7152	22.5724
FIN	1,128	0.0761	0.1041	0	0.7556
BT	1,128	0.1253	0.1564	0	0.1919
PAY	1,128	14.8154	0.7181	12.5707	17.6935
PAT	1,128	2.5872	1.2684	0.0000	6.2672
COST	1,128	0.4875	0.4277	0.0526	7.1063
RISK	791	0.5145	0.0510	0	0.5130

firms. Columns (1) and (2) present the results of the benchmark regression of economic policy uncertainty on innovation of pharmaceutical manufacturing firms. Column (1) presents the estimation results with only economic policy uncertainty included when the regression coefficient of economic policy uncertainty is significantly positive. The results in column (2) show that the economic policy uncertainty regression coefficient is still significantly positive after adding control variables. This paper chooses column (2) as the baseline regression estimation results. The results show that the regression coefficient of economic policy uncertainty is 0.0042, which is significant at a 5% statistical level. That is, economic policy uncertainty positively impacts the innovation of pharmaceutical manufacturing enterprises, which indicates that the rise of economic policy uncertainty presents the promotion of innovation investment in the pharmaceutical manufacturing industry. This result has the same significant economic result is also economically significant. When the economic policy uncertainty faced by firms increases by one standard deviation (2.03), firms are expected to increase the level of innovation investment by 1.16% (0.0057 × 2.03), which is 18.77% of the average innovation investment of pharmaceutical firms (6.18%). This result suggests that when facing the challenges posed by economic policy uncertainty, firms are more inclined to seize the opportunities presented by innovation, further improve the market competitiveness of pharmaceutical firms by increasing innovation investment, and obtain more resources to be lower than the negative impact of economic policy uncertainty. The hypothesis H1 of this paper is verified.

4.4 Robustness test

In order to improve the reliability of the estimation results of the research in this paper, the stability of the regression results is tested by using the replacement of the explanatory variables, the method of shrinking the tails and the replacement of the regression model. The results of the robustness tests are presented in Table 5.

4.4.1 Replacement of explanatory variables

In order to avoid the influence of the calculation of innovation input on the regression results, this paper, following the practice of Li et al. (50), Gao et al. (23), redefines the innovation input of the enterprise as the ratio of R&D investment to the total assets of the enterprise in the current period and redefines the innovation input as an explanatory variable to retest the H1 hypothesis, and the results are shown in Table 5. As can be seen from the figure, the results are significantly positive with the benchmark regression, and economic policy uncertainty helps to promote firms' innovation investment.

4.4.2 Tailoring

In order to eliminate the impact of extreme values, this paper uses the shrink-tailed processing method to detect the robustness of the benchmark results, this paper on continuous variables are at the 1% level Winsorize shrink-tailed processing, the results are shown in Table 5, the regression results and the benchmark regression results are all significantly positive, that is, economic policy uncertainty has a facilitating effect on pharmaceutical firms' innovation.

4.4.3 Replacement of regression methods

The base regression in this paper chooses the fixed effect model, so the OLS model is used to conduct the robustness test, and the results are shown in Table 5. The results from the table are the same as the results of the base regression, the coefficient of economic policy uncertainty is significantly positive, that is, in the face of increasing economic policy uncertainty, pharmaceutical manufacturing enterprises choose to increase investment in innovation to improve

TABLE 3 Results of variable correlation coefficient test.

	RD	LNPU	FIN	LEV	FCF	TQ	TOP	SIZE	GL	YX	YY
RD	1										
LNPU	0.088***	1									
FIN	0.067**	0.161***	1								
LEV	−0.069**	0.063**	−0.189***	1							
FCF	−0.079***	0.041	−0.004	−0.302***	1						
TQ	0.118***	−0.153***	0.003	−0.282***	0.233***	1					
TOP	−0.076**	−0.083***	−0.051*	−0.143***	0.207***	0.108***	1				
SIZE	−0.134***	0.149***	−0.036	0.236***	0.180***	−0.149***	0.158***	1			
GL	0.216***	−0.162***	0.028	0.085***	0.214***	0.042	−0.107***	−0.437***	1		
YX	0.022	0.105***	0.070**	0.007	0.047	0.098***	0.04	0.077***	−0.074**	1	
YY	−0.022	−0.059**	−0.048	0.024	0.01	−0.049*	−0.044	−0.022	0.043	−0.007	1

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

their market competitiveness to withstand the challenges brought by external environmental shocks.

4.4.4 Replacing explanatory variables

Davis et al. constructed a new set of economic policy uncertainty indices for China by keyword searching information from People's Daily and Guangming Daily. In order to avoid the influence of the calculation method of the economic policy uncertainty index on the results of the benchmark regression, this paper replaces the calculation method of the economic policy uncertainty index with that of Davis and uses the index as the core explanatory variable for the regression, and the regression results are shown in Table 5. Table 5 shows that the estimated coefficients of the explanatory variables are still significantly positive, indicating that the results of the benchmark regression are robust.

4.5 Endogeneity test

The estimation results of this paper may have endogeneity problems mainly caused by the following aspects: firstly, it is difficult to control all the factors affecting the innovation of pharmaceutical manufacturing enterprises in this paper, and omitted variables cause endogeneity problems; secondly, the estimation results of this paper may have reverse causality problems. For the problem of omitted variables in the regression model, this paper employs a fixed-effects model in the benchmark regression, which mitigates the impact of omitted variables on the estimation results to a certain extent.

4.5.1 Instrumental variable method

Following Peng et al. (51), this paper constructs instrumental variables by selecting the economic policy uncertainty of China's major trading countries. This paper selects the economic policy uncertainty data of seven countries, including Germany, France, Italy, Japan, South Korea, the United States, and the United Kingdom, for the period 2015–2022. The economic policy uncertainty of the above countries is weighted according to the weight of the annual import and export volume with China, and the economic policy uncertainty indices obtained after weighting are aggregated to derive an aggregated economic policy uncertainty variable as an instrumental variable, and a two-stage regression is conducted. The logic of selecting these variables is that the economic policy uncertainty of these countries

TABLE 4 Results of the baseline regression of economic policy uncertainty and innovation intensity.

	(1)	(2)
	RD	RD
LNPU	0.0034***	0.0057***
	(0.0011)	(0.0017)
LEV		−0.0385
		(0.0323)
FCF		−0.182**
		(0.0763)
TQ		−0.0001
		(0.0014)
TOP		0.0006
		(0.0006)
SIZE		−0.0071
		(0.0124)
GL		0.155*
		(0.0884)
YX		−0.0156
		(0.0401)
YY		−0.0007
		(0.0009)
Constant	0.0442***	0.191
	(0.0057)	(0.258)
N	1,128	1,128
R^2	0.013	0.063
Adj. R^2	0.013	0.055

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

TABLE 5 Robustness test results.

	Replacement of the explanatory variables	Tailoring	Substitution of explanatory variables	Replacement regression method
LNPU coefficient	0.0019***	0.0044***	0.0124***	0.0056***
Control variable	Yes	Yes	Yes	Yes
Fixed effect	Yes	Yes	Yes	No
Sample size	1,128	843	1,128	1,128
R^2	0.135	0.146	0.065	0.093
Adj. R^2	0.128	0.137	0.057	0.086

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

may affect China's economic policy uncertainty through the trade channel, and studies such as Li et al. (50) and Gu et al. (52) have proved that the economic policy uncertainty of other countries is highly unlikely to directly affect the business strategies of firms. Therefore, this instrumental variable is exogenous and relevant and can be used as an instrumental variable. Based on this, this paper conducts 2SLS regression with the weighted economic policy uncertainty of major trading countries as the instrumental variable, where the results of the first stage regression are shown in column (1) of Table 6, and the regression coefficients of the instrumental variable are significantly positive, and the results of the second stage regression are shown in column (2), the regression coefficients of the economic policy uncertainty index are significantly positive at the 1% level, and the F-statistic value of the instrumental variable is greater than the critical value of the Stock-Yogo weak identification test at the 10% level, indicating that the instrumental variable is not a weak instrumental variable.

TABLE 6 Instrumental variables approach.

Variables	(1)	(2)
	LNPU	RD
LNPU		0.0056***
IV	3.898***	
Control variable	Yes	Yes
Fixed Effects	Yes	Yes
Sample size	1,128	1,128
R^2 value		0.0860
F-statistic		20359.03

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

4.5.2 One-period lagged test of independent variables

In order to avoid reverse causality, this paper adopts a one-period lag treatment for the economic policy uncertainty index to circumvent the endogeneity problem and conducts regression analysis using the fixed effect model, as shown in Table 7, the economic policy uncertainty index is still positively correlated with the innovation intensity of the enterprise, and is significant at the 5% level.

4.6 Heterogeneity analysis

4.6.1 Management heterogeneity within firms

This paper conducts sample regressions by dividing the sample into the presence of two jobs, the absence of two jobs, the presence of overseas background, and the absence of overseas background based on the presence of two jobs for the management of the company and the presence of overseas background for the senior management. The results are shown in Table 8, where columns (1) and (2) are analyzed for the presence or absence of overseas background of management, and columns (3) and (4) are analyzed for the presence or absence of two-job integration of management. Firms with overseas backgrounds and dual jobs among executives are more likely to choose to increase the innovation intensity of their firms in the face of economic policy uncertainty than firms with no overseas backgrounds or dual jobs among executives. On the one hand, firms with two jobs tend to respond and adjust faster to external shocks or related policy changes. In contrast, firms without two jobs need to hold meetings to discuss shocks caused by the external environment, and their decision-making paths are longer, preventing them from making immediate decisions and delaying the time for the firm to make the optimal outcome. On the other hand, the fact that executives have overseas backgrounds indirectly verifies that executives have diversified educational backgrounds, are experienced in dealing with policy shifts, and have a wealth of theoretical knowledge in reserve so that they can grasp the general direction of the company, jump out of the existing thinking, and provide solutions to address external shocks. Therefore, a firm's management with a combination of both positions and an overseas background is more likely to significantly increase the firm's innovation intensity to cope with risks when economic policy uncertainty rises.

4.6.2 Enterprise ownership heterogeneity

In this paper, the sub-sample of SOEs and the sub-sample of non-SOEs are divided according to the type of ownership, and the sub-samples are regressed. Table 9 shows that non-state-owned enterprises tend to significantly increase their innovation intensity in the face of economic policy uncertainty compared to state-owned enterprises. The possible explanation for this is that due to the large size of SOEs and the complexity of their internal systems, SOEs face insignificant external risks and do not need to invest in innovation to capture the value of growth due to the long reaction time and dependence on national policies to cope with external shocks. Demand for reform and innovation is not strong, which has a negative impact on improving innovation intensity. In addition, SOEs are relatively less affected by the external policy environment and market competition and tend not to suddenly increase their investment in

TABLE 7 Lagged one-period regression of independent variables to test the endogeneity problem.

	(1)	(2)
	RD	RD
L.LNPU	0.0029**	0.0046***
	(0.0012)	(0.0015)
LEV		−0.0275
		(0.0389)
FCF		−0.168**
		(0.0721)
TQ		−0.0009
		(0.0018)
TOP1		0.0007
		(0.0007)
SIZE1		−0.0074
		(0.0144)
GL		0.158*
		(0.0944)
YX		−0.0418
		(0.0478)
YY		−0.0010
		(0.001)
Constant	0.05***	0.223
	(0.0058)	(0.3)
N	987	987
R^2	0.009	0.055
Adj. R^2	0.008	0.047

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

innovation, but continue to invest according to their previous plans. In contrast, in the face of external shocks, non-state enterprises tend to be more willing to optimize the internal environment and resist shocks and will increase the intensity of innovation investment in ongoing research projects in order to increase their market competitiveness and better cope with uncertainty.

5 Further analysis

5.1 Internal mechanisms of economic policy uncertainty affecting innovation in pharmaceutical manufacturing firms

Based on the analysis of the theory, increasing economic policy uncertainty strengthens the incentives for pharmaceutical manufacturing firms to innovate, and this is because economic policy uncertainty induces firms to undertake financialization shifts. Therefore, this paper first tests whether economic policy uncertainty induces financialization shifts within firms. Based on the idea of Jiang (48), the following model is constructed:

$$FIN_{i,t} / PAY_{i,t} = \alpha_0 + \alpha_1 EPU_t + \delta Contral_{i,t} + \mu_i + \varepsilon_{i,t} \quad (4)$$

According to the above model, observing whether α_1 in the equation is significant or not, it can be determined whether internal mechanisms are affected by economic policy uncertainty. Secondly, the above mechanism variables are included in the benchmark regression, which in turn tests whether the internal financialization of firms under economic policy uncertainty promotes firms to increase innovation intensity. The relevant econometric model is as follows:

$$RD_{i,t} = \omega_0 + \omega_1 EPU_t + \omega_2 FIN_{i,t} + \delta Contral_{i,t} + \mu_i + \varepsilon_{i,t} \quad (5)$$

$$RD_{i,t} = \gamma_0 + \gamma_1 EPU_t + \gamma_2 PAY_{i,t} + \delta Contral_{i,t} + \mu_i + \varepsilon_{i,t} \quad (6)$$

Observe whether the coefficients of the economic policy uncertainty index in Equations 5 and 6 are significant. On the degree of financialization (FIN). Based on Zhai and Dai (53) and others, it is measured by the ratio of financial assets to total assets of the company. Financial assets include trading financial assets, available-for-sale financial assets, derivative financial assets, long-term equity investments, held-to-maturity investments, and investment real estate, and the larger the indicator, the higher the business risk of the firm; for executive compensation, drawing on Zhu et al. (54), the natural logarithm of the total compensation of the firm's top three executives in terms of compensation is used to measure it, and the higher the indicator, the higher the level of incentive compensation. The control variables in Equations 2–5 are consistent with the benchmark regression.

Columns (1) and (2) of Table 10 present the estimation results of economic policy uncertainty on the degree of financialization of firms and executive compensation incentives. Based on the results in column (1), we can see that the coefficient of the effect of economic policy uncertainty on the degree of firm financialization is significantly positive, with a coefficient of 0.0067, i.e., an increase in economic policy uncertainty increases the degree of firm financialization. From column (2), the regression coefficient of economic policy uncertainty on firms' executive compensation incentives is 0.0703 and significant at the 1% level, i.e., an increase in economic policy uncertainty causes firms to increase executive compensation. It indicates that firms increase internal financialization and executive compensation when faced with economic policy uncertainty. Columns (3)(4) of Table 10 include financialization and executive compensation in the baseline regression, and from the results in column (3), the regression coefficient of financialization is 0.0555, which is significant and positive at the 5% level. The coefficient of economic policy uncertainty on firm innovation is also significant and positive, with a coefficient of 0.0053, which is lower than that in the baseline regression. It indicates that economic policy uncertainty leads firms to improve their innovation intensity by increasing their financialization. From the results in column (4), it can be seen that the regression coefficient of executive compensation is significantly positive when it is included in the base regression, and the coefficient of economic policy uncertainty on firms' innovation is 0.0042, which is significantly positive at the 5% level and lower than that of the base regression. It indicates that economic policy uncertainty will lead firms to improve their innovation strength by increasing the compensation of managers within the firm.

TABLE 8 Impact of management heterogeneity within firms.

	(1)	(2)	(3)	(4)
	No overseas background	Overseas background	Non-dual employment	Dual employment
LNPU	0.0011	0.0051*	0.004	0.0039***
	(0.0007)	(0.0028)	(0.0029)	(0.0014)
LEV	−0.0432**	−0.0563	−0.0212	−0.0404
	(0.0165)	(0.0478)	(0.0477)	(0.0254)
FCF	−0.0273	−0.260**	−0.168	−0.159***
	(0.0251)	(0.112)	(0.124)	(0.0564)
TQ	−0.0033***	0.0001	0.0009	0.0008
	(0.001)	(0.0013)	(0.0022)	(0.0027)
TOP1	0.0002	0.0002	−0.0001	0.00162**
	(0.0002)	(0.0006)	(0.0005)	(0.0007)
SIZE	−0.0034	0.0238	0.0148	0.0067
	(0.0076)	(0.0159)	(0.0152)	(0.0092)
GL	0.0715	0.375***	0.409***	0.141**
	(0.0504)	(0.0686)	(0.116)	(0.0645)
HB	0.0011*	−0.0008	−0.003*	0.0008
	(0.0006)	(0.0015)	(0.0017)	(0.0014)
YX	0.0356	−0.0185	−0.0204	0.0763
	(0.0286)	(0.0598)	(0.0499)	(0.0480)
Constant	0.0838	−0.473	−0.265	−0.221
	(0.183)	(0.330)	(0.321)	(0.216)
N	378	750	801	327
R^2	0.201	0.093	0.059	0.199
Adj. R^2	0.182	0.082	0.048	0.176

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

5.2 External mechanisms of economic policy uncertainty affecting innovation in pharmaceutical manufacturing firms

According to the theoretical analysis, increasing economic policy uncertainty increases the incentives for pharmaceutical manufacturing firms to innovate because economic policy uncertainty induces the government to intervene and subsidize firms. Therefore, this paper tests whether economic policy uncertainty leads the government to provide subsidies. Specifically, the following model is constructed:

$$Gov_{i,t} = \rho_0 + \rho_1 EPU_t + \delta Contral_{i,t} + \mu_i + \varepsilon_{i,t} \quad (7)$$

It is shown according to Equation 7, observing whether ρ_1 in the equation is significant or not, it can be determined whether internal mechanisms are affected by economic policy uncertainty. Second, we include the above mechanism variables in the benchmark regression and then test whether government subsidies induce firms to increase innovation intensity under economic policy uncertainty. The econometric model is as follows:

$$RD_{i,t} = \theta_0 + \theta_1 EPU_t + \theta_2 Gov_{i,t} + \delta Contral_{i,t} + \mu_i + \varepsilon_{i,t} \quad (8)$$

Observe whether the coefficients of the economic policy uncertainty index in Equation 8 are significant. Following the practice of Xie and Caij (55), the ratio of government subsidies to total assets or operating income is used as a measure, and the larger the ratio, the more government subsidies are invested.

Column (1) of Table 11 presents the estimation results of economic policy uncertainty on government subsidies. The results show that the regression coefficient of economic policy uncertainty is positive and significant at the 1% level, indicating that an increase in economic policy uncertainty leads to an increase in government subsidies. Column (2) includes government subsidies in the benchmark regression. The results show that the regression coefficient of government subsidies on gold is significantly positive when government subsidies are included in the benchmark regression. The coefficient of economic policy uncertainty on firm innovation is also significantly positive, indicating that economic policy uncertainty induces firms to improve their own innovation intensity by increasing government subsidies.

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TABLE 9 Analysis of ownership heterogeneity.

	(1)	(2)
	Non-SOEs	SOEs
LNPU	0.0055**	0.0003
	(0.0025)	(0.0007)
LEV	−0.0564	−0.0230*
	(0.0403)	(0.0127)
FCF	−0.254**	−0.0220
	(0.121)	(0.0165)
TQ	0.001	−0.0016**
	(0.0016)	(0.0007)
TOP1	0.0006	0.0006**
	(0.0007)	(0.0003)
SIZE	0.0171	0.0171***
	(0.0133)	(0.0056)
GL	0.327***	0.0667*
	(0.0623)	(0.0339)
HB	−0.0018	0.0004
	(0.0016)	(0.0004)
YX	0.0054	−0.0153
	(0.0405)	(0.0290)
Constant	−0.346	−0.355**
	(0.284)	(0.139)
N	840	288
R^2	0.087	0.198
Adj. R^2	0.077	0.173

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

TABLE 10 Internal mechanism of economic policy uncertainty on innovation in pharmaceutical manufacturing enterprises.

	(1)	(2)	(3)	(4)
	FIN	PAY	RD	RD
LNPU	0.0067***	0.0703***	0.0053***	0.0042**
	(0.0019)	(0.001)	(0.0017)	(0.0019)
LEV	−0.0292	−0.337*	−0.0369	−0.0312
	(0.0354)	(0.172)	(0.0319)	(0.0303)
FCF	0.0027	0.146	−0.182**	−0.185**
	(0.0626)	(0.277)	(0.0761)	(0.0752)
TQ	−0.0002	−0.0063	−0.0001	0.0001
	(0.0038)	(0.0081)	(0.0014)	(0.0015)
TOP1	−0.0013	−0.0017	0.0007	0.0006
	(0.0009)	(0.0047)	(0.0006)	(0.0005)
SIZE	0.0056	0.357***	−0.0075	−0.0149
	(0.0128)	(0.0739)	(0.0122)	(0.0113)
GL	0.0612	1.078***	0.152*	0.132
	(0.0799)	(0.287)	(0.0856)	(0.0896)
YX	0.160*	0.533**	−0.0244	−0.0271
	(0.0941)	(0.253)	(0.0411)	(0.0439)
YY	−0.003***	−0.0220*	−0.0005	−0.0002
	(0.0008)	(0.0111)	(0.001)	(0.0011)
FIN			0.0555**	
			(0.0256)	
PAY				0.0216**
				(0.0092)
Constant	−0.177	6.350***	0.201	0.0533
	(0.303)	(1.615)	(0.253)	(0.274)
N	1,128	1,128	1,128	1,128
R^2	0.099	0.332	0.066	0.076
Adj. R^2	0.091	0.327	0.058	0.068

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

5.3 Coping with operating cost shocks from economic policy uncertainty

Based on the analysis of internal mechanisms, this paper argues that firms increase the intensity of innovation investment by alleviating the financial pressure through internal financialization. Based on the theoretical analysis in the previous section, this paper argues that firms' innovation can cope with the negative shock to operating costs caused by increasing economic policy uncertainty. To test the above hypothesis from the perspective of whether firms can cope with the shocks caused by economic policy uncertainty by enhancing their advantages, the results are shown in Table 12.

Based on the research ideas of Zhu et al. (56) and others, this paper adopts a two-stage approach to analyze the economic effects of firms' innovation intensity to support the hypothesis. In the first step, the baseline regression is transformed into a differential form. Then, the change in firms' innovation intensity caused by the change in economic policy uncertainty is estimated:

$$\Delta RD / FIN_{i,t} = \omega_0 + \Delta EPU_{i,t} + \delta Contral_{i,t} + \mu_i + \varepsilon_{i,t} \quad (9)$$

In Equation 9, the fitted value of $\Delta RD_{i,t}$ is the real impact of economic policy uncertainty on firms' innovation intensity. In the second step, the following econometric model is constructed to estimate the impact of the change in firms' innovation intensity due to the increase in economic policy uncertainty on firms' operating costs, and then to test the economic consequences of the change in economic policy uncertainty.

$$\frac{\Delta cost_{i,t}}{\Delta cost_{i,t+1}} = \pi_0 + \Delta \overline{RD_{i,t} / FIN_{i,t}} + \delta Contral_{i,t} + \mu_i + \mu_t + \varepsilon_{i,t} \quad (10)$$

In Equation 10, $\Delta cost_{i,t}$ represents the difference between $cost_{i,t}$ and $cost_{i,t+1}$. The enterprise operating cost (cost) is calculated using the method proposed by Ye et al. (57) employs the operating cost ratio of operating income as a measure of enterprise operating risk (risk), which draws on the practice of Xin et al. (58) and utilizes the three-year rolling standard deviation of the total assets net interest rate.

The estimates of the relationship between firms' increased innovation intensity and their operating costs in the current and future

TABLE 11 External mechanisms of economic policy uncertainty affecting innovation in pharmaceutical manufacturing firms.

	(1)	(2)
	BT	RD
LNPU	0.001***	0.0053***
	(0.0002)	(0.0017)
LEV	0.0074	−0.0416
	(0.0057)	(0.0312)
FCF	0.0021	−0.183**
	(0.0095)	(0.0761)
TQ	−0.0004	0.0001
	(0.0005)	(0.0013)
TOP	−0.0001	0.0006
	(0.0001)	(0.0006)
SIZE	−0.0034**	−0.0057
	(0.0015)	(0.0119)
GL	0.0128	0.150*
	(0.0193)	(0.0837)
YX	−0.0073	−0.0125
	(0.0097)	(0.0401)
YY	−0.0003	−0.0005
	(0.0002)	(0.0009)
BT		0.424*
		(0.231)
Constant	0.0863**	0.154
	(0.0356)	(0.249)
N	1,128	1,128
R^2	0.045	0.069
Adj. R^2	0.037	0.061

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

TABLE 12 An analysis of the impact of operating cost shocks resulting from economic policy uncertainty on business strategies.

Variant	(1)	(2)	(3)	(4)
	D.CB	LD.CB	D.CB	LD.CB
RD	−12.45	−10.53		
	(510.97)	(58.07)		
FIN			−9.26	−7.83***
			(380.22)	(43.2)
Control variable	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes
Sample size	987	846	987	846
R^2	0.118	0.104	0.118	0.104
Adj. R^2	0.106	0.091	0.106	0.091

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

periods, respectively, are presented in columns (1) and (2) of Table 12. The effect of innovation inputs on current and future operating costs is found to be insignificant, with coefficients of −12.45 and −10.53, respectively. Columns (3) and (4) present the results of the estimation of the financialization indicator of the firms in relation to the change in operating costs in the current and future periods, respectively. The impact of financialization transformation within the firm on current period operating costs is inconsequential, with a coefficient of −12.45. However, the effect on future period operating costs is markedly negative, with a coefficient of −10.53. This suggests that increased investment in innovation is unable to offset negative shocks to operating costs caused by economic policy uncertainty. Financialization is unable to cope with the current cost shocks resulting from economic policy uncertainty. However, it is capable of coping with shocks to future operating costs. The reason may be that, although economic policy uncertainty has a negative impact on operating costs, the specific characteristics of innovation within the pharmaceutical industry, including the lengthy research and development cycle of new products, the stability of capital investment, and the increasing operating costs, prevent innovation investment from solving the problem of rising operating costs. Furthermore, financial transformation through the continuous configuration of its own financial resources serves to alleviate the phenomenon of financial mismatch, thereby reducing the cost impact of economic policy uncertainty.

The test results substantiate the hypothesis that pharmaceutical manufacturing enterprises are unable to mitigate the adverse effects of rising operational costs resulting from economic policy uncertainty through enhanced innovation intensity. Conversely, financialization has the potential to serve as a resilience mechanism against the anticipated negative impact of rising operational costs in the future.

5.4 Coping with operational risk from economic uncertainty

In light of the aforementioned analyses, it is postulated that firms are capable of adapting to adverse effects resulting from an increase in economic policy uncertainty. To substantiate this hypothesis, the same methodology is employed to conduct further tests, the outcomes of which are presented in Table 13.

Columns (1) and (2) of Table 13 present the estimated results of the business risk associated with firms' increased innovation intensity in the current period and the future period, respectively. The results demonstrate that there is a significantly negative correlation between firms' innovation intensity and business risk in both the current and future periods. The coefficients for the current period are notably lower than those for the future period, with values of −1053.4 and −79.6, respectively. This suggests that investment in innovation can serve to mitigate current and future business risks for enterprises, although the impact may diminish over time. This may be attributed to the fact that enterprises gain a competitive advantage by increasing their innovation intensity. Pharmaceutical enterprises enhance product competitiveness by increasing innovation investment and innovation pipeline research, which also strengthens enterprise confidence. This, in turn, prompts enterprises to adjust internal management and organizational structure and motivates management to enhance management work enthusiasm. The lengthy innovation cycle of the pharmaceutical industry, coupled with the fact that innovation funds are not utilized once, but rather at

various stages of the project, and that the subjects of the drugs in question must be evaluated over an extended period of time, means that the output of innovation does not serve to mitigate the risk faced by the enterprise in a timely manner. Consequently, the enterprise is still required to rely on the original product in order to generate profits for a period of time. Furthermore, augmented innovation investment disrupts the established market competition pattern. Consequently, enterprises must contend with heightened competitive risk, which in turn elevates the enterprise's future business risk. In the long term, the impact of innovation investment in mitigating risk will diminish.

Table 13, columns (3) and (4), present the estimation results of the financialization of firms with regard to the current period and the future period's business risk, respectively. The results demonstrate that the influence of firms' innovation intensity on both the current and future periods' business risk is markedly negative, with coefficients of −783.9 and − 59.2, respectively. Furthermore, the coefficients are notably lower. This demonstrates that financialization can persist in mitigating business risks by enhancing operational flexibility. However, due to the intrinsic nature of financialization, the capacity to navigate future enterprise risks has been diminished.

This demonstrates that the implementation of financialization and augmented innovation intensity by pharmaceutical manufacturing firms can effectively mitigate the business risks associated with rising economic policy uncertainty.

5.5 Impact of economic policy uncertainty on innovation outputs

The aforementioned theory is based on the innovation input aspect of the study. However, for a comprehensive analysis of the innovation process, it is necessary to divide it into two aspects: innovation input and innovation output. In order to examine the relationship between economic policy uncertainty and innovation, this paper employs the enterprise's patent applications in the current year as an explanatory variable in Equation 1, and performs a regression analysis. The results indicate that the coefficient of economic policy uncertainty is significantly positive at the 5% level, with a coefficient of 0. This suggests that economic policy uncertainty can facilitate firms' innovation output. It is anticipated that an increase in economic policy uncertainty by one standard deviation (2.03) will result in an 8.26% increase in the level of innovation output by firms (0.0407 × 2.03) (see Table 14).

TABLE 13 An analysis of the effects of coping with business risk shocks from economic policy uncertainty.

Variant	(1)	(2)	(3)	(4)
	D.risk	LD.risk	D.risk	LD.risk
rd_hat	−1053.4***	−79.6***		
	(222.07)	(28.34)		
FIN1_hat			−783.9***	−59.2***
			(164.30)	(21.08)
Control variable	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes
Sample size	705	564	705	564
R^2	0.024	0.031	0.024	0.031
Adj. R^2	0.009	0.013	0.009	0.013

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

6 Conclusions and recommendations

As economic development progresses, the normalization of economic policy uncertainty becomes a prevalent phenomenon. The rise of economic policy uncertainty gives rise to market turbulence and increased risk, which in turn have a far-reaching impact on the macroeconomy as well as corporate behavior. The question of how to deal with the impact of economic policy uncertainty has become a key area of research. The question of how to cope with the impact of economic policy uncertainty has also become a topic of considerable debate among high-tech and high-input industries, such as pharmaceutical manufacturing enterprises. This is particularly relevant in the context of China's pursuit of high-quality economic development and the objective of a healthy China. This paper examines the impact of economic policy uncertainty on corporate innovation in the pharmaceutical manufacturing sector. Additionally, the analysis is based on a review of Chinese A-share listed companies in the pharmaceutical manufacturing industry from 2015 to 2022. The final conclusions are as follows.

(1) An increase in economic policy uncertainty has been found to have a positive effect on the level of innovation undertaken by firms. (2) In comparison to state-owned enterprises (SOEs), non-SOEs demonstrate a greater propensity to adopt strategies that enhance innovation intensity in the context of economic policy uncertainty. (3) In the context of economic policy uncertainty, pharmaceutical manufacturing firms with management with overseas backgrounds and two jobs tend to increase the innovation intensity of their firms. (4) Further analysis indicates that rising economic policy uncertainty increases firms' own innovation intensity by prompting them to implement financial reforms, enhance executive compensation incentives, and secure government subsidies. (5) Further analysis reveals that while firms may enhance their innovation intensity and pursue financialization, this approach can help mitigate operational risk. However, the impact is often limited. With regard to operational costs, increasing innovation investment may not fully offset the adverse effects of economic policy uncertainty. Despite implementing financialization reforms, firms may not fully insulate themselves from the immediate impact of operational costs. However, they can anticipate and adapt to external operational cost fluctuations in the future. (6) An increase in economic policy uncertainty prompts pharmaceutical firms to enhance their innovation output.

In light of the aforementioned analyses, this paper puts forth the following policy implications in conjunction with the conclusions.

Firstly, for the government, the primary issue of research is the reduction of risk due to policy uncertainty, given the rapid changes in external macroeconomic policies. In light of the distinctive attributes of the pharmaceutical manufacturing industry, the industry's development is primarily driven by continuous innovation. The government's role is to provide guidance through signals to investors, facilitate information flow between investors and enterprises, and attract further investment. The influx of additional investors is expected to diminish the prevailing characteristics of the pharmaceutical manufacturing industry, namely

TABLE 14 The results of the basic regression of economic policy on innovation output.

	(1)	(2)
	PAT	PAT
LNPU	0.0511***	0.0407**
	(0.0152)	(0.0182)
LEV		0.214
		(0.399)
FCF		−0.161
		(0.532)
TQ		−0.0251
		(0.0306)
TOP1		0.0048
		(0.0072)
SIZE1		0.144
		(0.132)
GL		−0.368
		(0.493)
YX		−0.877
		(0.547)
YY		0.0345***
		(0.0122)
Constant	2.323***	−0.0480
	(0.0785)	(2.902)
N	1,128	1,128
R^2	0.019	0.035
Adj. R^2	0.018	0.028

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

its high cycle, high investment, and low return R&D. This is anticipated to have a stabilizing effect on the market for pharmaceuticals, while also reinvigorating the dynamism and vitality of China's drug research and development. It is incumbent upon the government to proactively disseminate efficacious policy information and to enhance the transparency, predictability, and efficacy of policy-making. The timely release of policy information via official channels serves to reduce market speculation and misunderstanding. In formulating and introducing economic policies, it is essential that the government conducts comprehensive market research, anticipates potential scenarios that may emerge following the implementation of policies, and strives to mitigate the risks that may arise. For state-owned pharmaceutical manufacturing enterprises, the introduction of appropriate incentives and penalty mechanisms can facilitate the rejuvenation of their innovative vitality. In addition, the establishment of a flatter management structure and process can enhance the enterprise's capacity to respond rapidly and flexibly to market changes. Furthermore, the challenges posed by economic policy uncertainty can be effectively addressed through the implementation of rapid decision-making and flexible adjustment.

Secondly, for enterprises in the pharmaceutical manufacturing industry, innovation represents a fundamental basis for their activities. Enterprise financial reform is frequently only a short-term solution that cannot address the underlying issue. It may, however, introduce a 'real to virtual' risk for pharmaceutical manufacturing enterprises. It is incumbent upon enterprises to define their own strategic innovation direction and goals. This must be done with an in-depth understanding of market demand, combined with macroeconomic policy and corporate development planning. The establishment of different cycles of innovation strategy is necessary to guide the enterprise in the face of fluctuations in different external environments and to maintain the stability of the innovation program. It is imperative that pharmaceutical manufacturing enterprises enhance their economic resilience and effectively navigate the challenges and opportunities presented by economic policy uncertainty. It is recommended that attention be focused on the training of internal management, the establishment of a reward and punishment mechanism, the integration of innovation into corporate culture, the encouragement of employees to actively participate in innovation activities, and the formation of a favorable atmosphere for all staff to innovate. It is essential to enhance the enterprise's innovation capabilities and accelerate technological innovation. It is essential to establish an effective risk management mechanism to identify, assess, and control the risks associated with economic policy uncertainty. In periods of elevated economic policy uncertainty, it is incumbent upon enterprises to proactively identify and pursue a multiplicity of financing channels, with a view to mitigating the financial costs and risks associated with their activities.

7 Limitations and future work

This paper is limited in that it focuses exclusively on the mechanism of innovation inputs, without analyzing the mechanism of innovation outputs or studying the quality of outputs. For the pharmaceutical manufacturing industry, the quality of innovation output may also be affected by certain factors. It would be beneficial for future research to investigate the impact of economic policy uncertainty on the quality of innovation output, with a view to proposing appropriate countermeasures.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: CSMAR.

Author contributions

ZW: Data curation, Investigation, Methodology, Project administration, Software, Writing – original draft. SW: Writing – review & editing. LK: Data curation, Methodology, Supervision, Writing – review & editing. YC: Supervision, Writing – review & editing.

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Conflict of interest

WZ and LK were employed by Betta Pharmaceuticals Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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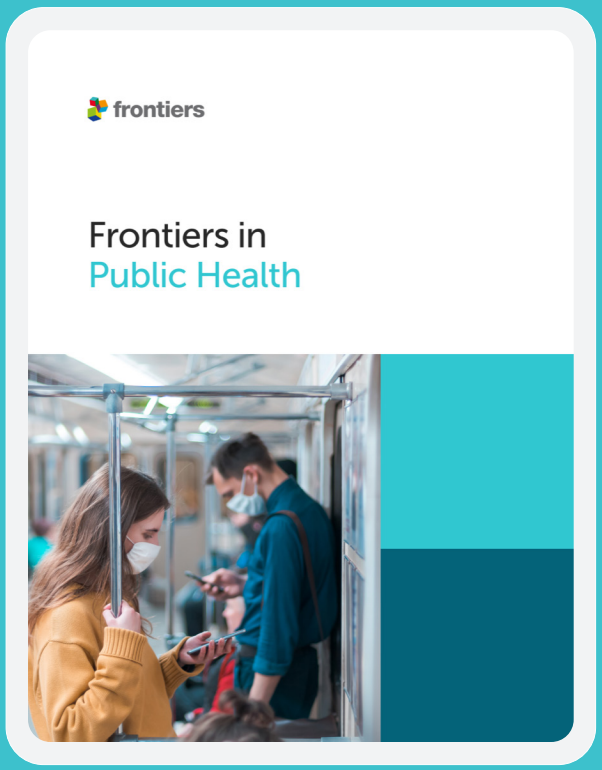

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